A framework to design and evaluate building integrated transpired solar collectors

by

Emmanouil I. Perisoglou

A Doctoral Thesis

Cardiff University

September 2022

Abstract

The present thesis develops a design and evaluation framework to integrate Transpired Solar Collectors (TSCs) into buildings and assess their performance. The aim is for the design to respond to heat and ventilation demand in conjunction with other traditional and novel systems. The aim for the evaluation is to be able to quantify the performance of real-life systems and their contribution to heat and ventilation demand. The work sets the scene by exploring the heating and ventilation demand for different building typologies and by studying the TSC technology parameters and developments. To this purpose, existing published case studies and design guides were reviewed. This revealed fragmented and abstract decision-making design and evaluation processes. The lack of a coherent design and evaluation framework was identified as a gap.

After literature data had been gathered, the framework was developed from findings analysed during 10 new experimental case studies in Wales, UK and supplemented with findings from a test rig. Data collection and monitoring techniques were utilised to provide high integrity information in both the design and evaluation sections. Modelling techniques were developed to enable feasibility studies and optimised design. Whereas monitoring using appropriate instrumentation ensured high data integrity for performance evaluation, which iteratively supported development of the design components of the framework. Communications with stakeholders and end users assisted in forming a framework that was tailored to occupant and market needs.

The framework was applied to the experimental case studies to demonstrate its pertinence and flexibility. The results from applying the framework to experimental case studies revealed challenges and opportunities when incorporating TSCs to innovative systems such as mechanical ventilation with heat recovery or exhaust heat pumps. This work is of benefit to anyone looking to integrate TSC systems in buildings, such as architects, engineers, designers and housing associations among others. Furthermore, the findings, methods and tools of this study can be extrapolated for other solar thermal systems, so it could provide additional benefits to designers and other disciplines.

To my beloved wife, Katerina

Acknowledgments

I wish to express my deepest gratitude to Dr Vicki Stevenson, my main supervisor, who deserves my sincerest and warmest thanks for her patient guidance, support and attention to detail throughout my research. I would also like to thank my second supervisor, Dr Simon Lannon for his supporting and productively provocative role and insightful comments.

In addition, I wish to thank various people for their continuous support; Professor Philip Jones, Professor Joanne Patterson, Huw Jenkins, Dr Gabriela Zapata Lancaster, Dr Ester Coma Bassas, Dr Xiaojun Li, Miltiadis Ionas, Dr Shan Shan Hu and Dr Hu Du for their useful comments and scientific and moral support. I would also like to recognise the invaluable assistance of the research teams I have been part of; The Sustainable Building Envelope Demonstration (SBED), Low Carbon Built Environment (LCBE) and LCBE SPECIFIC for their technical and managerial support and especially Dylan Dixon for his unconditional collegiality during our collaboration within the SBED monitoring tasks.

I wish to acknowledge the funding bodies that supported this work providing funding for the case studies implementation and research, the European Regional Development Fund (ERDF) through the Welsh Government, the Innovate UK, the Engineering and Physical Sciences Research Council (EPSRC) and the Wales and West Housing Association. Also, I am particularly grateful for the support of the Welsh School of Architecture, Cardiff University for funding my tuition fees and creating an equal, diverse and inclusive environment for me to complete this work.

I am extremely grateful to my parents for their love, prayers, caring and sacrifices for supporting my education and most importantly for supporting my exposure to new challenges. Also, I express my special thanks to my sisters and their families for their emotional support and encouragement. From the bottom of my heart, I would like to thank my life partner Dr Aikaterini Chatzivasileiadi who has been patiently supporting me in multiple levels, as a wife, friend, inspirer, reviewer and role model. Aikaterini's sacrifices during the writing up made me want to be a better person. Finally, I would like to thank our little son, Markos, and baby Arya whose arrival motivated me to complete this thesis and enjoy quality time with them.

List of Publications

- Jones, P., Li, X., Coma Bassas, E., Perisoglou, E. and Patterson, J. 2020. Energy-positive house: performance assessment through simulation and measurement. Energies 13(18), article number: 4705
- Perisoglou, E., Li, X., Ionas, M., Patterson, J., Coma Bassas, E. and Jones, P. 2019. Evaluation of building and systems performance for a deep domestic retrofit. Presented at: Climate Resilient Cities - Energy Efficiency & Renewables in the Digital Era (CISBAT 2019), Lausanne, Switzerland, 4-6 September 2019, Vol. 1343. IOP Publishing pp. 12176.
- Perisoglou, E, Ionas, M, Patterson, J. and Jones, P. 2019. Building monitoring protocol development for deep energy retrofit. IOP Conf. Ser.: Earth Environ. Sci. 329 012038
- Hou, S., Patterson, J., Li, X., Perisoglou, E. and Jones, P. 2019. Investigating the energy and thermal implications of installation of an air curtain and an automatic door in convenience stores in Wales. Presented at: 16th IBPSA International Conference, Rome, 2-4 September 2019.
- Li, X., Hou, S., Patterson, J., Perisoglou, E., Ionas, M., Jenkins, H., Jones, P., Lannon, S. and Coma Bassas, E. 2019. Modelling and Developing a neighbourhood low carbon system for five dwellings in the UK. Presented at: The 16th IBPSA International Conference, Rome, 2-4 September 2019.
- Drozynski, C., Brown, C., Jones, P., Schmieder-Gaite, T., Dixon, D., Jenkins, H., Perisoglou, E. and Waldron, D. 2018. Introduction of the TSC into emerging local markets in Wales. Presented at ZEMCH Network, 2018, Jan, Melbourne, Australia. Published at ZEMCH International Conference Proceedings, 2018.
- Perisoglou, E., Coma Bassas, E., Lannon, S., Li, X., Jenkins, H., Patterson, J., Jones, P. and Hou, S. 2018. Steady state and dynamic modelling of residential transpired solar collectors performance. Oral presentation at: BSO18, 2018 Sep, Cambridge, UK. Published at BSO Proceedings, 2018.
- Barclay, M., and Perisoglou, E. 2018. Experimental and numerical investigations of discrete heat storage materials. Presented at: UK Energy Storage Conference, Newcastle, UK, 20-22 March 2018.
- Jones, P., Li, X., Perisoglou, E. and Patterson, J. 2017. Five energy retrofit houses, in south Wales. Energy and Buildings. 2017 154:pp. 335-342.
- Perisoglou, E., Patterson, J., Stevenson, E.V. and Jenkins, H. 2017. Investigating the application of small scale transpired solar collectors as

air preheaters for residential buildings. 2017 Sep, Sustainability in Energy and Buildings: Research Advances, Vol. 6. No. 1: pp. 29-34.

- Perisoglou, E. and Dixon, D. 2015 Experimental monitoring of different dimensions of transpired solar collectors. Energy Procedia. 2015 May 31;70:111-120.
- Brown, C., Perisoglou, E., Hall, R. and Stevenson, E.V. 2014. Transpired solar collector installations in Wales and England. Energy Procedia. 2014 Dec 31;48:18-27.
- Perisoglou, E. 2007 Quantification and elimination of the thermal radiation in the calibration of isothermal chambers. 2nd National Metrology Conference, 2007 Oct, Thessaloniki, Greece. Published in Conference Proceedings, 2007.

Contents

List of Figures

List of Tables

Abbreviations

ACH	Air Changes per Hour
AHU	Air Handling Unit
BizEE	Business Energy Efficiency
BMS	Building Management System
BPIE	Building Performance Institute Europe
BRE	Building Research Establishment
BREDEM	British Research Establishment Domestic Energy Model
BSRIA	Building Services Research & Information Association (UK)
CAD	Canadian Dollar
CCA	Climate Change Act
CCC	Committee on Climate Change (UK)
CHP	Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of Performance
COVID-19	Corona Virus Disease 2019
DECC	Department for Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DHV	Direct Heating and Ventilation
ECO	Energy Company Obligation
EN	European Norms
EPBD	Energy Performance of Buildings Directive 2010/31/EU
EPC	Energy Performance Certification
ERP	Energy Research Partnership
EU	European Union
EU27	European Union of 27 countries (between 2007 and 2013)
FEMP	Federal Energy Management Program (US)
FIT	Feed-in Tariff
GBP	British Pound (Sterling)
GDPR	General Data Protection Regulation (EU)
GHG	Greenhouse Gases
HDD	Heating Degree Days
HE	Heat exchanger
HP	Heat pump
HSE	Health and Safety Executive (UK)
HTB2	Heat Transfer in Buildings – version 2

HVAC	Heating Ventilation and Air Conditioning
ICE	Institution of Civil Engineers
IDA	Indoor air quality (IAQ) classification (IDA 1 to IDA 4)
IEA	International Energy Agency
IES	Integrated Environmental Solutions
ISO	International Standards Organization
IPF	Investment Property Forum
KOE	Kilogram of oil equivalent
LCB	Low Carbon Buildings
LCBE	Low Carbon Built Environment (WSA research team)
LCDS	Low Carbon Development Strategies
LEDS	Low Emission Development Strategies
LPG	Liquid Petroleum Gas
MVHR	Mechanical Ventilation with Heat Recovery
NEED	National Energy Efficiency Data-Framework
NHS	National Health System (UK)
NREL	National Renewable Energy Laboratory (US)
NTC	Negative Temperature Coefficient
NZEB	Nearly Zero-Energy Buildings
NUT	National Union of Teachers (UK)
PDS	Process Drying Systems
PhD	Doctor of Philosophy
PHV	Pre-Heat and Ventilation
PHPP	Passive House Planning Package
PT100s	Platinum 100s (type of resistance temperature sensor)
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
PVGIS	Photovoltaic Geographical Information System
RED	Renewable Energy Directive
RHI	Renewable Heat Incentive
RTU	Roof Top Units
SAP	Standard Assessment Procedure
SBED	Sustainable Building Envelope Demonstration (WSA research project)
SBEM	Simplified Building Energy Model
SHC	Solar Heating and Cooling (IEA Group)
SPECIFIC	Sustainable Product Engineering Centre for Innovation in Functional Coatings

TM	Technical Memoranda
TMY	Typical Meteorological Year
TRNSYS	Transient Systems Simulation Program
TSC	Transpired Solar Collector
TUC	Trade Union Congress
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
WSA	Welsh School of Architecture

Symbols

A	Area of the TSC (m^2)
A_p	Projected area of the TSC (m^2)
A_d	Duct cross sectional area (m^2)
C_f	Fan's power conversion factor
C_p	Specific heat of air (1.007 to 1.048 kJ/kg.K around environmental Conditions at 1 atm pressure (1, 2)
I	Solar radiation (W/m^2)
L	Litre
$\dot{m}$	Air mass flow rate (kg/s)
Q_{del}	Heat delivery (W)
Q_{TSC}	Heat delivery at the TSC outlet (W)
s	Second
T_{amb}	Ambient air temperature (K or °C)
T_b	Baseline temperature (°C), in UK 15.5°C
T_{av}	Daily average ambient temperature (°C)
T_{coll}	Surface temperature of the collector (°C)
T_d	Air temperature in the beginning of the duct (K or °C)
T_{del}	Air temperature at the HVAC system outlet (K or °C)
T_{rec}	Air temperature recirculated back to the HVAC (K or °C)
T_{rise}	Air temperature rise caused by the TSC (K or °C)
T_{room} or T_{space}	Air temperature in the room or space (K or °C)
T_{TSC}	Air temperature at the TSC outlet (K or °C)
u_d	Centreline duct air velocity (m/s)
u_a	Average duct air velocity
W_{fan}	Specific work of fan (W)
β	Duct velocity coefficient =0.86 (3)
ε_{HX}	TSC heat exchange effectiveness
η	instantaneous efficiency of the collector
η_{eff}	Instantaneous effective efficiency of the collector and fan
ρ	Average density of air in the collector (kg/m^3)

1 Introduction

1.1 Aim and objectives

The principal aim of this PhD study is to develop a framework to design and evaluate building integrated Transpired Solar Collectors (TSCs) responding to heat and ventilation demand of buildings. The thesis presents decision-making processes to design TSCs in conjunction with other traditional and novel systems aiming to fulfil heat and ventilation demand. It also presents performance evaluation strategies to assess and quantify TSCs' real-life contribution to heat and ventilation demand.

The objectives of this study outline the steps to achieve the overarching aim of the thesis and are presented below:

Establish the current state of the art research status and gaps in relation to design and evaluation of TSCs by using existing literature TSC case studies to:

A. Analyse the design process followed.
B. Analyse the evaluation process and assess the energy contribution of the TSC with respect to heating and ventilation requirements.

Develop a framework to:

A. Integrate heat and ventilation demand, building envelope and systems into TSC design. Optimize control of TSCs through a commissioning process.
B. Evaluate the energy contribution and performance indicators of full scale, building applied TSCs.

Apply the framework to experimental case study and discuss the results.

1.2 Scope and focus

This research examined the TSCs heat and ventilation contribution to buildings and proposed a framework to effectively integrate and evaluate this technology in buildings. The study considered UK data, yet the framework is adaptable and expected to be applicable globally. Only unglazed TSCs were explored, as capital cost for glazed TSCs is significantly higher (section 3.1), thus these are out of the scope of this study.

The study analysed heat and ventilation demand for both the residential and non-residential sectors with a focus on houses, offices, schools, retail and industrial buildings within the UK context. TSC parameters found in the literature with a further focus on the building integration of TSC were also analysed. The study reviewed existing design guides and case studies with monitored results worldwide and identified gaps in the design and evaluation of the real-life installations.

Then the study indicated methods for the development of framework that suggested a holistic approach of designing and evaluating building integrated TSCs. The main principle of the TSC design framework was to fulfil the heating and ventilation demand with respect to the specific characteristics of the site and building including the effective integration of TSC with other air-based heating and ventilation systems. The framework was applied to residential and non-residential case studies in Wales, where design and evaluation details and results are presented and discussed (Chapters 7 & 8). The evaluation framework includes a proposal of monitoring techniques, instrumentation and a data analysis process which aims to overcome real application challenges and deliver robust performance indicators on the effectiveness of the system. The framework discussed has been structured to apply worldwide for both new buildings and retrofits.

1.3 Context

The UK has an ambitious target to reduce Greenhouse gas emissions by at least 80% against the 1990 levels by 2050 (4). This means a reduction from 800 $MtCO_2$ To 160 $MtCO_2$ whereas the 2022 figure is at 417 $MtCO_2$.(5). Significant efforts were made to reduce grid related emissions however 24% of the emissions come from buildings (6) as indicated in Figure 1-1.

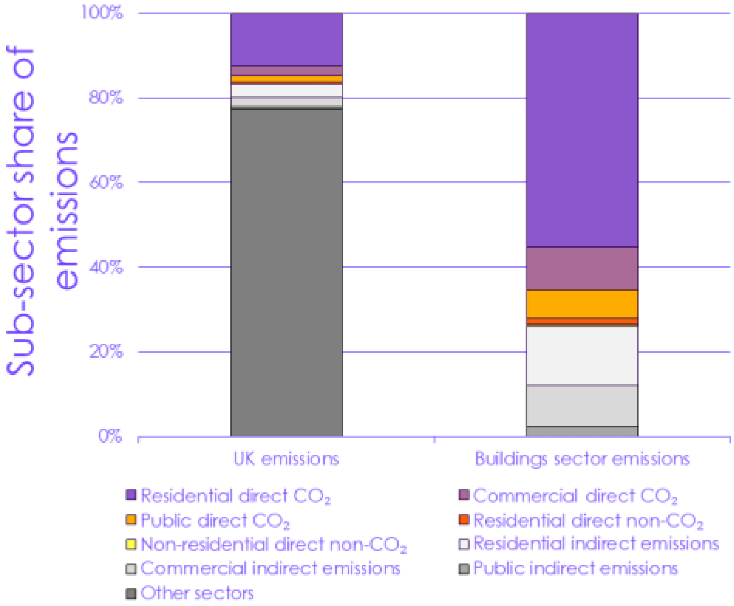


Figure 1-1. Emissions by sector in UK 2020 (6)

Buildings' emissions are primarily due to fossil fuel use in space heating; indirectly, buildings are also responsible for two-thirds of the power generation sector's emissions, mainly due to electricity demand from lighting, appliances and heating, ventilation and air conditioning (HVAC) (7). In industry, despite the noticeable structural efforts towards decarbonisation of the industrial output, there is a significant inflexible demand for space heating and mechanical ventilation (8).

Renewable energy share in the electricity generation has been remarkably increased in the UK reaching 40% in 2019, while in 2015 it accounted for 25% and in 2011 for about 10% (9, 10). Despite the encouraging figures, the aging power grid is not suited to the addition of significant further renewable energy (11). In addition, district heating has several limitations in terms of transportation methods and distribution length. For all these reasons, standalone renewable sources, especially building integrated heating systems is a sound fossil fuel reduction alternative. As low-carbon heat currently accounts for less than 2% of UK buildings' heat demand (7), solar thermal systems fits the low carbon building agenda using a technology which can be integrated into the building design and aesthetically pleasing.

1.3.1 UK building stock

The Town and Country Planning (Use Classes) Order 1987 (12) and its latest amendment in 2015 (13) places uses of land and buildings into various categories known as 'Use Classes'. The "A" use class refers to shops, financial and professional buildings and drinking and food establishments and in this document will be referred to as "Commercial". "B" use class includes premises used for research and development of products and processes, light and heavy industrial buildings and storage and distribution properties and in this study will be referred to as "Industrial". Use class "C" will be named "Residential" as it contains all accommodation such as houses, residential institutes and hotels. Finally, "D" use class describes all the non-residential institutes such as academic, assembly, leisure, etc. buildings and in this research will be called "Institutional". Categories A, B and D form the non-residential building stock.

UK making which It is estimated that 2.9 billion[1] m^2 are built in the UK. 25% of the country's total building capacity is non-residential; a sector that is complex and heterogeneous in terms of style, size, demand and usage patterns. Commercial buildings are the dominant player of the sector, accounting for 85% of the sector's value with an area of 679 million m^2 (including small industries) (14). The UK

[1] American English definition of billion (i.e. 1,000,000,000)

residential stock is one of the oldest in Europe as 75% of the homes are built before 1983 (2021 data) (15).

1.3.2 Building Heating and thermal comfort

Heating of a building has been historically a priority for human beings in order to create comfortable living conditions from the cave era until nowadays. Additionally, heating is necessary in activities such as drying and cooking and is also a crucial part of several industrial processes. For its “journey” from the source to the user, heat must be generated (through energy conversion), distributed and delivered.

There is a substantial variety of heat sources; a list based on the fuel and source medium can be found in Figure 1-2.

Figure 1-2. Heating source fuels and mediums (created by the author, based on ICE list (13)), photos collated from public domain.

Following generation, heat is then transferred to the building and to the end user (the human body) through one of the heat transfer mechanisms: radiation, convection, conduction.

The generation of heat is a process that involves the use of centralised or localised sources. The distribution method can be divided into two main categories: the district heating network from a central heat supplier and the local heating network (within a single room, flat or building). Centralised heat is usually transferred through pipes carrying steam, water or other fluid. Local heat can be transferred and distributed by passive air movement or diffusion through thermal mass, or actively by fan coils or air handling units, radiative panels (with supplementary fans) or pipes embedded in thermal mass (underfloor heating) (16, 17).

If the heating generation, distribution and delivery is the vehicle of heat supply, the driver is the control system. The amount (rate and temperature) of the heat delivered to the space can be controlled and scheduled. There is a range of automation systems regarding control systems, from manual thermostats to sophisticated multifunction processors which run decision-making software in order to create the desirable thermal comfort. The control is set during the commissioning; however, it is common to be re-evaluated and readjusted after a period of the building's occupation (16). The range of automatic decisions taken by the control system is a debatable topic within the building stakeholders' community. On one hand, there is a trend of "smart" highly automated systems which optimise the performance with minimum/no user intervention. On the other hand, there is a belief that occupants should have maximum involvement and be appreciative of full access and control.

A key factor of the control process of a heating system is the identification of the set temperature in order to manipulate air temperature surrounding the human body and provide thermal comfort. However, thermal comfort is not a number to reach; BS EN ISO 7730 (18) defines thermal comfort as *'…that condition of mind which expresses satisfaction with the thermal environment'*, i.e. the condition when someone is not feeling either too hot or too cold (19). In addition to fabric heat loss and by using the satisfaction definition, thermal comfort is also related to environmental factors other than air temperature, such as radiant temperature which is affected by the thermal radiation from a warm object, air velocity and humidity. Thermal comfort is also affected by personal factors such as clothing insulation and metabolic heat which is related to the work rate and activity (20). As all six factors describe satisfaction (by definition), they are affected by both the person's physical characteristics (size, weight, age, fitness level and gender) and personal preference which is a mixture of cultural and sociological parameters, described by Dodge et al. (2012), such as wellbeing (21). The quantification of heating demand and comfort within the building context will be discussed further in the literature review section.

1.3.3 Building Ventilation

Ventilation is the introduction and distribution of fresh air into a space. Awbi (2003), suggested that the quantity of the fresh (or outdoor) air has to be sufficient for the occupants to breathe and to dilute the concentration of the internal air pollution generated by humans, materials and equipment (22). The replacement of the "stuffy" air by fresh air is also strongly related to thermal comfort, as it can also assist to partly regulate internal temperatures and moisture and to create a breeze which could be essential for the comfort of the occupants. Ventilation can also be a provision of air for fuel-burning appliances and in many cases is subject to a legal minimum requirement (23).

Building ventilation can be produced mechanically, which is also called forced ventilation, or naturally (natural ventilation) as a result of pressure difference. Mechanical ventilation is driven by fans that are placed on the building envelope directly (walls or windows) or in ducts; in both cases, they can force the air into or out of the building for supplying or exhausting respectively. Natural ventilation refers to intentionally designed passive methods of bringing outside air into a space without the use of mechanical systems (24).

During the heating season incoming fresh air significantly increases space heat demand. When mechanical ventilation is mandatory and a priority, considering to bring heat or "coolth"[2] (25) into the building through the ventilation system by the use of combined units such as Air Handling Units (AHU) could be effective. Ventilation needs and systems will be analysed in depth in Chapter 2.

1.3.4 Low Carbon Buildings

Every time we burn fossil fuels such as gas, coal or oil, we release greenhouse gases (GHG), such as CO_2 that is the main GHG, into the atmosphere. In a natural carbon cycle, CO_2 is re-absorbed by natural "sinks" and turned into a form of carbon. However, this is a long process and, in some cases, it takes millions of years. The anomaly in the natural carbon cycle started from the industrial revolution when people began to burn fuels so quickly that the planet had no chance of soaking it up. A 40% increase of CO_2, which is the main carbon emission has been calculated for a time period from 1750 to 2015 (26). GHG absorb or/and emit infrared radiation in the wavelength emitted by the earth (27). Excess of GHG due to human activity results in warming effects in the atmosphere, the ocean and the land (28).

This section considers the policies that have been developed towards the enhancement of low carbon buildings, followed by building integrated technologies which could make this feasible.

[2] Coolth is not a scientific term as there is not such form of energy. The accurate term is "lack of heat or reduced heat; however, the term is recently defined in oxford dictionaries as "pleasantly low temperature" and used by building service engineers and the market to communicate system's air conditioning mode.

1.3.4.1 Policies and initiatives

The concept of low carbon development and strategies has its roots in the United Nations Framework Convention on Climate Change (UNFCCC) adopted in Rio in 1992 (29). In the context of this agreement, low carbon development is accompanied by the terms ‘Low Emission (or Carbon) Development Strategies’ (LEDS or LCDS), which are also known as low-carbon growth plans. LEDS are generally used to describe forward-looking national economic development plans or strategies that include low-emission economic growth (30).

The building sector is a dominant player in economic growth and a prevailing contributor to carbon emissions. On the positive side, it has significant potential for delivering substantial and cost-effective GHG emissions reduction (27, 31). Hence, various studies and projections were made by institutes, numerous strategies were considered by organisations and a series of policies were adopted by governments in order to reduce building carbon emissions. There are no emissions thresholds under which a building would qualify as a Low Carbon Building (LCB); however, LCBs can be indirectly defined following UK emissions reduction targets at 100% in 2050 relative to 1990. This optimistic target firstly appeared in the Stern Review (32) at 80% and adopted by CCC in 2008 through the Climate Change Act (CCA) (33) and later revised and adopted by the UK government at 100% in 2019 (34).

Since 1995 when the UK and other countries signed the Kyoto Protocol, the British Government took several steps to limit UK GHG emissions. The CCA established a framework to develop an economically credible emissions reduction plan. CCC was setup as the advisory panel and two key government departments were charged with setting climate policy: the Department for Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (DEFRA) (35). The Energy Performance Building Directive (EPBD, 2010 recast) (36) is the main legislative instrument, at the European level, for improving the energy efficiency of buildings (37). A key element of the EPBD is its requirement for Nearly Zero-Energy Buildings (NZEB). Following the directive, in 2011 the ambitious “Carbon Plan” was published as a CCA continuation strategy with a focus on the fourth carbon budget which required 50% reduction below 1990 levels from 2023 to 2027 (38). The Carbon Plan authorised DECC to extend Energy Performance Certificates (EPC) to the commercial building sector. However, the ground-breaking commitment of the Carbon Plan was to deliver zero carbon new homes from 2016 and zero carbon new non-domestic buildings from 2019 (39). The plan was later abandoned as non-realistic after pressure from the market, articulated in “Fixing the foundations: creating a more prosperous nation” in August 2015. It indicated that the market needed time to adopt the measures: *"existing measures to increase energy efficiency of new buildings should be allowed time to become established"* (p.46 (40)).

EPC is an energy rating certification firstly introduced in England and Wales for domestic properties with four or more bedrooms and over time this requirement was extended to smaller properties and the commercial sector. The assessment is a result of the European Union Directive 2002/91/EC discussing the energy performance of buildings, as transposed into British law by the Housing Act 2004 and the energy performance of buildings regulations (certificates and inspections for England and Wales - Regulations 2007 (41, 42)). EPCs are required by law whenever a property is built, sold or rented and the assessment performed by an accredited assessor who examines items that passively (e.g. insulation) or actively (e.g. radiators) affect the energy performance of the building. A calculation protocol is used for the numerical evaluation that gives a number from 0 to 100 and a letter from G to A for the energy efficiency rating and another one for the potential improvement. It also contains information about energy cost and recommendations about how to achieve improvements and save money (43). If the building is a house, flat or apartment, the Standard Assessment Procedure (SAP) calculation method is used whereas any non-domestic building requires a Simplified Building Energy Model (SBEM) calculation. The accuracy of EPCs have been criticised (44, 45) and changes have been discussed to improve the system, engage consumers and support net-zero GHG emissions policies .

The Minimum Energy Efficiency Standard (MEES) came into force in England and Wales in April 2018. This applies to private rented residential and non-domestic properties and is aimed at encouraging landlords and property owners to improve the energy efficiency of their properties by a restriction on the granting and continuation of existing tenancies where the property has an Energy Performance Certificate Rating of F and G. The MEES is E and above with a deadline for landlords to have complied by the 1st of April 2020 for domestic and by 1st of April 2023 for non-domestic buildings (46).

Several other governmental environmental programmes aim to boost low carbon buildings culture and economy and a selection is presented below:

- **Energy Company Obligation** (ECO) is an energy efficiency scheme. It requires larger energy suppliers to deliver energy efficiency measures to domestic premises and focuses on the installation of insulation and heating measures.

- **The Feed-in Tariff** (FIT) scheme was a government programme designed to promote the uptake of a range of small-scale renewable and low-carbon electricity generation technologies.
- The domestic and non-domestic **Renewable Heat Incentive** (RHI) is a financial incentive to encourage a switch to renewable heating systems (47). The RHI considers four eligible domestic technology categories: biomass boilers and biomass pellet stoves, air source heat pumps, ground source heat pumps and solar thermal (47). All renewable heating systems in the domestic RHI must be certified by MCS (Microgeneration Certified scheme). This is an internationally recognised quality assurance scheme supported by the UK government. Participation in the non-domestic RHI scheme demands a case-by-case accreditation - the installation has to meet several eligibility criteria. Unfortunately for the domestic scheme, only hot water solar thermal panels such as liquid filled flat plate or evacuated tube solar collectors are eligible (October 2019), meaning that any solar thermal space heating technology such as TSCs are not currently eligible.

1.3.4.2 Renewable Energy in Buildings

Despite the significant global, European and UK efforts, almost half of the UK's GHG emissions still come from the energy used to generate heat (35). Another relevant statistic is that half of all CO_2 emissions come from the building sector (48). The vast majority of the British building stock is poorly insulated and relies on fossil fuel powered boilers (7).

Building retrofitting is high up in the EU's energy efficiency agenda; the Building Performance Institute Europe (BPIE) claims that 97% of the buildings in the EU need to be upgraded (49). This is more significant in countries with old buildings such as the UK where emissions from buildings accounts for 37% of the total emissions and 2/3 of this comes from residential properties (50, 51). The Welsh building stock is one the oldest in Europe with 75% of the houses built before 1980 and 36% before 1944 (52). From 1976 building standards have been established to ensure high standards of energy efficiency in old and new-build properties. Improvements to the existing building stock is of a major importance, in order to reduce emissions, energy bills and levels of fuel poverty and increase the standards in comfort and health (51, 53-55). Governments push the market by providing incentives and schemes to offer a variety of routes towards low carbon retrofitting. However, the design and implementation of technologies in existing, occupied dwellings is a challenging process involving a variety of stakeholders and expertise. Deep retrofitting based on a mixture of well-established and innovative technologies with respect to aesthetics has significant and measurable benefits whereas it can be a costly and challenging process.

The construction market is increasingly responding to low carbon policies and initiatives by implementing active and passive strategies in new or retrofitted buildings. There are a number of renewable energy technologies that can be applied in, on or near a building or a set of buildings. These can be categorised by the form of energy they produce. Renewable energy technologies generate electricity, heat or both and the most representative methods are shown in Table 1-1 (based on data from Carbon Trust (56)).

Table 1-1. Renewable energy forms, technologies and feasibility for building applications based on (56), autho (continued overleaf)r.

Renewable energy forms for application on/near building	Renewable energy technologies for application on/near building	Feasibility, applicability and considerations
Electricity generation	Wind power - small scale wind turbines	Low feasibility. Better for large buildings, large area is needed. Noise and flickering problems.
	Solar power – PV Solar Panels	High integration, restrictions due to orientation and inclination of elevation and roof. High aesthetic solutions.
	Hydro power – Small-scale immersed water turbines	Low feasibility. Better for large buildings. Highly site-specific as it requires flowing body of water with specific drop in level.
Heat generation	Solar water or air heaters	High integration. Variety of technologies, good applicability in existing buildings. Storage losses considerations.
	Biomass – burners of organic material	Small burners more feasible. Fuel should be carbon cycle neutral; space, exhaust and air quality considerations.

Renewable energy forms for application on/near building	Renewable energy technologies for application on/near building	Feasibility, applicability and considerations
	Anaerobic digestion – Organic break down by bacteria	Low feasibility. More feasible for industrial plants with high organic waste products. System balance considerations.
	Ground/Air/Water heat pumps	Ground is more suitable for new builds. Water heat pumps require appropriate body of water nearby. Air to air is more feasible, but there are efficiency, heat transfer and storage considerations.
Combined Heat and Power (CHP)	PV+Thermal PV panels with embedded water or solar thermal technologies	High aesthetic integration. PV cooling benefit. Heat transfer and storage considerations.
	CHP plants – Fuel cells/ combustion engines or anaerobic digesters using renewable power source	Low feasibility. More suitable for industrial applications. Large area is needed.

1.3.4.2.1 Renewable Energy Systems and Building Envelope

In the last decades there is a technological effort to harness the wind and sun power that reaches a building. In this regulatory context which pushes zero/nearly- zero carbon buildings, aesthetically pleasing renewable energy technology solutions are becoming increasingly required by the stakeholders. Whole house approaches such as Passivhaus or Energiesprong (citation) would prioritise super-efficient thermal wrap with renewables. Technologies that are integrated in or attached to the building shell have been developed prioritising aesthetic considerations. From the building element point of view, there are integration possibilities on the cladding (façade, roof), the glazing (façade, roof, skylights) and the shading devices.

Some futuristic building designs have incorporated wind turbines (57), either attached or integrated; yet this technology raises many concerns such as safety, structural difficulties, noise, vibration, flickering, low efficiency etc., which prevent the market from a sustainable development (58).

On the contrary, building integrated solar systems are now routinely able to provide electricity, heat or both (hybrid). Solar panels are relatively easy to integrate in a building because of their shape, modular nature, lack of mechanical components and lack of noise. There are constraints such as orientation, weight, area availability, sun intermittency and cost (59); however, they offer greater flexibility and in most of the cases medium- and long-term predictability compared to wind technologies (60). In some instances, compromises have to be made between the efficiency and the aesthetic quality of the solar panel installation; however, nowadays, solar technologies can be extremely flexible, thin and of high efficiency which allows existing building products to be developed with integrated solar technologies (61).

1.3.4.2.2 Building Integrated Solar Thermal Technologies

A large number of solar collector systems are available in the market (62); yet only a portion is considered suitable for building integration. Besides the necessity of technical and structural effectiveness, solar thermal systems should consider aesthetic criteria for good practice such as the ones set by IEA-SHC Task 41 (63). Achieving both high architectural quality and high energy performance is a significant challenge for a technology that requires a medium with significant volume specifications in order to convert, transport and store the extracted energy.

Geothermal can be considered an indirect solar thermal technology; however, it is integrated to the building site rather than the building skin. In this study, building integrated solar thermal technology includes two main categories: solar thermal collectors and Photovoltaic/Thermal (PV/T) collectors. According to Buker and Riffat (64) there are a number of different systems that fall into these two categories, which are listed in Table 1-2.

Table 1-2. Categories of Building Integrated Solar Thermal Collectors, author

Building Integrated Solar Thermal Collector Categories	
Solar thermal collectors	**(PV/T) collectors**
Solar thermal air collectors	PV/T air collectors
Solar thermal water heaters	PV/T water collectors
Roof integrated mini-parabolic solar collectors	Refrigerant based PV/T collectors
	Heat pipe-based PV/T collectors
Ceramic solar collectors	Concentrating PV/T collectors
Polymer solar thermal collectors	Hybrid PV/T transpired collectors
Solar louvre collectors	

Although there are technical difficulties in combining a photovoltaic and a solar thermal panel, there are significant benefits as well. The overall efficiency increases as waste heat from the photovoltaic panel is used by the thermal collector, allowing the photovoltaic process to operate at a more efficient temperature range (65).

The fundamental principle of any solar thermal technology is the heat exchange mechanism that converts solar radiation to thermal energy embedded in a transport medium. The solar thermal collector absorbs the energy and transfers it to a fluid (usually water, glycol, air or oil). The fluid is then circulated either to a wet or air distribution system or to a storage tank in order to be used on demand. Most of the flat plate collectors have a transparent surface in front of the dark-colour high absorptivity plate. Glass is commonly used as the transparent cover in order to reduce convection losses from the absorber and moderate radiation losses as it traps long-wave thermal radiation which is emitted back by the plate (66).

Installation of the circulation system and storage is challenging, and in some cases, freezing issues have to be dealt with in cold climates. The cost of installation and maintenance is considerable. On the other hand, these systems are very efficient, as more than 80% of radiation is turned into heat energy and they can provide both domestic hot water and heating (67). Solar air heating systems are less complicated and expensive, they do not suffer from freezing issues and leakages do not have such severe impacts. However, air has poor heat transfer properties which means that a large volume of air is needed to heat the space and storage of warm air is not practical (68).

When it comes to the selection between solar water or solar air system, there is no overall established argument to support a global preference. It is fair to say that the two technologies are very different as they serve different purposes. Air heaters provide ventilation with the supplementary benefit of warm air, whereas water systems provide hot water. Both mediums face heat transfer challenges but when heat is transferred through air, low gradient heat recovery and utilisation challenges occur.

Air heaters can be glazed or unglazed which depends on the heat conversion process. They can provide heat and ventilation as individual systems or in conjunction with existing or new HVAC systems. This study focuses on transpired solar collectors, which is an unglazed system with high building integration potential for all type of buildings (residential and non-residential), as there is a range of aesthetically accepted metal cladding types in a range of colours commercially available (69).

1.3.5 Transpired Solar Collector

Transpired Solar Collector (TSC) is a solar thermal technology which heats or preheats the ventilation air supply to buildings and can be integrated into the building envelope (69). Figure 1-3 demonstrates the operational principle of the technology. Fresh external air is drawn through micro perforations by using a fan. As the air is driven in the cavity, it gets heated predominantly from the solar absorbing front sheet, then by the evenly spaced perforations and finally by the cavity itself. The heated air can then be directly distributed into a building through a mechanical ventilation system or ducted into an air heating or HVAC system. In the first case the TSC is a standalone system that heats the ventilated air and in this study it will be referred to as a Direct Heat and Ventilation (DHV) TSC. In the second case TSC is feeding the HVAC system with pre-heated air and will be referred as a Pre-Heat and Ventilation (PHV) TSC. In both cases a feasibility study should be performed to investigate suitability.

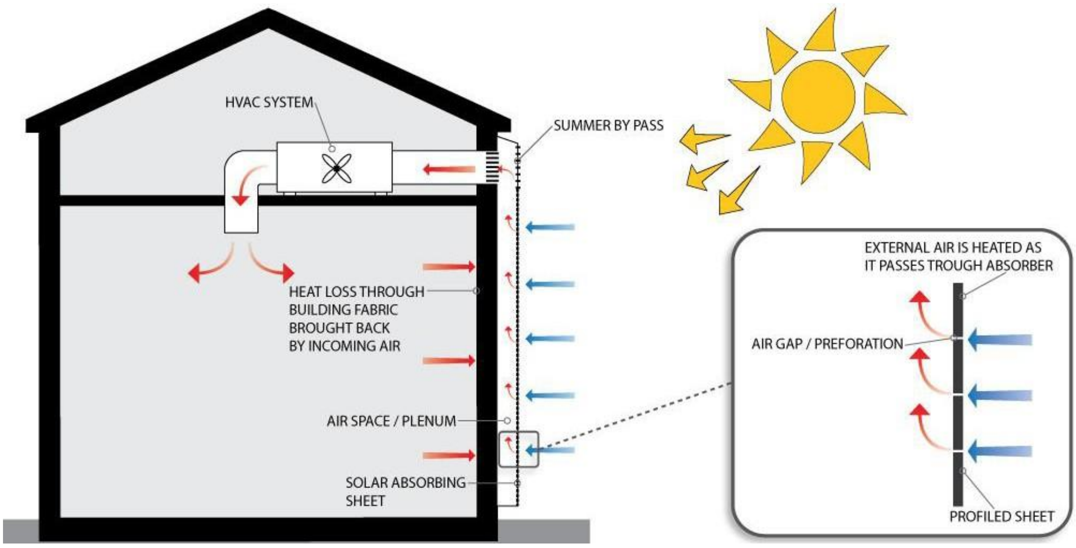


Figure 1-3. TSC generic diagram (69).

A TSC system includes the perforated panel, one (or more) fan(s) and appropriate connection and distribution ducting. Further optional components could be a summer bypass input or a recirculation input which redistributes internal air (Figure 1-4). Also, dampers, filters and diffusers could be necessary, as well as sensors and controls in order to run the system.

The TSC increases the air temperature from ambient (T_{amb}) up to TSC output temperature (T_{TSC}). This equals the delivery temperature (T_{del}) unless there are other mixing flows (recirculation or bypass). This is a typical DHV system. For a PHV system, the main heating and ventilation system will drive the flow, and appropriate control adjustments are needed. The main parameters of the technology will be analysed in Chapter 3. Although the TSC technology has been used extensively in USA and Canada since early 1990s, it is a relatively new technology in the UK (69). TSCs have other applications especially in drying processes; however, this study will focus on building integrated TSC and their relationship to building demand only.

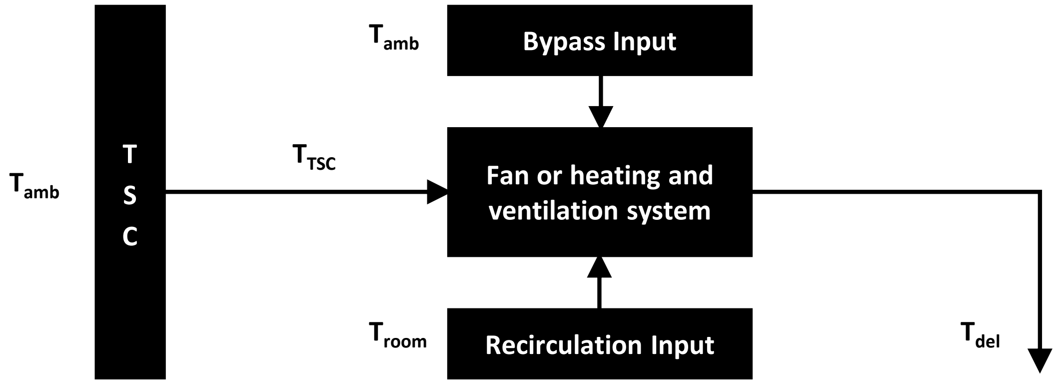


Figure 1-4. TSC system diagram, author.

1.4 Significance of study

A TSC design and evaluation framework was developed based on findings from literature and empirical case studies. Although the empirical case studies have been based in South Wales, the framework has been developed to be applicable to a wider geography, through the input of project specific details.

Through this study a framework is developed and proposed where findings from the literature, existing case studies and experimental case studies are integrated and critically discussed in order to develop and propose a framework that can be used to design and evaluate building integrated TSC systems. The process followed in the literature and existing case studies was found to be fragmented and occasionally included abstract decision-making, whereas the framework proposes a holistic approach taking into consideration ventilation needs and heat demand. This work is of benefit to anyone looking to integrate TSC systems in buildings, such as architects, engineers, designers and housing associations among others. Furthermore, the findings, methods and tools of this study can be extrapolated for other solar thermal systems, so it could provide additional benefits to designers and other disciplines. The framework is presented in detail in Chapter 6 and discussed accompanied by a framework workflow and a concise framework design guide in section 8.3. The concise design guide aims facilitate design feasibility and decision by a broad audience interested in TSC application in building.

1.5 Thesis structure

Chapter 1 is the introduction which sets the aims, objectives, methods, principles and context of the work. The context follows a demand-supply approach; it starts with an overview of UK building stock and the need for thermal comfort, heat and ventilation and then low carbon buildings are analysed with a focus on integrated renewable energy technologies and especially solar heating. Elements of the TSC technology are introduced in order to establish the relevant vocabulary for the following Chapters. The Introduction also includes a significance of study statement and a structure section that is summarised in Figure 1-5.

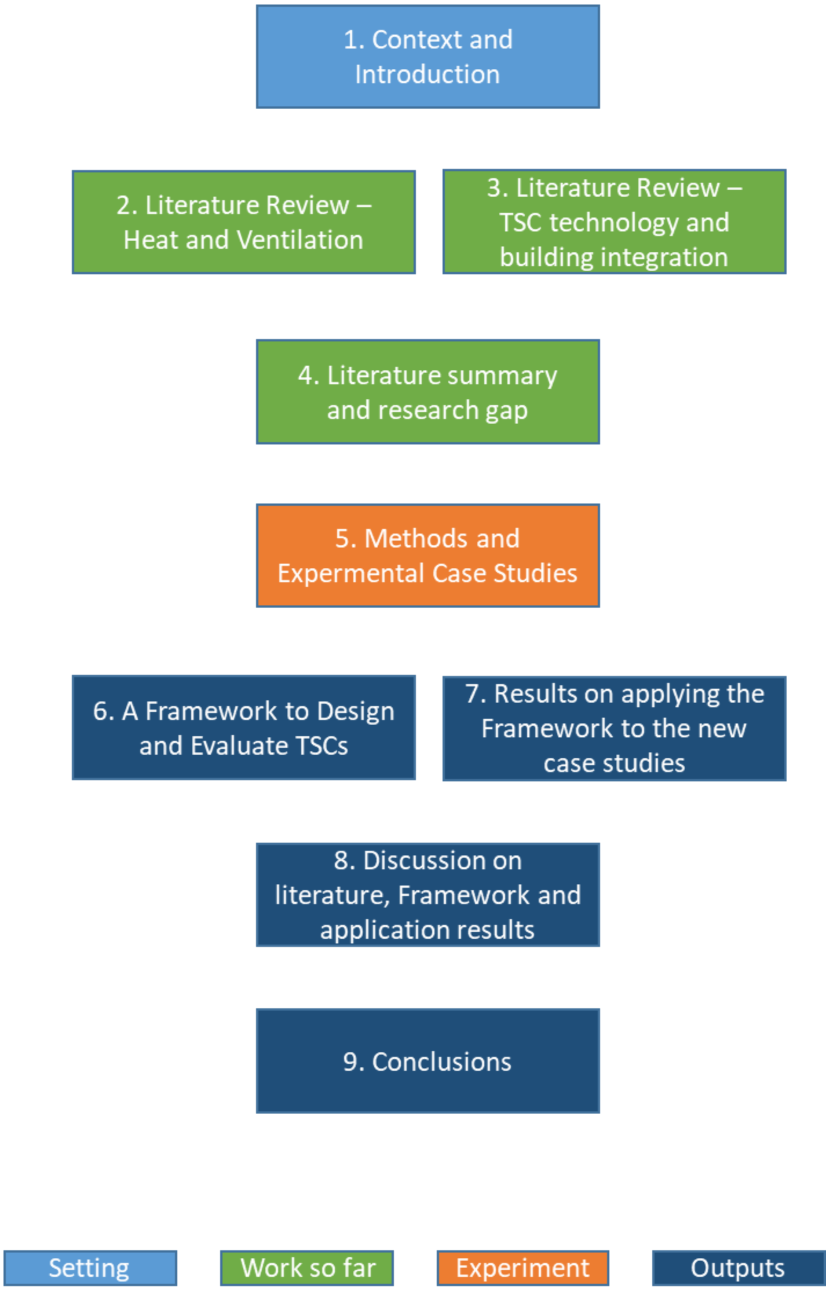


Figure 1-5. Structure of the thesis, author.

Chapters 2 and 3 are the literature reviews which form the foundation of this research. Building heating and ventilation demand is investigated for the UK building stock for both residential and non-residential buildings. The TSC technology is parametrised as a collector and as a building integrated system. Existing design guides as well as 15 existing, real case studies with building integrated TSC are grouped and analysed with a further focus on:

- The TSC design principles and how these are related to the heating and ventilation demand in conjunction with other heating and ventilation systems.

- The performance evaluation procedure including monitoring, instrumentation and data analysis and visualisation.
- The commissioning and optimisation methods to adjust controls and ensure effective performance.

Chapter 4 summarises the literature and frames the research gap; it establishes the need for introducing and studying fresh, new real-life case studies with a holistic view on the design of the TSC with respect to demand priorities as well as on an effective performance evaluation mechanism.

Chapter 5 communicates the methodological approach taken in this work in order to respond to the research objectives. The tools that have already been introduced are explained and correlated to specific objectives and outputs. The chapter also introduces the new experimental case studies used to produce the outputs of this work including the author's detailed contribution.

Chapter 6 is the development of a framework to design and evaluate TSCs is presented. A demand-based design approach is proposed, where the building and the occupants' needs drive the TSC design decision-making process. A monitored-data evaluation approach is also proposed, where the TSC contribution to heat and ventilate a building is quantified.

Chapter 7 is the application part of this study and includes the results of the experimental case studies. A variety of different buildings with different occupancy patterns and services are used to demonstrate a design and evaluation approach in real applications. The Chapter follows and discusses the framework in practice. Post-installation monitored data are compared and discussed against modelling and monitored pre-installation findings. Cost parameters are also considered.

Chapter 8 discusses the literature and how it compares to the introduced and applied framework. The feasibility, applicability and limitations of the framework are considered with respect to building heating and ventilation demand. The match between demand profiles and TSC supply is summarised and assessed.

Chapter 9. The conclusions of this study discuss the objectives and how they were fulfilled by the analysis. This Chapter also evaluates the progress made in answering the stated aims. Also, as this study includes a variety of real-life bespoke and innovative applications involving a variety of stakeholders, a "lessons learnt" discussion is included in this Chapter. The final part refers to any potential research pathways triggered by the findings of this study.

2 A review of Heat and Ventilation Demand

As a TSC heats or preheats the ventilation air supply, it has an impact on both heating and ventilation of the building. In order to quantify, evaluate, compare and optimise this impact and design a TSC system, a review on buildings' heating and ventilation demand is necessary prior to the analysis on the potential TSC heat and ventilation supply side.

The UK heating and ventilation demand is established in this Chapter based on legislation and recommendations of appropriate organisations. Heating demand, energy use and comfort are also discussed with a focus on how to predict or measure such quantities in domestic and non-domestic building types. Moreover, indoor temperature is discussed as a vital component of comfort that affects both heating and ventilation strategies in a building. Then, ventilation types and demand are discussed with a focus on mechanical ventilation that works with a potential solar air heater. For both heating and ventilation metrics, benchmarks from a variety of sources are included as a reference associated to any heating and ventilation analysis. The benchmarks refer to residential, institutional, commercial and industrial buildings to respond to the range of case studies discussed later in this study.

Literature then focuses on the supply side – the TSC, which is the solar air heating technology investigated in this study (Chapter 3). The parameters of the technology are initially discussed in the context of the TSC as a standalone collector, and through a number of case studies, as a building-integrated system. The aim of the technology literature review is to provide a better understanding of how the panel was optimised and the key factors that would affect its performance. The aim of extending the literature review to real case studies is to understand how design and optimisation decisions were taken and how the system was evaluated and performs in domestic and non-domestic buildings.

2.1 Space Heating demand and comfort

Space heating demand is the amount of active heating input required to heat a building and is usually expressed in kWh, or kWh/yr ([3]) or kWh/m^2/yr ([4]) (70). It is often calculated using building energy software applications, calculation platforms and interfaces such as EnergyPlus, IES, Tas, TRNSYS, HTB2, SAP, SBEM, PHPP, Design Builder, Open Studio, Sefaira, Insight, Grasshopper (70-72). Heating demand does not equal to the energy used (consumed) for heating which is an indication of how users use a building which at times can be over- or underheated and is also measured in the same units. Also, energy consumed for heating is not always the same as heating delivered, as systems are not always 100% efficient; boilers could deliver approximately 80 to 90% of what they use, whereas heat pumps could have a Coefficient of Performance (COP) of 3 or more. Thus, heating demand is the theoretical and heating delivery is the pragmatic quantity indicating the real-life active heating input to the building. A supplementary metric is the space heating peak demand which is the maximum instantaneous heating demand of a building expressed in power units (kW, kW/m^2) and is the dominant factor in sizing a heating system in order to meet the maximum heating load requirements.

VHK Research Engineers, a technical consultant for EU, after calculating the average ambient heating season ambient temperature for EU capitals and the UK, commented that heating services in EU buildings is a priority (73). The heating requirements are defined by the users' building comfort levels and especially the desirable indoor air temperature. Despite several Europeans Norms (EN) on calculating energy for space heating (i.e. EN13790 or EN15316) when it comes down to providing comfort temperature targets, they refer to national codes (73). For this reason, before the exploration of buildings' heating requirements, the identification of a comfortable indoor temperature is crucial for any heating study. There are two main comfort models, the predicted mean vote model, and the adaptive model. The first was developed using heat balance principles and climate chamber experimental data under steady state conditions. The second was based on field studies and suggests that people dynamically interact with their environment, including ventilation controls.

[3] Energy can be also calculated for a different duration, i.e., per month or per day or per average day for a specific duration, i.e., month, year, heating season.

[4] The term "per m^2" in heating delivery/demand context means 'per square meter of floor area'. In some cases that will be clarified later in this work it could mean 'per square meter of TSC collector'.

2.1.1 Indoor Temperature

Indoor air temperature is affected by the ambient air temperature, building fabric, internal gains, heating elements and occupants' comfort needs. The climate and technical factors can be objectively modelled or measured; however, thermal preference is a result of socioeconomic, cultural, physiological, and psychological variables. It is evident that indoor temperature is lower in poverty causing health issues. Also, overheating is expected to increase due to the environmental crisis. Desirable indoor temperature is a vital component in designing of HVAC systems and controls. It also applies to modelling and monitoring exercises as it is a dominant factor in heat balance and heat demand equations, as well as in quantifying a meaningful heating delivery. Guidance on indoor temperature aims to assist the control of heating/cooling technologies to avoid underheating or overheating.

2.1.1.1 Residential buildings

Building energy models in the past were broadly based on the British Research Establishment Domestic Energy Model (BREDEM) (74). The literature on BREDEM (1995) suggested a global[5] thermostat setting of 21°C and a heating period of 9 hours per day (16 hours during weekend was added in BREDEM version 8). One step further, the West Midlands Public Health Observatory (UK) recommends 21°C for the living room temperature, and 18°C for the bedroom as mentioned in Michelle Roberts article (2006) on BBC (75). Since then, a number of temperature monitoring studies have been undertaken in the UK that started to gain insight into indoor temperatures in dwellings. Oreszczyn et al. (76, 77) monitored the temperature in over 1600 low income dwellings and the average living room temperature was reported to be 19.1°C. Summerfield et al. (78) monitored indoor temperatures in 14 UK dwellings built to high thermal standards and found that the average living room temperature was 20.1°C. Both of the two latter studies have standardised temperatures for an external temperature of 5°C. The temperature difference in these two studies indicate the socioeconomic differences on what is desirable or achievable indoor temperature as they refer to different occupancy standards and priorities. Shipworth et al. (79) measured temperature in 427 houses across the UK and the average daily peak temperature was calculated to be 21.1°C; a value that is affected by high internal or solar heat gains.

Indoor temperatures were measured in a representative sample of UK households in the BRE EFUS 2011 project (80). The project report revealed mean monthly

[5] "Global" here refers to a consistent setting across building types.

temperatures for the whole dwelling at a range from 18.1°C in December to 21.5°C in July and August. The mean heating season (Oct-Apr) room temperatures were 19.3°C for the living room, 18.8°C for the hallway and 18.9°C for the bedroom, from which a mean temperature of 19.0°C for the dwelling is derived (80). The UK SAP calculates indoor temperatures as a function of, amongst others, the long term weather data (outdoor temperatures) and determines a mean heating season dwelling temperature of 18.2°C, differentiated between 19.2°C for the living room and 17.9°C for the rest of the heated dwelling areas (80). The BRE report found an indoor temperature of 0.8°C higher compared to SAP averages calculated for long term. When the SAP data were recalculated for the BRE weather data sampling period, the differences were negligible. Overall, BRE found that measured averages were in line with SAP values (80) and the need for data normalisation according to specific weather conditions was raised. BRE did not report on time-of-day temperature differences, but research in Loughborough University in almost 300 dwellings suggested that the temperature fluctuates within a 2°C range, approximately between 17.5°C and 19.5°C (Table 2-1), where flats were on average the warmest and detached dwellings the coldest (81).

Table 2-1. Living room temperature averages for different time ranges and dwelling types from 292 case studies (81).

		Mean living room temperature (°C)				
		Whole day	Morning (7:00-9:00)	Day (9:00-7:00)	Evening (17:00-23:00)	Night (23:00-7:00)
All dwellings	(n=292)	18.4	17.5	18.2	19.4	18.1
Detached	(n=29)	17.6	16.3	17.2	18.6	17.1
Semi detached	(n=130)	18.5	17.5	18.2	19.6	18.2
End terrace	(n=29)	18.2	17.6	18.2	19.5	18.2
Mid terrace	(n=70)	17.9	17.1	17.8	18.9	17.7
Flats	(n=34)	19.6	19.1	19.6	20.2	19.3

Huebner et al. (82), in a 635 England household study, monitored average winter temperatures for bedroom at 18.2°C, living room at 18.9°C and hallway at 18.3°C. This study also examined the number of days and hours that the living spaces were above 18°C as this is the day and night minimum temperature for those 65 and older or anyone with pre-existing medical conditions recommended by NHS (Cold Weather Plan for England) (83). Results indicated that approximately half of the buildings did not meet the requirements regardless of occupants' age and disabilities, which means that many households are at risk of negative health outcomes because of temperatures below recommendations.

The definition of domestic overheating is challenging due to its complex and subjective nature. Zero Carbon Hub claims that "*overheating is the phenomenon of a person experiencing excessive or prolonged high temperatures within their home, resulting from internal and /or external heat gain and which leads to adverse effects on their comfort, health and productivity*" (84). Even though current Building Regulations do not cover overheating explicitly in UK, references and guidance exists in governmental documents. The Housing Health and Safety Rating System Guidance published by the Government in 2006, provided 25°C as a threshold temperature above which mortality rates will increase (84). The Heatwave Plan advices that cool rooms maintaining temperatures below 26°C should be provided in the case of hot weather in hospitals, care/nursing homes and other residential environments occupied by vulnerable individuals (NHS England, 2015) (85). Passive House certification criteria include a requirement for overheating prevention actions as temperature should not exceed 25°C in all living spaces for more than 10% of the hours in a year (86). Overheating challenges have become more important especially when looking into future climate data.

Amongst various comfort criteria, the UK Chartered Institute of Building Services Engineers (CIBSE) suggests operative temperature ranges for different types of domestic rooms in the CIBSE Guide A (87). Recommended ranges are split into winter and summer operative temperatures and shown in Table 2-2.

Table 2-2. Summer and winter temperature range for different residential spaces suggested by CIBSE Guide A (87).

Space	**range in winter (°C)**	**range in summer (°C)**
Bedrooms	17-19	23-25
Bathrooms	20-22	23-25
Kitchen	17-19	21-25
Living rooms	22-23	23-25
Hall/stairs/landing	19-24	21-25

2.1.1.2 Non-Residential buildings

Occupancy time ranges is a dominant parameter when discussing indoor temperatures in non-residential buildings. Also, building type and use need to be considered especially with regard to physical activity. The first edition (2013) of CIBSE guide A recommended 13°C for heavy work in factories, 16°C for light work in factories, 18°C for hospital wards and shops and 20°C for office and dining rooms. Health and Safety Executive (HSE) adopted 16°C as a minimum temperature in a workplace; however, there is no guidance for a maximum temperature limit (88). The Trades Union Congress (TUC) has called for a maximum temperature of 30°C and 27°C for those doing physical work, although employers should still attempt to reduce temperatures if this exceeds 24°C and employees feel uncomfortable. The National Union of Teachers (NUT) believe that, because of the nature of teachers' work and the presence of children, a maximum indoor working temperature lower than the TUC recommendation is appropriate. The NUT policy therefore, as agreed at the Annual Conference 2007, recommended that 26°C should be the absolute maximum temperature in which teachers should be expected to work in, other than for very short periods (89). The Education (School Premises) Regulations also include provisions relating to risks from hot surfaces and hot water. They suggest that water, radiators and exposed pipes which are located where pupils might touch them must not become hotter than 43°C (90). This could be a potential limitation for publicly accessible (within reach) solar thermal collectors in a school.

CIBSE understood the seasonal variability and amended temperature suggestions from a specific temperature target to ranges for winter and summer. Thus, CIBSE Guide A (2015) (87) moved from a temperature value of 20°C for offices to a temperature range for comfort that should be 21-23°C in winter and 22-24°C in summer for serviced offices (87). This range agrees with Seppanen et al. (91) reviewed studies in office temperature comfort; a summary graph (Figure 2-1) indicates that productivity reduces below 21ºC and above 25°C. Lan et al. (92) performed a series of tests in workers' well-being, workload and productivity at 17°C, 21°C and 28°C. All indicators showed reduced productivity for the low and high temperature band.

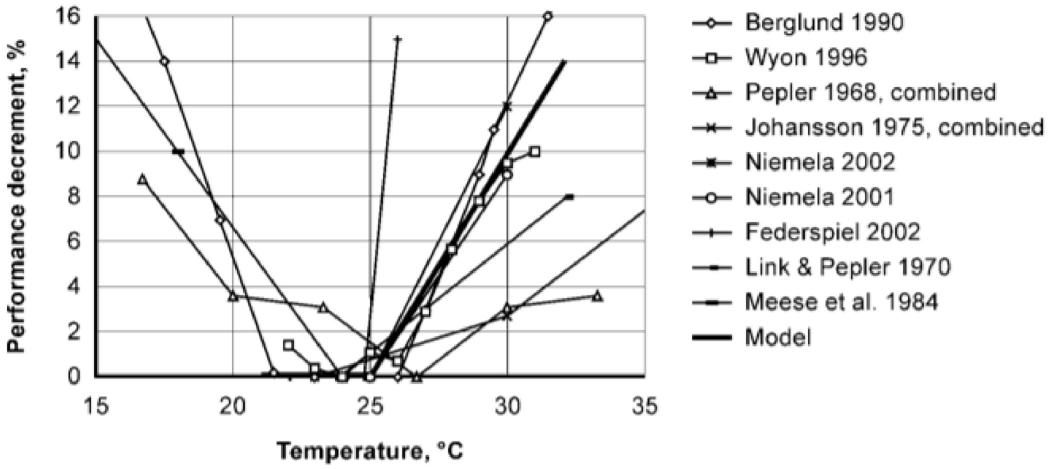


Figure 2-1. Performance decrement percentage against indoor temperature. A summary graph from Seppanen et al.'s review (91).

CIBSE suggests operative temperature ranges for a wide selection of buildings in CIBSE Guide A (87). A selection of temperature ranges that correspond to the buildings examined in this work is shown in Table 2-3 where the recommended ranges are split into winter and summer operative temperatures.

Table 2-3. Summer and winter temperature range for a selection of different non-residential spaces suggested by CIBSE Guide A (87).

Space	range in winter (°C)	range in summer (°C)
Office conference/open plan	21-23	22-25
Office small room	21-23	22-25
Educational corridor/ lecture hall/ teaching space	19-21	21-25
Educational theatre/ concert hall	21-23	24-25
Retailing supermarkets	19-21	21-25
Industrial heavy work	11-14	-
Industrial light work	16-19	-
Industrial sedentary work	19-21	21-25

2.1.2 Space Heating

Space heating is one of the most important factors in buildings' energy use, considering that in EU, space heating is the dominant consumer (Figure 2-2). The quantification of the buildings' space heating requirements is a challenging process as it contains a number of assumptions on the climate, building fabric, building services and occupants' requirements. Also, there is a significant mismatch between actual performance and leading practice. This gap is due to demanding building regulations, retrofit barriers, inaccuracies in performance prediction, poor implementation and incorrect operation (93, 94). Even if all the climatic and technical parameters are carefully included in a modelling exercise, the predicted heating demand and the monitored energy delivered for heating could differ significantly. Building users would heat buildings to their subjective variable preferences, or/and to their financial abilities. For this reason, when a supplementary heating system is introduced, such as a TSC, it is important to identify what the design heating demand reduction is and what the real heating delivery displacement is.

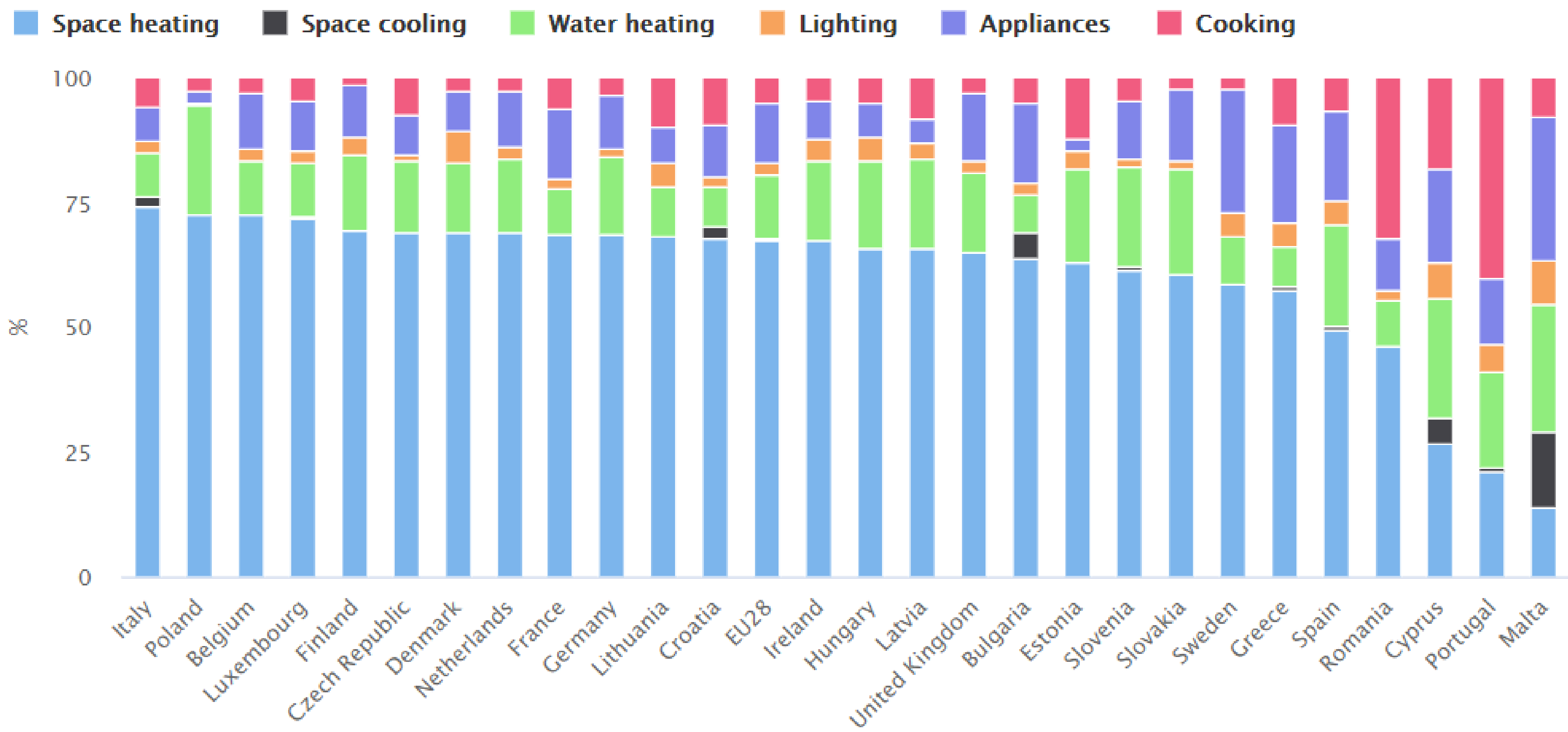


Figure 2-2. Share of energy consumption for buildings in EU (95).

2.1.2.1 Space Heating and Energy Use

The Energy Research Partnership (ERP) (93) states in the "Heating buildings" 2016 report that space heating is the major end-use energy consumption for UK homes and workplaces. This is evident in Figure 2-3, where space heating accounts for approximately 65% of the homes' and 55% of the workplaces' end-use energy consumption. In both sectors, space heating is approximately a three -times greater consumer than the appliances and lighting together, contributing to significant emission percentage – approximately 50% in homes and 30% in workplaces. In the same report, a space heating demand overview is presented for the UK domestic sector normalised per m^2 per year.

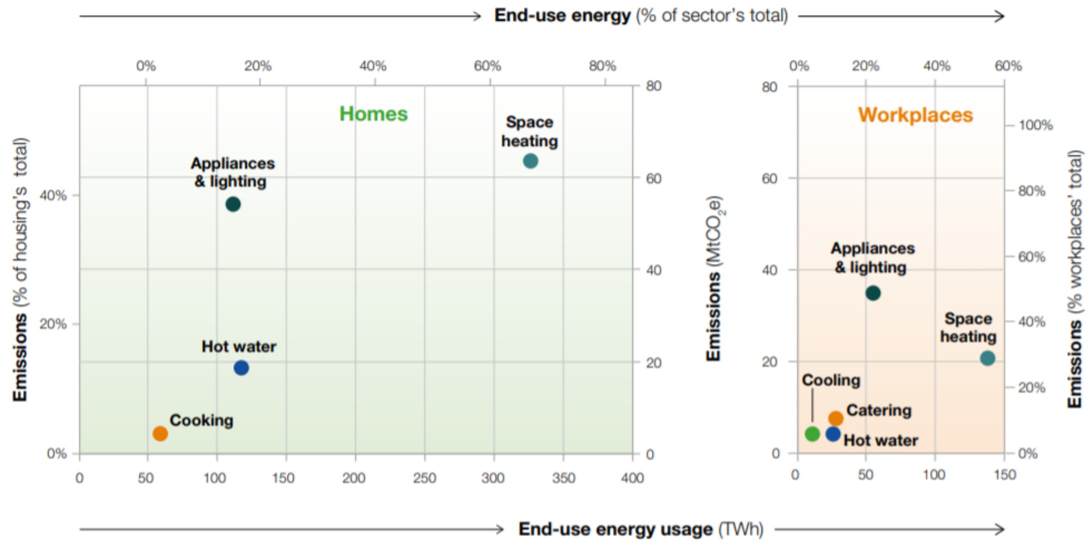


Figure 2-3. Space heating contribution in homes and workplaces in end-use energy and as a percentage of usage and emissions (93).

In Figure 2-4, specific (meaning per m^2) domestic heat demand is indicated for an average UK house (orange). Also, modelled performance of homes from different eras (dark green) and leading practice (light green) are illustrated in the same figure. A substantial difference in heat demand is presented between leading practice such as Passivhaus standards (15kWh/m^2 per year), old UK housing stock (260kWh/m2 per year), and average UK stock (140kWh/m^2 per year).

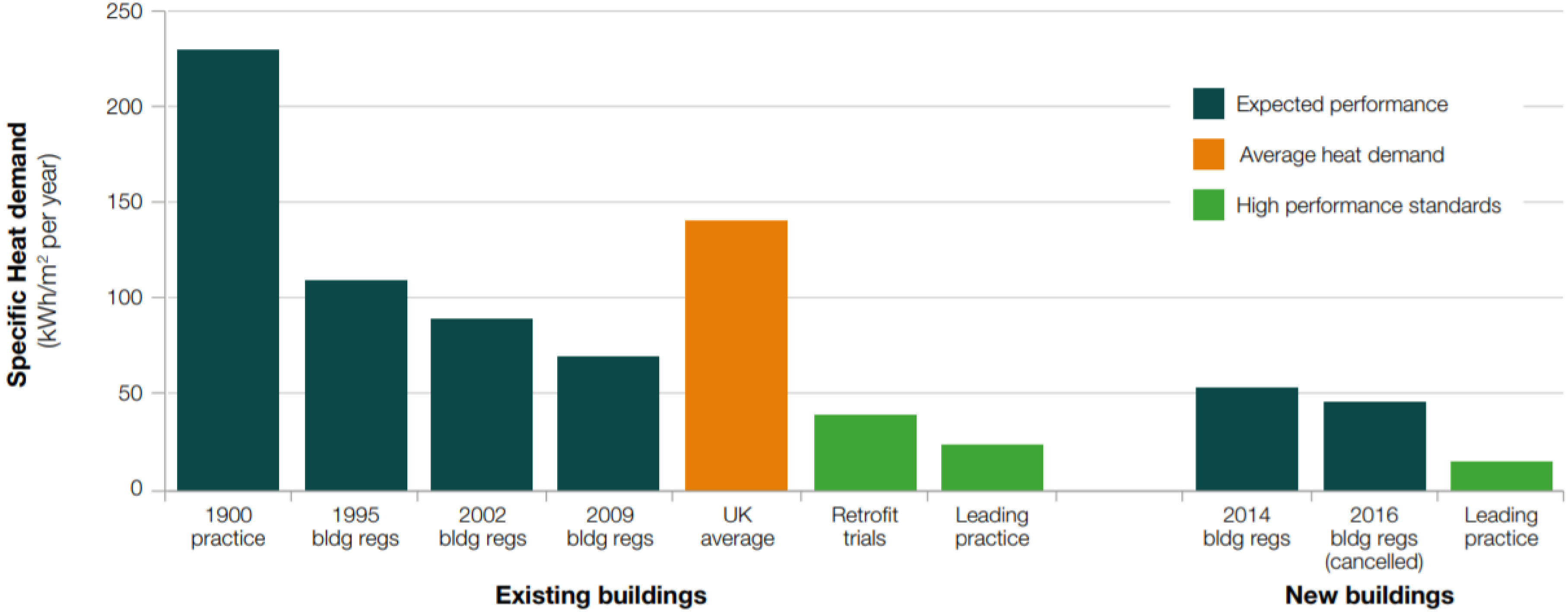


Figure 2-4. Annual domestic space heating demand for different building regulations and practices (green) against the UK average (orange) (93).

2.1.2.2 Heating Degree Days

Heating degree days (HDD) is a medium to estimate a building's heating needs related to weather data. It is the accumulation of temperature differences to one side of a baseline temperature over time, usually monthly or annually. This can be calculated from either 24-hour values or algorithmically from daily maximum and minimum. The annual summation is an indication of the ambient temperature in a specific location. Monthly calculations may be more useful as an indication of seasonal variations. CIBSE TM41 describes the methodologies on calculating degree days (96). In the UK, the baseline temperature widely used is 15.5°C (96, 97), however there are studies claiming that building type-specific base temperatures must be developed for increasing accuracy in energy analytics and legislative compliance (98). Baseline external is below the desired internal temperature as internal gains are not considered for the external one. CIBSE Guide A identifies the HDD limitations especially for high internal gains or well-insulated buildings where the HDD should be lower (87). Also heating degree days and heating demand are affected by climate changes (99), thus the weather file used to extract degree days should be representative for the location and the era. Through the degree days, the cooling and heating energy demand can be determined by using the heat loss characteristic (96, 100). This is briefly described in Equation 2-1, where the number of heating degree days (HDD) is obtained by the sum of the daily values (only positive values are considered) [31].

$$HDD = \sum_m (T_b - T_{av}) \qquad \text{Equation 2-1}$$

Where HDD is the heating degree days for one year (or over a period of time)

T_b (°C) is the baseline temperature and

T_{av} (°C) is the average daily temperature.

HDD are often used to normalize the energy consumption of a heated building so that, the normalized figures can be compared on a like-for-like basis. This method facilitates heating demand comparisons between buildings in different locations or between different heating seasons and years. The normalisation between HDD and heating energy consumption can be done in a simple ratio or a linear regression technique (101). HDD can be calculated from a weather station on site, or from a weather station close to the case study. Long term data can also be obtained by trusted sources such as Met Office, PVGIS and the BizEE database.

2.1.2.3 Space Heating Modelling

Building heating demand can be modelled by applying energy balance equations that allow the additional heat needed to be calculated. The difference in the calculation methods mostly lies on the time period of the calculation and accuracy of the construction and meteorological data sets used. Annual estimations can be derived if the floor area and the type of building are known (102, 103). Non-dynamic models use seasonal or monthly average temperatures, while dynamic models use aggregated results (profiles) from an hourly analysis. The monthly models can be based on HDD calculations or quasi-steady calculations of the heat balance equation which is the case in SAP where monthly averages of external and internal temperatures are inputted. Dynamic models such as EnergyPlus or HTB2 are able to use hourly (or even one-minute) weather data sets to calculate all the transient changes in the heating demand. Verification tests and guidance for dynamic modelling are included in several CIBSE guides (87, 102-105).

2.1.2.4 Space Heating Monitoring

The importance of space heating delivery and energy used for heating has been already analysed. Heating delivery can be calculated or measured by heat meters or by a combination of instruments able to quantify the components of the fundamental heat transfer equation for fluids (Equation 2-2).

$$Q_{del} = \dot{m} C_p T_{rise} \qquad \text{Equation 2-2}$$

Where Q_{del} is the heat delivered through heat transfer

$\dot{m}$ is the mass flow rate of the medium

C_p is the specific heat capacity of the medium and

T_{rise} is the temperature rise caused by the heating system(s).

Heat metering could be an eligibility requirement for schemes such as RHI, where high interval data should be collected (106). Heat delivery can also be calculated indirectly by measuring the energy used for heating. Heating delivery systems are characterised by a conversion factor (efficiency) that describes the useful energy delivered as a percentage of the energy used. This is 100% for electric radiators, and 88% for modern condensing gas boilers but can go down to 55% for an old boiler (107). These efficiencies refer to the end users systems efficiency; primary energy conversion factors should also be considered as when comparing different fuels.

The system efficiency for conventional systems is not related to the efficiency of renewable systems. The term efficiency in renewable solar thermal systems often refers to the conversion of renewable energy source into heating (for example solar radiation to heating). When describing the percentage of the conventional energy used to deliver the heating output, especially for heat pumps, the term that is commonly used is the coefficient of performance (COP) which is the heat delivery divided by the conventional energy used to run the system (usually electricity).

Monitoring gas/oil/LPG (fossil thermal fuels) consumption in the end-use could be an indication of the heating delivery of conventional space heaters (e.g. boilers). If the boiler is used both for space heating and hot water, the separate efficiencies for space heating and water heating have to be considered. Also, a building's total gas consumption could include gas cooking or other activities and has to be subtracted from total gas use.

2.1.2.5 Space Heating Benchmarks

Gas and heating benchmarks are critical in the process of evaluating a heating system in this study for two main reasons. The first reason is that in a real case study if the heating/gas demand/consumption is known, it can be compared against benchmarks and classified accordingly. The second reason is that the impact (e.g. heating reduction) of an application (e.g. solar thermal collector) can be compared against the total demand/consumption of a benchmark building in the sector which allows extrapolations and conclusions on the applicability of the technology in the building sector. There is no straightforward guide that relates building types to space heating requirements; thus, a deeper look in the literature is deemed necessary to source relevant information.

The Odessy-Mure indicators (108) estimated the average floor area for UK dwellings at 94.8m^2 for 2016 (85.5m^2 for 2006). This value can be used to normalise benchmark data for annual domestic gas and space heating data that do not include a "per meter square" analysis. This was applied in the NEED governmental report, where houses' consumption was grouped in several characteristics; but at the same time the "per area" bins are quite broad at <50m^2, 50m^2-100m^2, 100m^2-150m^2, 150m^2-200m^2 and over 200 (109).

A large survey on UK non-residential buildings conducted by DECC estimated the average area of an office at 90m^2 (110). Clarke (111) used a number of UK benchmark sources to create a table for gas and electricity consumption per floor area. When it comes to offices, Clarke used the ECG (formerly ECon19 Guide) (2003) data where offices were divided in four categories: naturally ventilated cellular and open plan and air conditioned standard and prestige (112). The four categories include benchmarks for typical and good practice use. In this study the air-conditioned office benchmark is most relevant to the case studies which will be introduced in Chapter 5. The same guide visualises a breakdown of the total energy used in an air-conditioned standard office normalised per treated floor area (Figure 2-5).

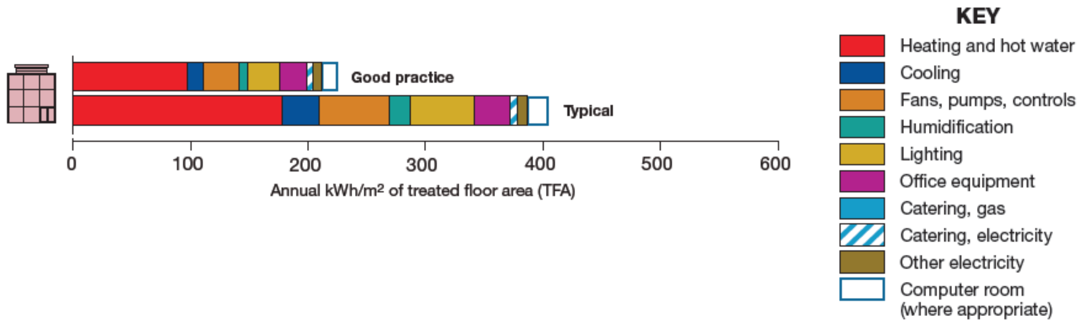


Figure 2-5. Good practice and typical annual energy consumption for an air conditioned standard office in kWh per m^2 of treated floor area (112).

When it comes to space heating consumption of large commercial, institutional and industrial buildings, CIBSE TM46 (102) and more recently Clarke's work (111) include benchmarks for various sub-categories; however, they only refer to gas consumption. For this reason more information on the break-down of energy-use were collected from a DECC report (110). In the report there is a breakdown of the total energy consumption in non-domestic buildings, where the non-electrical energy is split into space heating, hot water, catering and other purposes. Approximately 77% of the total non-electrical heating accounts for space heating (Figure 2-6). There is a further break down of the non-electrical consumption for each sector in Figure 2-7, where space heating accounts for 85%, 93%, 83%, 95% of the non-residential office, retail, educational and industrial buildings respectively. The uncertainty in these percentages is significant regarding industrial and commercial buildings as the area and building types of these sectors are very wide.

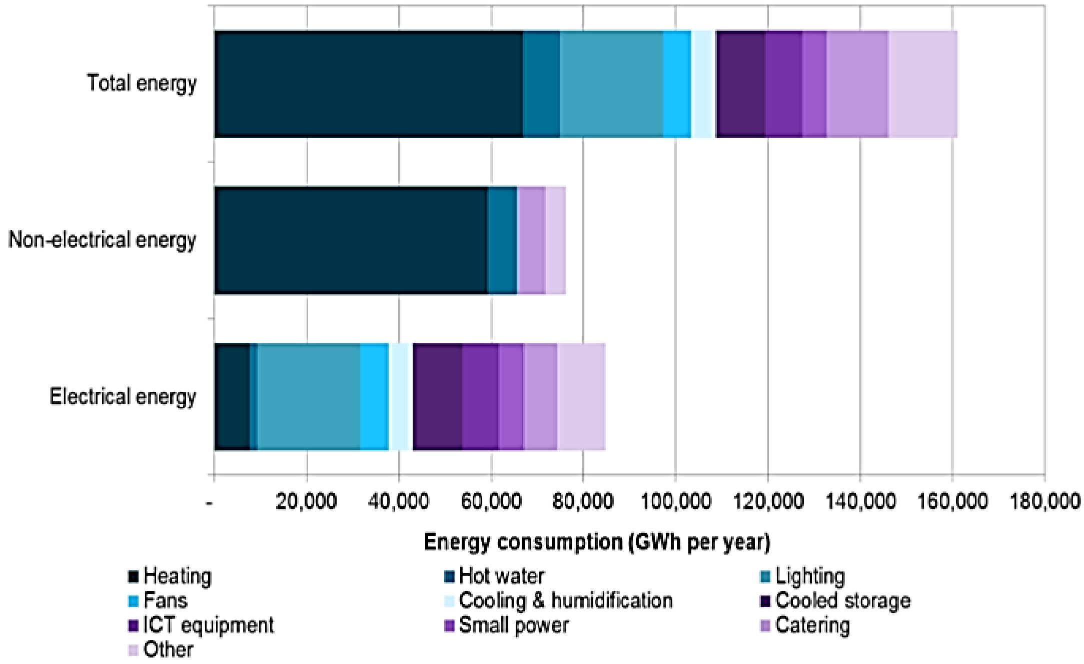


Figure 2-6. Non-domestic energy consumption breakdown (110).

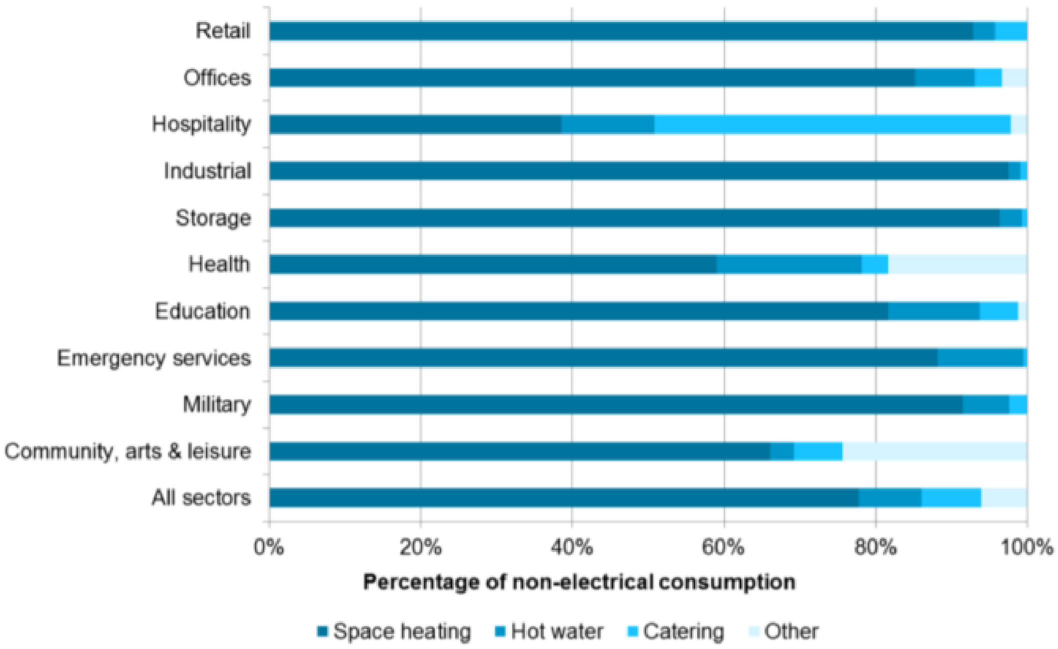


Figure 2-7. Percentage of non-electrical consumption in a range of non-residential buildings (110).

Summarising the sources above, Table 2-4 was created to indicate the gas and space heating requirements for domestic and non-domestic buildings that suits the case study range used in this work. Values were normalised based on processes and percentages analysed earlier in this section and a synopsis of the calculations used is stated in the "Comments" column.

Table 2-4. Annual gas and space heating requirements for various building types; author's own.

Building (UK)	Gas (kWh/m^2)	Space heating (kWh/m^2)	Comments
Domestic average	141 (109)	118 (108)	$94.8m^2$ area used (108) koe to kWh:11.63 (113)
Passive House	-	≤15 (114)	or ≤ 10W (peak demand) per m^2 of usable living space
Air-conditioned office (typical)	178 (111)	168(103)	
Air-conditioned office (good practice)	97 (111)	90 (103)	
School (primary)	111 (115)	92	Space heating = 83% of gas heating (110)
School (secondary)	99 (115)	82	
Large non-food stores	170 (111)	158	Space heating = 93% of gas heating (110)
Industrial workshop or open working area	180 (102)	171	Space heating = 95% of gas heating (110)

The lack of benchmark data for specific building types relevant to this study was addressed by calculating space heating from fuel consumption data. UK buildings generally require 90 to 171 kWh/m^2 annually depending on building use and type. However, it is possible to achieve space heating fuel consumption below 15 kWh/m^2

where Passive House accreditation has been achieved. The quantified heating needs / benchmarks will assist in a solar thermal feasibility study, as well as in calculating percentages of heat displacement. However, to quantify space heating requirements for a specific building, consideration of climate, building and occupants' data are needed. The quantification is achieved using all available data and model the space heating demand or monitor the real-life consumption.

2.2 Building Ventilation

It is calculated that up to 79% of English dwellings are under-ventilated (116). Natural and mechanical ventilation was briefly introduced in the section 1.3.3. In this section, parameters and variations of mechanical ventilation, as well as ventilation demand for va variety of buildings, are analysed. As seen in Figure 2-8, approximately 50% of retail and office buildings have a mechanical ventilation system according to the 2016 DECC survey (110). The solar thermal technology analysed in this work requires fresh ambient air; hence, the literature will focus on systems with mechanical fresh air supply.

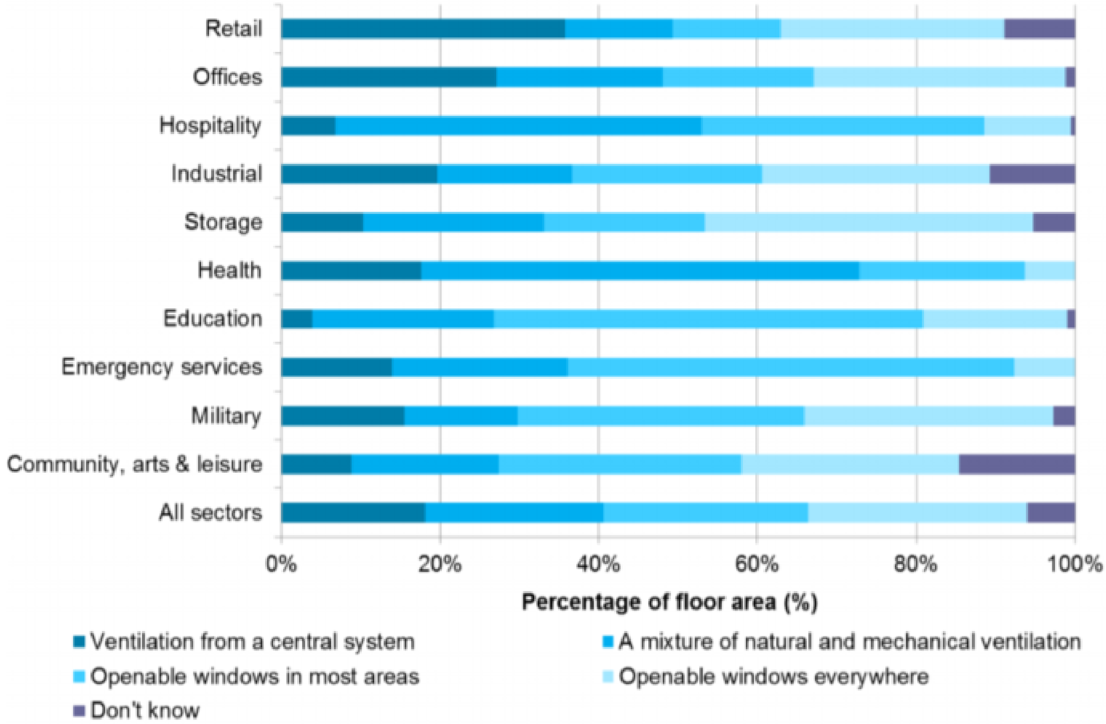


Figure 2-8. Natural, Mechanical and Mixed ventilation in non-residential buildings in UK (110).

2.2.1 Mechanical ventilation systems

This section provides a better understanding about forced ventilation, which is necessary to transfer heat to a building through a TSC system. Also a review on air permeability and pressure balance is included to describe the building physics occurring when air passes to/from the building.

2.2.1.1 System types

The range of mechanical ventilation systems can be classified depending on the inlet and outlet mechanism to one of the following categories:

- **Circulation systems:** These systems create an internal air movement that would redistribute and de-stratify the air in a space without the introduction of fresh air resulting to a more homogenised and comfortable environment (117). A variant called recirculation is used in conjunction with a fresh air inlet or HVAC systems in order to mix air and raise the temperature of the incoming air. In high-ceiling buildings the warm air rising through buoyancy would be de-stratified through the re-circulation. They are low-cost systems but, on the downside, the circulated air, if not cleaned, is contaminated.
- **Natural air supply with mechanical air exhaust:** This ventilation type uses fan(s) to move indoor air out of a room or building, while outdoor air is drawn in through leaks, inlets or trickle vents. In modern residential buildings extraction takes place from at least the kitchen, the bathroom and the toilet where extraction ducts and inlets are essential (though houses that haven't been modernised might still have the above). In non-residential buildings extraction mostly takes place from the corridors. Some benefits of this type include the low costs of installation, operation and maintenance, but there are also several drawbacks. Exhaust-only ventilation can draw contaminants into buildings from areas such as an attic, shared corridors or adjacent buildings, and could also move moisture from the outside into a wall cavity that then leads to problems such as rot and mould. They are also called vacuum systems as they under-pressurise the building which can cause or contribute to back-drafting of combustion appliances (117-119).
- **Mechanical air supply with natural air exhaust:** This type of mechanical ventilation refers to systems that control the air supply mechanically and the air exhaust takes place in a natural way via ventilation openings, windows, airshafts, trickle vents and envelope cracks. A ventilator controls the air supply and the outdoor air is transported into the building by ducts. There could be

an over-pressurisation in the building as air tries to find the way out which creates two opposite phenomena: from one hand there is a potential heat loss when conditioned air is escaping and from the other hand excess pressure prevents ambient drafts to enter the building through cracks and other openings. In order to prevent draughts, the air supply to a room is usually placed as high as possible and the air inlet can be regulated. Controls adjust the supply air which is transported from outdoors continuously or intermittently into the building by ducts. A filter can be applied before the distribution to reduce contaminants and particles. This approach can be integrated in other systems that work with fresh air delivery. It has a relatively low installation cost; however, it can still result in moisture problems in the walls that are caused by humid air drawn in from outside whereas inside moisture is pushed through cracks and fabric (118-121).

- **Mechanical air supply and exhaust:** With these systems, equal quantities of air are brought into and sent out of the building. This is usually achieved by using two fans: one to bring fresh air in and another to send indoor air out. By this way, there is a good control of the ventilation capacity with minimum dependence on outdoor weather conditions protecting from possible external noisy environments. For best practice the building should be relatively airtight (air permeability ≤ $5m^3/h.m^2$ @50Pa (103)) otherwise leaks will dominate and disturb a balanced circulation. However, the pressure in a building may be kept under slightly positive or negative pressure by using marginally different flow rate between supply and exhaust. This type embraces all the benefits of exhaust-only and supply-only; it reduces contaminants and control of air supply without many of the drawbacks like moisture and under or over pressurisation. In addition, the presence of two streams (supply and extract) creates possibilities of heat and moisture exchange between the two flows (MVHR). However, both installation and operational cost is higher than the other options and system balancing is a challenging process (118, 121).

2.2.1.2 Air permeability and pressure balance

When the building or room is negative pressurised in relation to outside then the air tends to find a way through cracks and micro-perforations and this is called infiltration, conversely, exfiltration is the process where the air finds a similar way out when the pressure in the building is higher to outside. The infiltration rate is an indication of air tightness and can be calculated through air permeability tests which are included in the latest building guidelines and regulations (122) for both residential (123) and non-residential (124) buildings. Infiltration and exfiltration has also been modelled (125-128) and is considered to be a dominant parameter of the mechanical ventilation strategies.

The pressure in a building may be kept under slightly positive or negative levels by using marginally different mechanical ventilation flow rate between supply and extract. Under-pressurisation and over-pressurisation strategies are used in regards to many considerations such as the climate, season, air pollution, temperature and condensation (24). Balanced strategies are also commonly used where both inlet and extract fans are in an equilibrium mode to maintain the internal air pressure at a similar level to the outside air. There are also cases that mechanical ventilation is not used to bring directly fresh air in the building. A common non-fresh air set is the circulation mode where a ceiling fan creates an internal air movement and de-stratifies the air. Another common scenario is the use of extract local fans in order to exhaust unwanted heat, smoke or contaminants at their generation location (129). The extracted air carries heat that can be exchanged with a supply system affecting the temperature of an incoming fresh air without recirculating the contaminant air.

2.2.1.3 Mechanical ventilation in conjunction with other systems

Mechanical air supply has the possibility to work with air heating or cooling systems or both (HVAC). If needed, the air can also be humidified, dehumidified or filtered. Heat can be added through conventional systems such as electric resistive elements or fossil fuel boilers or through air to air heat pumps. Also, heat exchanger mechanisms can be added to recover some of the energy that the air carries on its way out (or in). The two most common recovery systems are the Heat Recovery Ventilation (HRV) and the Energy Recovery Ventilation (ERV). HRV systems transfer heat from exhaust air to incoming air during the heating season and from incoming air to exhaust air during the summer to reduce the heating and cooling load and improve comfort (119, 121). ERV systems also capture some of the humidity in the exhaust air and transfer it to the incoming air to help always keeping the ambient internal humidity level at a reasonable value.

Mechanical ventilation systems that combine exhaust heat pumps for heating, cooling and hot water with the addition of a heat exchanger for heat recovery are in the market (130, 131). Any exhaust heat from the MVHR is used by the evaporator of the heat pump. These sophisticated systems are still quite expensive and need specialists for installation and commissioning; however, the operational costs can be drastically reduced as the advertised COP (6.8) is impressive (130).

Mechanical ventilation can also be combined with solar air preheaters that can be glazed or unglazed, transpired or not transpired. The air is heated/preheated during the heating season enhancing comfort and reducing the effort (energy needed) of conventional air heating systems (132). There are very few studies that assess solar heaters in conjunction with other systems. Noguchi (133), focuses on the cost effectiveness of PV/T working with MVHR; the warm air from the back of the PV is considered linearly beneficial for the performance of the MVHR without any quantification investigation. Kamel et al.'s (134) extensive review on solar systems integration to heat pumps indicated that most of the reviewed solar systems are liquid and there is a lack of investigation on connecting an air-based solar system with an air source heat pump. The study concluded that "air has significant advantages over liquid such as no freezing and leakage issues, however, it has low thermal capacity, low heat transfer and low density, leading to high mass flow rate required for a given application". Combined air solar heaters and heat pumps is investigated in very few papers where solar preheating exchanges heat with the circulation fluid of the heat pumps, a technology that by default neglects the ventilation component (135). There is no literature found combining exhaust air source heat pumps (mentioned above) where the source is preheated air from an air solar system such as the TSC.

There are some case studies that investigate TSC in combination with conventional HVAC systems with some additional components and controls, such as summer bypass and recirculation. These studies will be analysed in depth in section 3.2 after the fundamentals of the TSC technology are introduced in section 3.1.

2.2.2 Ventilation benchmarks

Ventilation rate benchmarks are a central criterion when mechanical ventilation systems are designed and installed. In addition, good understanding of ventilation needs in conjunction with heat demand can facilitate decisions in the applicability and sizing of the add-on systems. Especially when an air solar thermal system is designed, ventilation needs should drive the decision-making process. For this reason, Table 2-5 below summarises ventilation needs for a selection of buildings and rooms based on CIBSE Guide A (87); the selection is based on the case studies that will be explored in this work and follows the temperature ranges presented in Table 2-2 and Table 2-3.

Table 2-5. Summer and winter temperature ranges accompanied by ventilation rates for different residential and non-residential spaces suggested by CIBSE Guide A (87) (unless otherwise indicated) (continued overleaf).

Space	Temperature range in winter (°C)	Temperature range in summer (°C)	Ventilation rate (L/s per person)
Bedrooms	17-19	23-25	0.4-1ACH (136)
Bathrooms	20-22	23-25	15
Toilets	19-21	21-25	>5ACH
Kitchen	17-19	21-25	60
Living rooms	22-23	23-25	0.4-1ACH (136)
Hall/stairs/landing	19-24	21-25	-
Office conference/open plan	21-23	22-25	10
Office small room	21-23	22-25	10
Educational corridor/ lecture hall/ teaching space	19-21	21-25	10
Educational theatre/ concert hall	21-23	24-25	10
Retailing supermarkets	19-21	21-25	10
Industrial heavy work	11-14	*	**
Industrial light work	16-19	*	**
Industrial sedentary work	19-21	21-25	**

* In the UK, air-conditioning is not appropriate/recommended for this application. Cooling may be provided by local air jets.

Space	Temperature range in winter (°C)	Temperature range in summer (°C)	Ventilation rate (L/s per person)
** As required for industrial process, if any, otherwise based on occupants' requirements.			

Also, the Building Regulation F (136) indicates minimum extract ventilation rates for all the dwelling's rooms that need air extraction (Table 2-6). The Regulation provides different benchmark rates for intermittent and continuous extract. Furthermore, it includes minimum whole house ventilation rates per number of bedrooms and the figures are based on two occupants in the main bedroom and a single occupant in all other bedrooms. The minimum rate for a one-bedroom dwelling is 13L/s and the regulation adds 4L/s for every extra bedroom (Table 2-7) with a note that ventilation should not be less than 0.3l/s per m^2 of internal floor area (for each floor) adding 4l/s for more than three occupants.

Table 2-6. Extract intermittent and continuous ventilation rates for dwellings, **(87, 137),**

Room	**Intermittent extract minimum rate (L/s)**	**Continuous extract Minimum high rate (L/s)** (87)	**Continuous extract Minimum high rate (L/s)** (136)
Kitchen	30	13	>0.3L/s per m^2 of internal floor area Add 4L/s per extra occupant (3 assumed).
Utility Room	30	8	
Bathroom	15	8	
Sanitary accommodation	6	6	

Table 2-7. Whole dwelling ventilation rate (87, 137),

Number of bedrooms in dwelling	1	2	3	4	3
Whole dwelling ventilation rate (l/s)	13	17	21	25	29

In addition, the British Standard 13779 for ventilation for non-residential buildings (87, 137), classifies the indoor air quality (IDA) as low, moderate, medium and high, recommending ranges and default values for each of these categories; (see Table 2-8). The Building Regulation F (136) specifies ventilation supply rate for offices at 10L/s if there are no extra significant pollutant sources, smoking or regular use of machines such as printers for more than 30min per hour.

Table 2-8. Ventilation rates classification for non-residential buildings according to British Standards 13779 (87, 137).

Classification	Indoor air quality standard	Ventilation range (L/s per person)	Default value (L/s per person)
IDA1	High	>15	20
IDA2	Medium	10-15	12.5
IDA3	Moderate	6-10	8
IDA4	Low	<6	5

The benchmarks drive the decision-making process for any ventilation system. The TSC systems will be investigated as part of the ventilation system as this is the reason that they were designed and patented for by John C. Hollick from 1988/89 (U.S. Pat. Nos. 4,774,932 and 4,934,338) (138, 139). Thus, the ventilation rate should be the key parameter in the design and sizing of the systems. For residential buildings, Building Regulation F benchmarks should be followed for UK applications. For non-residential ones, UK CIBSE guidance and Regulations agree for a minimum ventilation at 10L/s. Similar regulations should be followed for other countries in any application of a ventilation system.

2.3 A summary of space heating and ventilation

A heating system that delivers air would affect comfort and should be driven by both heating and ventilation needs. Space heating demand is not the same as space heating delivered in practice as the demand is a theoretical value determined by comfort expectations. Also, the delivered heat does not necessarily equal to the energy used to generate this heat as different systems would convert fuel to heat in different efficiencies.

Studies have monitored real temperature in the buildings indicating spatial, seasonal and socioeconomic deviations (76-80). CIBSE recommendations are broadly used in the UK suggesting temperature values for different rooms or spaces and seasons. The difference is driven by the activity thus industrial heavy workspaces would have a recommendation range from 11 to 14ºC whereas offices would have from 21-23ºC in the winter and 22-25ºC in summer.

Space heating has the greatest share in EU buildings' energy consumption especially in dwellings where it is responsible for approximately 70% of the total end-use energy (93) (95). With the use of appropriate tools, space heating can be modelled by using historic weather data and or monitored; however, monitoring data should be normalised for historic weather data to enable comparability of case studies and monitored years. When these data and tools are not available, benchmarks can be used to quantify space heating requirements for different buildings. Also, standards such as Passivhaus are used to enumerate best practice (114). When a supplementary heating system is introduced, such as a TSC, it is important to identify what the design heating demand reduction is and what the real heating delivery displacement is to calculate applicability and cost benefits.

Mechanical ventilation is extensively used in the non-domestic sector and lately in the domestic sector as new builds become more airtight. There are a lot of systems' variation to provide fresh air with the MVHR being the most effective one with cost and system balancing to be challenging (118, 121). MVHR can work with HVAC systems and has recently used together with Exhaust heat pumps. Ventilation rates are suggested by CIBSE guidance but also included in UK Building Regulations for both domestic and non-domestic sector (87, 136).

3 A review of TSC technology and building integration

TSC was briefly introduced in section 1.3.5 as the perforated solar system that could directly distribute warm air in the building (DHV) or feed the building's heating system (PHV). Before we focus on the building integration, it is necessary to analyse the TSC technology outside the context of a building, to review the physics and technology development. For clarity, the TSC will be reviewed separately from the building integrated TSC system and the two terms are defined below:

- The TSC collector is the structure that warms up air including the panel, the plenum and a fan to create the suction needed for the heat transfer. The panel is the transpired solar absorption plate including the special coating. This can be seen in Figure 3-1.
- The TSC system is the building integrated collector, including potential add-ons and collaborative heating and ventilation systems, designed and controlled to fulfil specific needs.

To review the literature on the TSCs, sources were split into two groups. The first group refers to literature on the collector's technology development through modelling, and/or mathematical analysis or monitoring of laboratory TSC. The second group refers to literature on building integrated TSC guidance and case studies where TSC systems were evaluated to quantify their impact on the building/occupants.

The Chapter introduces the significance of the TSC technology exploring its unique charasterics as well as its thermal performance indicators and how these have been modelled over the years (section 3.1). The review then focuses on the collector's parameters (section 3.2) aiming to facilitate design decisions in real life applications and feed the proposed framework (Chapter 6).

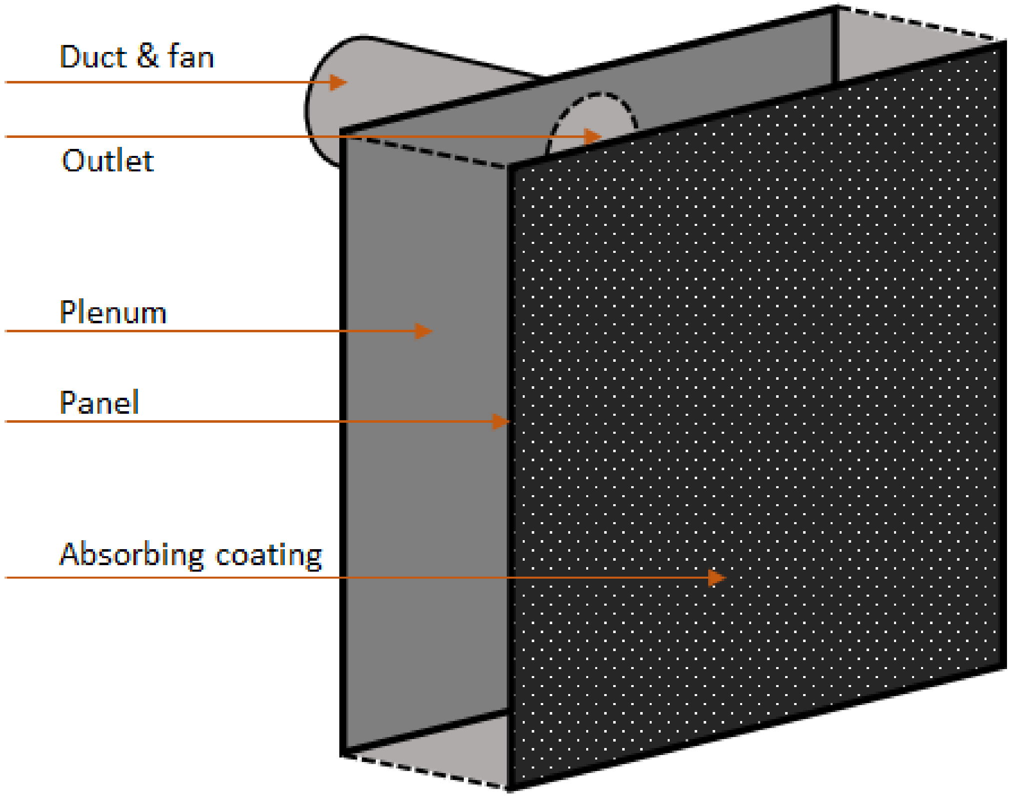


Figure 3-1. TSC collector; author.

The next stage in this review is to investigate how transpired solar collectors were integrated in buildings. The focus will move from the collector to the TSC as an integrated system that is designed and evaluated. This involves the design and integration on the building envelope (roofs or walls), the integration with the building services as well as any evaluation. Many researchers have worked on the development and optimisation of the collector; however, there is little information on how to integrate TSCs.

This chapter introduces and discusses existing guidance on TSC integration in buildings (section 3.3). Section 3.4 presents the literature case studies chosen to be included in this work and the reasoning behind this selection is explained. Then an overview for each case study is given (further details can be found in Appendix I). A discussion on design and evaluation accompanied by summary tables indicating the variation of the applied systems and allowing comparisons follow. The discussion on design intends to explore the decision-making process on sizing and integration of building envelope and building services with a view to understand the reasoning and replicability of the process. The performance indicators and the monitoring methods and tools are also discussed, and results are gathered and compared for later use in this study. Any optimisation process that was applied after obtaining initial results is also discussed.

3.1 Why TSC?

A variety of solar air heater designs have been explored to provide solar energy to fresh or recirculating air (140). Solar heating of ventilation air is an economical application to introduce fresh air with the supplementary benefit of heating. It can be implemented using panels that are perforated or not perforated or panels that are glazed or not glazed (140, 141). Chan et al. (142) evaluated the thermal performance of perforated and unperforated solar air collectors in the laboratory for a variety of solar radiation intensities and mass flow rates concluding that the perforated option gave a significantly better performance compared to the flat plate options. Perforations were associated with a higher thermal efficiency of 59%, compared to a value of 36% for a flat plate solar collector without perforations (142). Amongst others, Gao et al. (143) studied the benefits of the glazed transpired solar collectors especially in cold climates. The glazed collector is more robust to winds especially in cold climates where the efficiency of the unglazed collectors can decrease considerably (143, 144). It also reduces the convection losses of the absorbing cover (143, 145, 146). On the other hand, glass-covered air collectors can partially reflect the solar radiation and they use more material resulting to cost increase and installation and maintenance disadvantages (146, 147). There is also research on vacuum glazed (148), concentrating (149) and two-stage (combination of glazed and unglazed) (150) transpired solar collectors; however there is a lack of real life examples. The transpired unglazed collectors for air heating are both economical and efficient, thus have been used in real-life applications (67, 151, 152).

3.1.1 Parameters overview

The purpose of the TSC literature study is to firstly review the TSC technology development and then how TSC have been applied to buildings so far. The parameters that refer to the optimisation of the collector are listed in Table 3-1 and will be analysed in this Chapter. The parameters that refer to the design of the TSC systems are listed in Table 3-2 and will be further studied through literature on case studies.

Table 3-1. TSC collector parameters

Parameter category	Collector related parameters
Geometry	Panel thickness Porosity Perforation pitch Hole diameter & shape Surface shape Plenum width
Coating thermal characteristics	Absorptivity Emissivity Conductivity Colour
Heat transfer	Flow rate Temperature rise
Environmental	Ambient air temperature Air properties Solar radiation Wind (approach) velocity

Table 3-2. Building-integrated TSC system parameters

Parameter category	Integrated system related parameters
Design Drivers	Design intent Sizing driver (heating and/or ventilation) Simulation
Envelope integration	Size Colour Shape Inclination Orientation Shading Size Actual plenum width Back wall
Services integration	Variants Functions Air flow rate Controls
Commissioning	Performance Gap Optimisation

The modelling and monitoring tools used to evaluate the parameters from both tables were also studied. The modelling tools are split into those analysing the physics of the collectors and others which inform the real-life design of TSC on buildings. Monitoring techniques are more relevant to the case studies literature as the experimental process of this thesis refers to real-life building integrated TSC.

3.1.2 Thermal performance indicators

Before delving deeper into the TSC engineering, it would be useful to provide an overview of the fundamental thermal performance indicators and equations. Kutscher's initial studies (153-156) constituted the foundation of the parametrisation and quantification of TSC performance. Heat transfer was studied and proved to be significantly influenced by TSC geometry, mass flow rate and crosswind speed. There are two essential equations that describe the performance of the TSC, which were firstly used in studies by Kutscher (154-156):

a. The heat exchange effectiveness (ε_{HX}) equation which describes the ability of the panel to exchange and transfer heat through air (Equation 3-1). Heat exchange effectiveness is defined as the ratio of the actual air temperature rise when the air passes through the absorber plate to the maximum possible temperature rise. For a given TSC, the decrease of the airflow will increase the heat exchange effectiveness. Kutscher's study showed that the important parameters in determining heat exchange effectiveness are suction flow rate, wind speed, hole pitch and hole diameter (155).

b. The instantaneous efficiency (η) equation which defines the percentage of solar power converted into heat (Equation 3-2) and is the ratio of the heat delivered by the TSC to the incident solar radiation.

$$\varepsilon_{HX} = \frac{T_{rise}}{T_{coll} - T_{amb}}$$ ***Equation 3-1***

Where ε_{HX} is the TSC heat exchange effectiveness

T_{rise} is the air temperature rise

T_{coll} is the surface temperature of the collector and

T_{amb} is the ambient air temperature.

$$\eta = \frac{Q_{TSC}}{\mathrm{I} A_p}$$ ***Equation 3-2***

Where η is the instantaneous efficiency of the TSC

Q_{TSC} is the heat delivered by the TSC

I is the radiation and

A_p is the TSC projected area, calculated from the flat surface dimensions.

The numerator (Q_{TSC}) in Equation 3-2 is calculated using the fundamental equation for fluids heat transfer introduced previously in section 2.1.2.4 (Equation 2-2) and applied here for the TSC output Equation 3-4. The denominator of Equation 3-2 includes the incident solar radiation that reaches the collector (I*Ap).

The temperature rise (T_{rise}) is the ambient air temperature (T_{amb}) subtracted from the TSC output air temperature (T_{TSC}) (Equation 3-3).

$$T_{rise} = T_{TSC} - T_{amb}$$ ***Equation 3-3***

Where T_{rise} is the air temperature rise

T_{TSC} is the TSC output temperature and

T_{amb} is the ambient air temperature.

$$Q_{TSC} = \dot{m} C_p T_{rise} \qquad \textbf{Equation 3-4}$$

Where Q_{TSC} is the heat delivered by the TSC

$\dot{m}$ is the air mass flow rate

C_p is the specific heat of air and

T_{rise} is the air temperature rise

The air mass flow rate in a duct could be calculated by measuring the air velocity in a pipe of known diameter (Equation 3-5).

$$\dot{m} = \rho \beta u_d A_d \qquad \textbf{Equation 3-5}$$

Where $\dot{m}$ is the air mass flow rate

ρ is the average density of heated air

β is the duct velocity coefficient (used to convert the centreline to average velocity)

u_d is the centreline duct air velocity and

A_d is the internal cross-sectional area of the ducting.

The term effective efficiency (Equation 3-6) was firstly introduced by Cortes and Piacentini in 1990 and then used as a TSC performance descriptor by Gupta and Kaushik, and other researchers (157, 158). The equation includes the additional mechanical energy (electricity consumption-thermal gains) for moving the air through the ducts and plenum.

$$\eta_{eff} = \frac{Q_{TSC} - \frac{\dot{W}_{fan}}{C_f}}{\mathrm{I}A_p} \qquad \textbf{Equation 3-6}$$

Where η_{eff} is the instantaneous effective efficiency of the collector and fan

Q_{TSC} is the heat delivered by the TSC

W_{fan} is the specific work of the fan

C_f is the fan's power conversion factor

I is the radiation and

A_p is the TSC projected area, calculated from the flat surface dimensions.

3.1.3 Thermal performance modelling

The most commonly used modelling tools will be split into two categories. The first one refers to the physics of the collector's heat transfer and the tools used to facilitate the development of the technology. The second category refers to simulation tools that inform the decision-making process in real-life applications.

Kutscher was the first to use simulation processes for studying the TSC in 1993 (153, 154, 159). Later, two-dimensional and three-dimensional CFD tools were used by a variety of researchers to understand TSC fluid mechanics, such as Gunnewiek et al. (1996), Dymond and Kutscher (1997), Arulanandam et al. (1999), Gunnewiek et al. (2002), Wang et al. (2006), Badache et al. (2013) and Li et al. (2013); most of them used Fluent Inc. or similar Ansys Inc. family tools (160-166). Another tool used to simulate transient systems such as complex solar thermal processes is TRNSYS which was used by researchers such as Maurer (2004), Delisle (2008), Collins (2008), Hall et al. (2013), Januševičius et al. (2016) and Kuhe et al. (2019) (159, 167-169).

Conserval Engineering Inc. was the first to design modelling software specifically for building integration of TSC. The computer tool, named TCFLOW, is now used for "Solarwall" installations which is the name of the first commercial TSC product and company founded by John Hollick in Toronto, Canada (170). RETScreen is the Canadian government energy management software package including the RETScreen SAHPM add-on for modelling residential and non-residential TSC applications. Also, TSC calculations were included in the UK commercial building energy model (SBEM) for Building Part L Regulations compliance (67). The Energy Plus simulation engine also includes TSC calculations however this is not embedded in Design Builder or other platforms using Energy Plus. Swift, developed by Enermodal Engineering, is a simulation tool specialised in TSC performance prediction (171), based on empirical models (102). It can be adjusted by monitored data and includes a broad spectrum of parametrisation. It has been used to validate other models such as RETScreen and SBET (Sustainable Building Estimation Tool for Tata Steel) (172). Swift has the additional advantage that is free and was not produced by a TSC commercial organisation. Also, Swift simulations have been normalised by test data and monitoring results; thus, it is considered very accurate. The latest version (2017) improved some of the limitations pointed out by Hall et al. (2011), Cho et al. (2012) and Shukla et al. (2012) (67, 141, 172).

3.2 A study on the collector's parameters

The transpired collector allows the external air to be drawn into a plenum (cavity) through evenly spaced perforations (white dots in Figure 3-1. TSC collector; author.). A summary of the parameters referred to the collector are shown in Table 3-1 and will be analysed in this section.

The geometry of the collector and the thermal characteristics of the absorbing coating are the two main categories of characteristics that refer to the TSC panel. In 2001, Van Decker et al. (173) reported that about 62% of the heat transfer is due to the absorbing coating, while another 28% occurs within the perforations and the remaining 10% is caused by the back of the collector. Also, the plenum width (Figure 3-1) was explored, as this parameter combined with the flow rate determines the time that the air stays in the cavity. On real-life installations the plenum width may be affected by the building envelope's geometry, cladding mechanism and aesthetics; thus, it will be re-examined in section 3.5.

In all theoretical, simulation, experimental or real-life studies, in order to transfer heat, the TSC has a flow rate. This interacts with all the collector parameters thus the change in the air flow rate is investigated in this section together with its effect to temperature rise. However, in real case studies, the flow rate can be controlled responding to design criteria and will be re-examined. The parametric analysis of the environmental conditions is also important; this includes air and solar radiation.

Many of the parameters interact and some of them will be examined in parallel. For example, solar radiation or the presence of crosswind, would impact differently on a flat or a sinusoidal shape collector.

3.2.1 Collector geometry

3.2.1.1 The perforation

Porosity is the percentage of the total area of the holes in relation to the total area of the panel; this is a function of perforation pitch (which determines the number of the perforations) and the perforation size. The pitch is the perforation pattern length (P in Figure 3-2 inset) and the size is defined by the hole's diameter (D in Figure 3-2 inset). After Sparrow and Ortiz's initial work on heat transfer of a high porosity perforated plate in 1982 (174), Kutscher et al. investigated low porosity plates with pitch from 13 to 27mm with hole diameter 0.8 to 3.2mm and porosity from 0.1% to 2.2% and provided a correlation equation between porosity and diameter, wind speed, suction velocity and pressure drop (153-155). Dymond and Kutscher claimed that the porosity should be typically between 0.5% and 2% to avoid pressure drops (161) and established the TSC panel as it is known today.

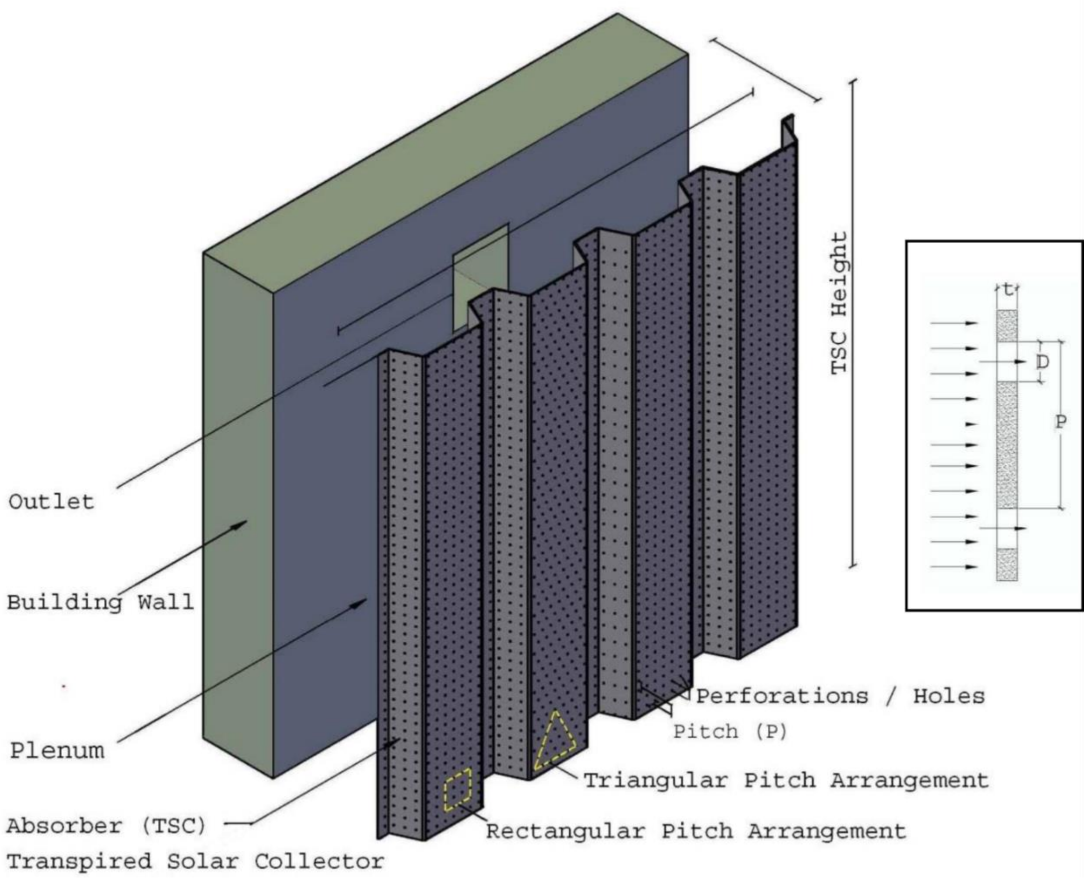


Figure 3-2 Schematic diagram illustrating the geometry of TSC (159).

As initial studies indicated that the selection of suitable pitch size and hole size is crucial as both affect the TSC performance, many researchers experimented on these parameters. Van Decker et al. (2001), Gawlik and Kutscher (2002) and Leon and Kumar (2007) used ranges similar to Kutcher's for pitch and hole size (173, 175, 176). Leon and Kumar found that for constant parameters (flow rate and radiation), the temperature rise increased with decreasing porosity and hole diameter (176). They showed that modifications on the diameter and pitch would cause moderate impacts on the heat exchange effectiveness and less moderate effects on efficiency. In their simulations the exit air temperature fell by 5.5°C with an increase from 12 to 24mm and from 0.8 to 1.6mm of pitch and diameter respectively. They also reported that the best performance of TSC was obtained at the minimum pitch (12mm) and diameter

(0.8mm), seen in Figure 3-3. This is the limit that keeps the pressure drop above 25Pa to ensure uniform flow distribution around the collector resulting in an approach velocity of 0.02m/s (176).

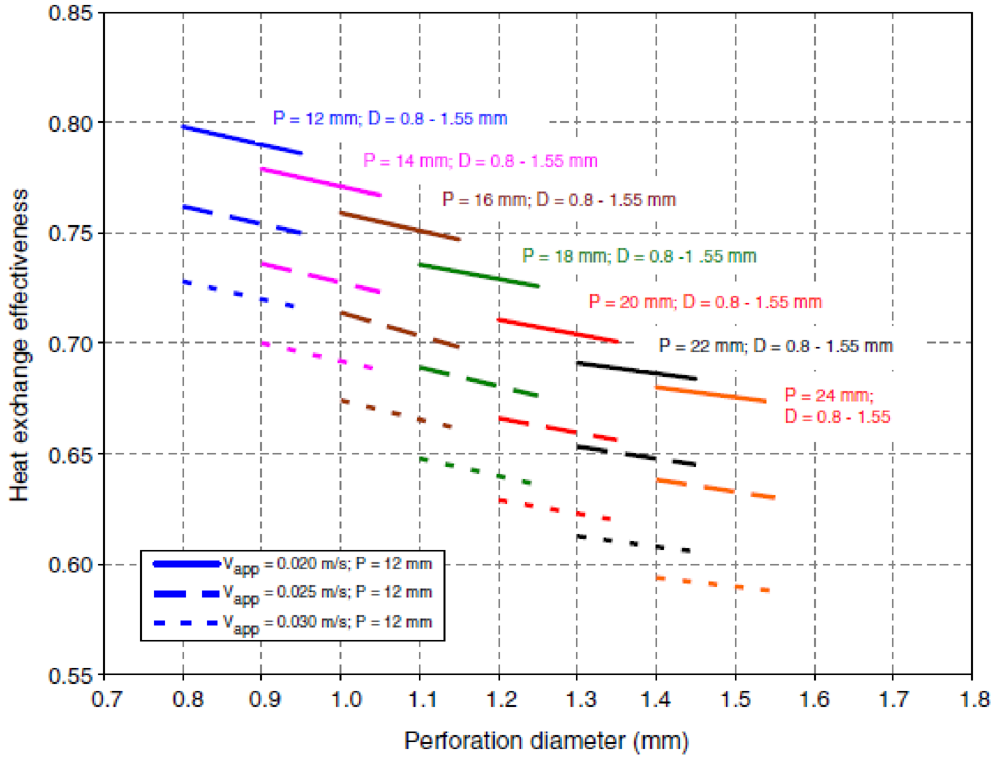


Figure 3-3. Heat exchange effectiveness as a function of collector pitch and perforation diameter (176).

Leon and Kumar indicated that for a constant pitch, increasing the porosity (i.e. increasing the hole diameter) has a minor effect on the collector's efficiency and heat exchange effectiveness (176). In a slightly different narrative, Zheng et al. (145) found a more significant relationship between porosity and efficiency. When the porosity value is doubled, from 0.2% to 0.4%, an efficiency decrease from 55% to 41% and temperature rise decrease from 14°C to 11°C are expected (145). Differences between the two studies are shown in Figure 3-4 and Figure 3-5; however, it has to be noted that Zheng et al. used a special glazed transpired solar collector and thermal behaviour is expected to be different.

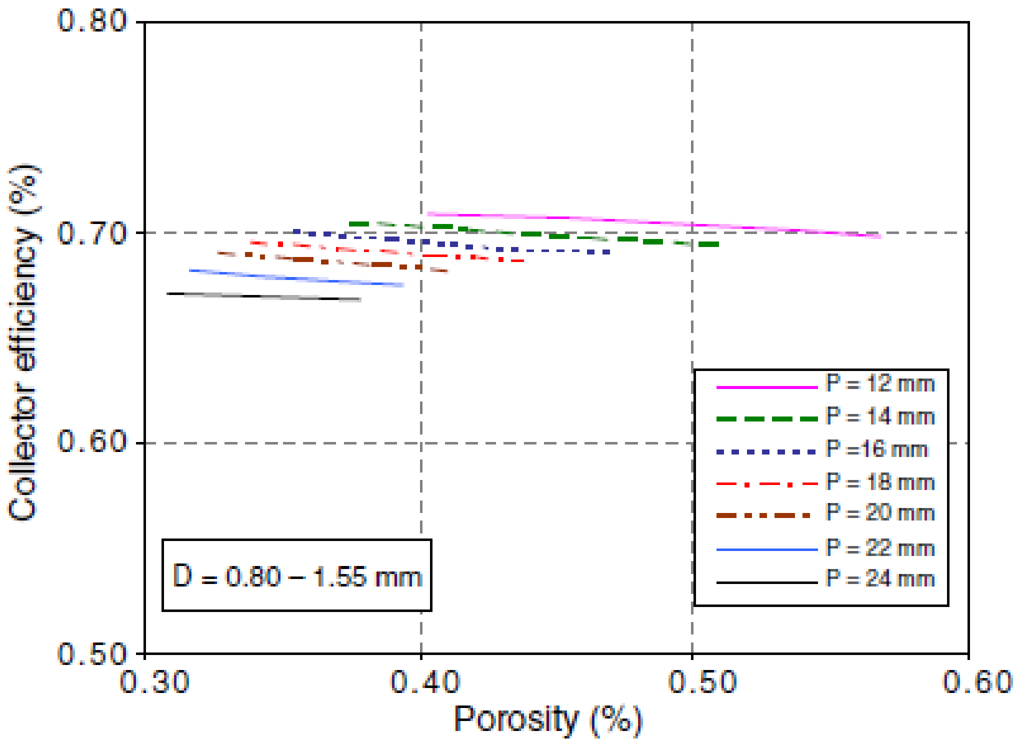


Figure 3-4. Leon and Kumar indicate moderate impact of porosity to efficiency(145).

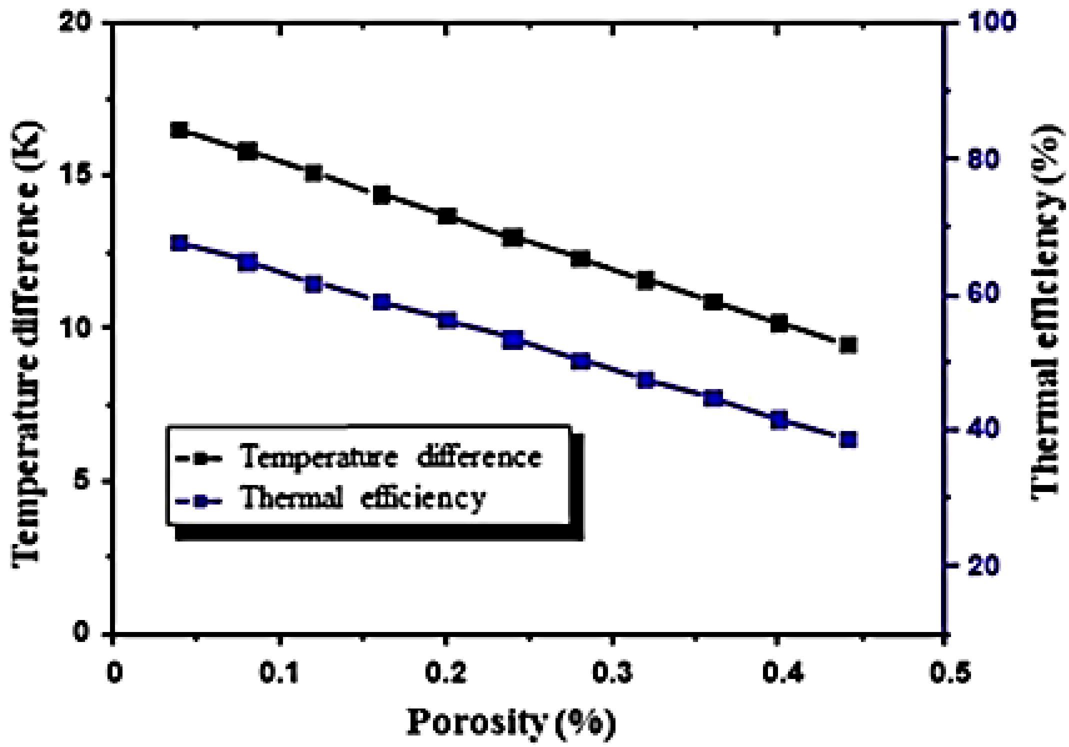


Figure 3-5. Zheng et al. indicate significant impact to temperature rise and efficiency with porosity increase (176).

Most studies discussed below, agree with Leon and Kumar on a minor less substantial impact of the porosity efficiency whereas pitch size reduction would increase efficiency (176). Motahar and Alemrajabi (2010) indicated that the optimum pitch and hole diameter dimensions were 12mm and 0.9mm respectively (177) shown in Figure 3-3. Gao et al. (2014), who investigated pitch design and hole geometry, also found that hole and pitch diameter have a slight impact on the thermal performance of TSCs (143). In addition, Li et al. (2016) confirmed that the diameter of perforation and the pitch shape have a low impact on the heat delivered, raising the importance of other measured outputs, such as the pressure drop (178). This last finding agrees with Kutcher's observations and is a driver in real-life applications where fan specifications determine pressure drop.

Different pitch arrangements are available. Square (rectangular) and triangular pitch are presented in Figure 3-2; however, staggered pitch and other special pitches are also available (179). Three kinds of pitch arrangement have been used in numerical and experimental studies, i.e. square pitch (162, 173), triangular pitch (173, 176) and hexagonal pitch (153). Van Decker et al. found a higher effectiveness in triangular pitch compared to square pitch (173).

Also, different types of holes are available, such as circular, square, elliptical, single slots (or slits) and other special designs, with the circular holes and slits being the prevalent ones in TSCs (143). Croitoru et al. (2016) found that the interleaved "x" and "+" perforations, especially when not aligned, provide better thermal performance compared to other geometries. Moreover, they found that the round hole has a lower heat transfer of about 15% compared to other geometries for low flow applications (50-150 $m^3/h/m^2$) (180).

3.2.1.2 Panel thickness and shape

The typical thickness in the late 1990s studies was 0.8mm and the bulk of the researched plate thicknesses ranged from 0.8 to1.55mm (159). Brown et al. referred to three different profiles (Figure 3-6), the tongue and groove planks, the cassette panels and the profiled metal sheeting which is applied in the majority of large installations (69). The first two are considered flat and the third one could be corrugated or sinusoidal and comes in several patterns' variations with a range of pitches, shapes and valleys and crown widths. In real applications the choice is led by design decisions and the availability of the facade metal cladding in the market (69).

Abulkhair and Collins (181) claimed that corrugated TSC loses heat three times faster than a flat perforated TSC. In all Li et al.'s experiments, flat profiles performed better than the corrugated ones in both temperature rise and efficiency. Both shapes have the same projected area meaning same incident solar; however, corrugated facades have more exposed area resulting to more losses. Low performance was attributed to the level of turbulence intensity in the approach flow being the dominant effectiveness factor for corrugated TSCs, but being less important for flat TSCs (166).

Figure 3-6. Examples of the three types of metal cladding available for TSCs (69).

3.2.1.3 Plenum width

Wang et al. (2006) investigated two parametric models of plenum width in their study, at 50mm and 200mm, while porosity was kept constant at 1.12%. The plenum width of 50mm was found to provide 72% effectiveness value versus 70% for the 200mm plenum indicating a minimal impact on the TSC effectiveness (164). Badache et al. also studied plenum width indicating a moderate impact of the width to the TSC performance. When the plenum decreased from 150mm to 50mm, the efficiency increased approximately 2% (165). Badache et al. explained that a decrease in plenum width would slightly increase the convective heat transfer, but would also require an increase of fan power to keep the suction the same (165, 182). As the plenum width has minimal impact on effectiveness and efficiency, it is designed based on suction velocity and construction limitations. Also, in real-life applications the plenum interacts with the back wall, thus further information about plenum width on real-life applications will be presented in the case studies later in this Chapter.

3.2.2 Coating thermal characteristics

In this section conductivity, emissivity and absorptivity related to material and colour variations will be studied. Heat transfer occurs at a lower rate in materials of low thermal conductivity than in materials of high thermal conductivity. Arulanandam et al. (1999) found that there was a decline in effectiveness of about 10-20% for similar plate geometries, when plate conductivity increased from about 50 to 500 W/mK (162). This was confirmed by Croitoru et al. (2016), as they claimed that the system is performing reasonably well if thermal conductivity is kept low (183). In addition, Gawlik et al. (2005) studied the performance of low-conductivity unglazed TSC numerically and experimentally and concluded that for practical low-conductivity materials, the performance differed little from the equivalent plate geometry for high-conductivity materials. This means that non-metallic, flexible, non-corrosive and inexpensive materials could be used in TSC applications (184) if they absorb solar radiation effectively.

Solar absorptivity is a key factor that affects the collector's performance by determining the percentage of solar energy captured by the plate of the total solar radiation striking the collector. Absorptivity is related to the material of the coating as well as its colour. Leon and Kumar (176) found that there is a direct relationship between the absorptivity and the collector's thermal efficiency. In their experiments, as absorptivity increased from 50% to 95%, the collector's efficiency rose by approximately 35% (Figure 3-7). Their findings also suggest that the impact on the efficiency due to the increase of the collector's thermal emissivity is rather insignificant at low (ambient) delivery air temperatures, as it only affects the radiant heat loss from the collector (176). This is consistent with the findings presented in 1999 IEA report by Cali et al. and also in a 2016 study by Li et al., where it is stated that solar absorptivity has a much greater impact on the collector's efficiency compared to emissivity (178, 185). Leon and Kumar also presented findings when high delivery air temperatures are employed, where emissivity has a slightly higher impact on collector's performance; this is consistent also with the findings in Pesaran and Wipke's study (176, 186).

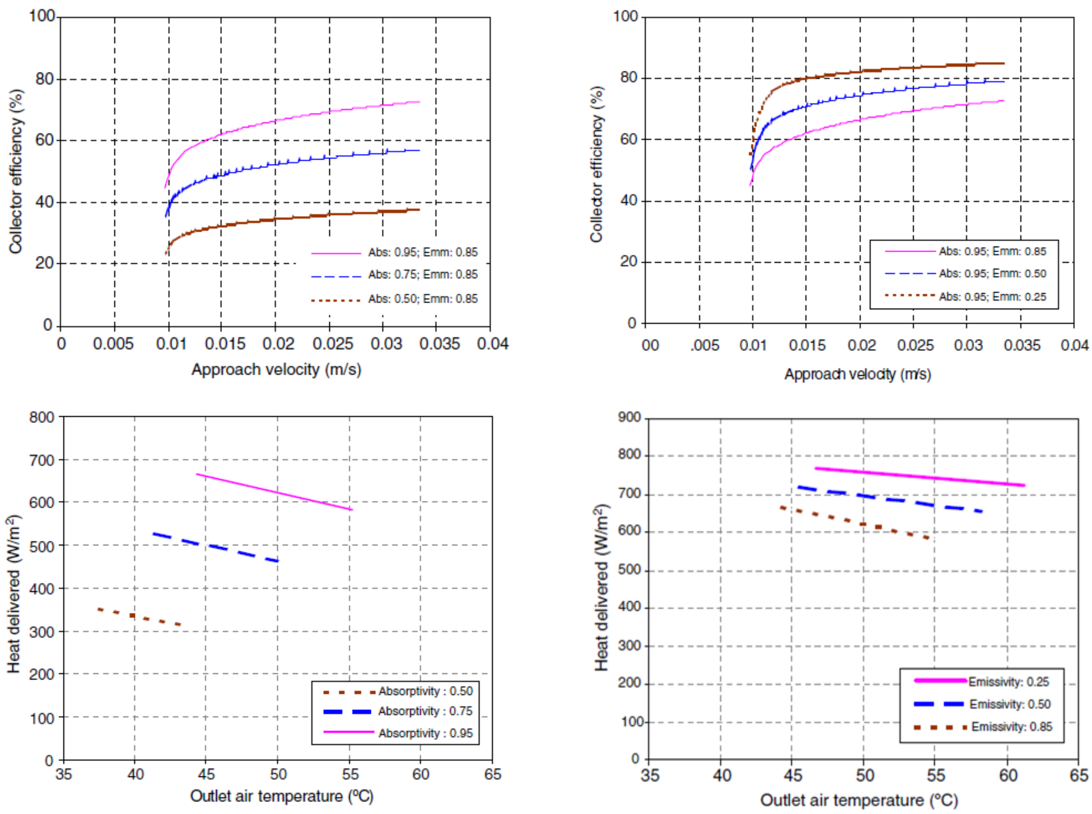


Figure 3-7. Collector's efficiency for different approach velocity with varying absorptivity (top-left) and emissivity (top-right). Collector's heat delivery for different outlet air temperatures with varying absorptivity (bottom-left) and emissivity (bottom-right) from Leon and Kumar's study (176).

The TSC as part of the cladding can be an aesthetically pleasant feature of the building envelope, especially when available in a wide range of colours. Dark colours are mainly used as these generally have higher absorptivity than pale colours. However, a variety of colours were tested and are available in the market with different heat transfer abilities. Some numerical and experimental studies dealt with the impact of the collector's colour on the TSC's performance (147, 180, 187). Croitoru et al. (180) stressed the importance of the black metal cladding's absorptance, as they found that it enhances the efficiency by up to 25% compared to metal claddings of other colours. Gao et al. (187) installed three experimental TSC of equal dimensions using three colours - black, dark blue and dark green – on a vertical wall. The total annual gains from the three TSCs were measured indicating that the green and the blue delivered 83.1% and 82.3% respectively of the energy delivered from the black one (187). Vaziri et al.'s (147) experiments showed that the highest efficiency values of 85%, 84%, 76%, 65%, 61%, 54%, and 55% corresponded to black, green, blue, red, violet, light yellow and white collector respectively. The study was on glazed TSC; however, colour impact on performance can be extrapolated for unglazed collectors. The “engineering toolbox” index includes materials with an absorptivity higher than 80% (steel typical absorptivity), including a variety of potential materials such as linoleum, black tiles, asphalt etc. (188).

The colour of the collector is a good indicator of the absorber's ability to convert solar radiation to heat. As dark colours absorb more sunlight, black is the obvious choice in terms of solar thermal performance. TATA steel introduced a wide range of steel coatings with improved solar absorption including light colours claiming good performance in the UK market. Alfarra’s survey, including architects, engineers and others, showed that there is sufficient variation in the market regarding TSC colour choice (159). There is a variety of surveys indicating that the availability of a range of collector colours is an important factor affecting the acceptance of solar energy technologies (189, 190). In Munari et al.’s survey, participants rated grey colour the highest (more desirable), which is consistent with the choice of colour made for TSCs in the UK indicated in Brown et al.’s review on TSC installations in Wales and England. Despite the extended range available, grey/anthracite is the dominant colour used in TSC applications (69).

3.2.3 Heat transfer – mass flow rate

It is clearly seen by the heat delivery and the instantaneous efficiency equations (Equation 3-2, Equation 3-4) that the air mass flow rate and temperature rise are parameters of great significance on the TSC performance. Kutscher et al. (1993) first stated that increasing airflow rate will increase the collector’s efficiency but decrease the outlet air temperature (154). Similar results were obtained by Pesaran and Wipke (1994) and Leon and Kumar (2007) who stated that there is an inverse relation between flow rate and exit air temperature for each given value of solar radiation (also seen in Figure 3-9) (176, 186). A large scale test of TSC performance by Paya-Marin et al. (2015) also proved that a decrease in the temperature rise (under constant solar irradiation) will be a result of an increase in flow rate within a range of 40 to 140 m^3/h per m^2 of collector (191). An increase of the mass flow rate means that air (approach velocity) moves faster in the collector; this allows less time for the absorber plate to transfer heat to the medium (air), resulting in a decrease in the temperature rise.

Cali et al.’s study for IEA stated that any reduction in the flow rate can lead to a decrease in TSC efficiency (185). Shukla et al. and Cho et al. indicate that this trend is not linear; with an increase of flow rate, the collector’s instantaneous efficiency raises at a descending trend, peaking at around 78% (141, 172). The increase of air flow rate had a positive impact on the heating energy savings, as by increasing the velocity of air passing collector, a higher proportion of the collector's absorbed heat would be transferred to the air mass (172). Cho et al. compared Carpenter et al.'s "RETScreen" model (192) against TATA steel "SBET" model (Figure 3-8) and found that collector's efficiency reaches a plateau for flow rate values above 100m^3/h per m^2 of TSC (172). The figure is in good agreement with Cali et al.'s (185) real case study (Ford Assembly Plant) where efficiency was calculated for radiation levels higher than 75W/m^2 and for wind speeds up to 3.5m/s to decrease impact of extrinsic factors. In another case study by Cali et al., similar outcomes were obtained for solar radiation exceeding 300 W/m^2 (185).

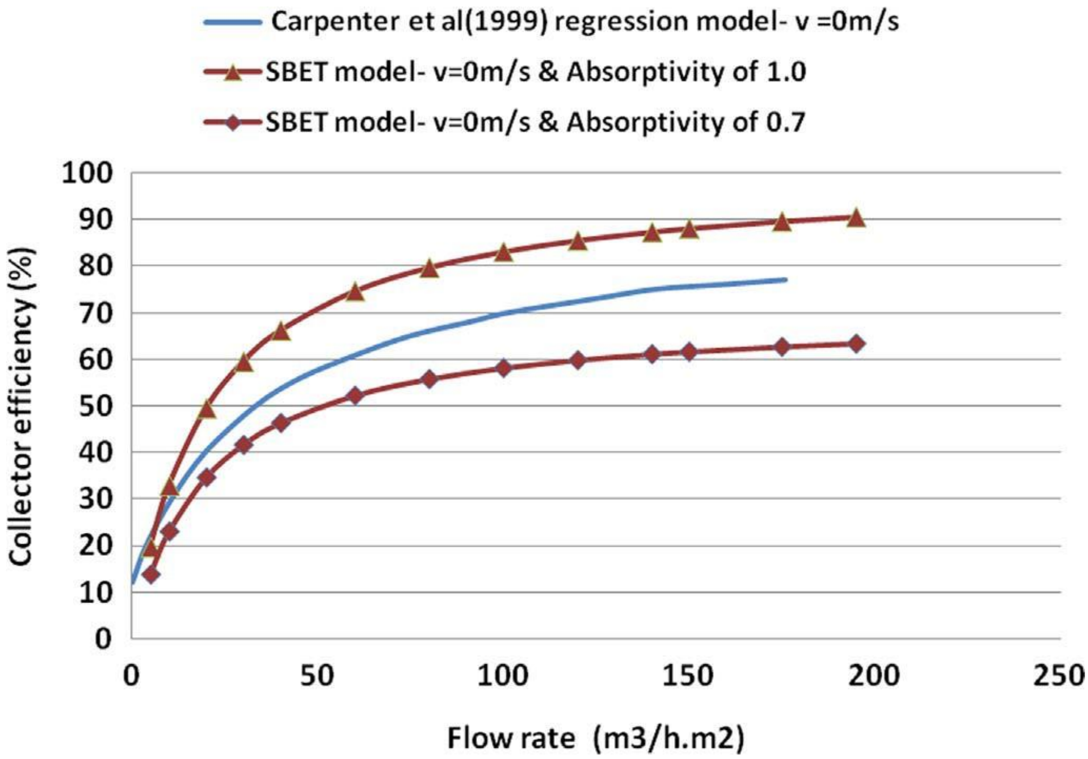


Figure 3-8. Effect of flow rate on TSC efficiency. A comparison between SBET and RETScreen model (193).

The heat transfer study raises a significant compromise: if the challenge is to deliver maximum heating output, the method is to maximise mass flow rate (and suction face velocity). This requires that temperature rise (TSC output temperature) is not a priority in terms of delivered power; however, comfort reprioritises the impact of the delivered temperature in real-life case studies. For this reason, these parameters have to be re-approached through operational terms of design.

3.2.4 Environmental

The meteorological parameters are key for all solar technologies with solar radiation having a dominant effect on the performance of solar thermal collectors and systems.

Additionally, when air is used as a medium, there is an increased uncertainty of the performance due to the variability of its characteristics such as the air temperature, approach velocity vector and uniformity. In this section, the microclimate parameters that affect the performance of the panel and collector will be analyzed using theoretical, simulation and experimental studies.

3.2.4.1 Solar radiation

Solar radiation is defined as the radiant energy emitted by the sun, while solar irradiation, a term used by Dymond and Kutscher (161), describes the direct, diffused and reflected radiation. For simplification purposes, in this study the term solar radiation describes the total solar energy reaching the TSC plane. Solar radiation has a significant impact on the panel's heat output (Equation 3-4), as it affects the air delivery temperature. The panel absorbs the radiation, converts it into heat which is then transferred to the incoming air. Solar radiation also influences the efficiency and effectiveness equations (Equation 3-1, Equation 3-2) directly as it appears in the denominator of the efficiency equation and will indirectly impact all air temperatures involved.

Leon and Kumar studied the impact of solar radiation from 150 to 900W/m^2 on the TSC output air temperature (T_{TSC}) for a variety of volume flow rates (from 45 to 135m^3/h per m^2 of TSC) (176). There is a linear correlation between the T_{TSC} and solar radiation. The impact is more significant for low flow rates where the heat is transferred to smaller amounts of air volume (and mass) (Figure 3-9). The results of their model were in good agreement with the Pesaran and Wipke's, Ben-Amara et al.'s, Gunnewiek et al.'s, and Wang et al.'s studies (160, 164, 186, 194).

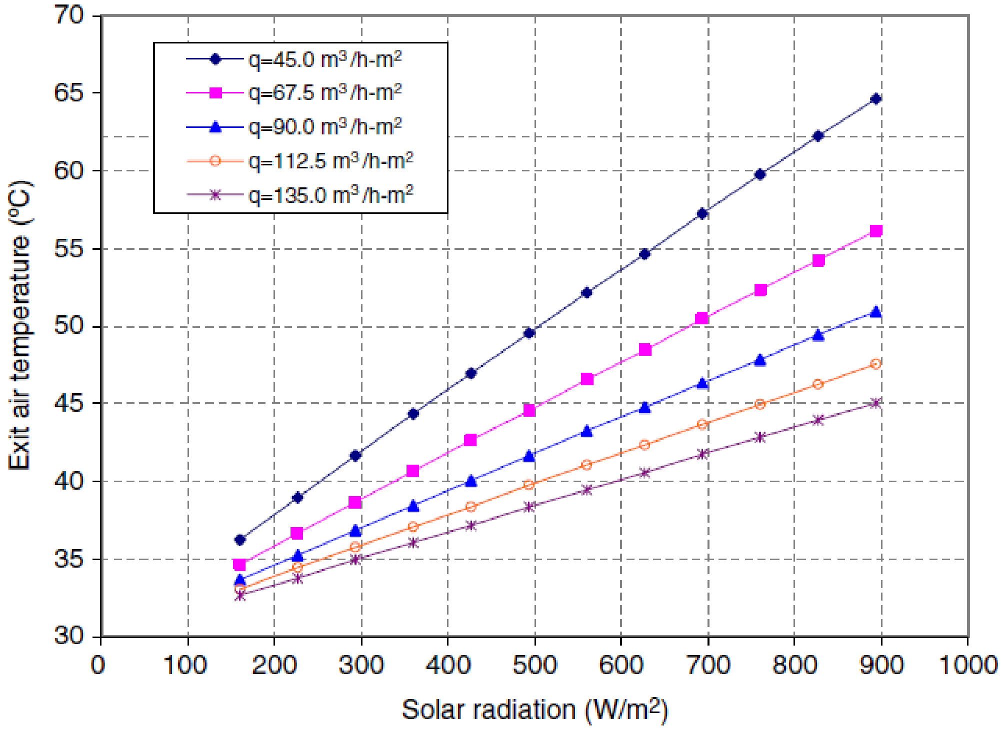


Figure 3-9. TSC output air temperature ('Exit air temperature' here) change for different solar radiations and different volume flow rates (176).

Similar results were obtained from Tajdaran et al.'s model which used Hall et al.'s experimental data for calibration (167, 195). The study demonstrated an increase of both surface temperature and temperature rise by increasing solar radiation. From 150 to 600W/m^2, the surface temperature rose by 33% and the temperature rise increased by 70%. Comparable results were also observed in Gao et al's simulations for glazed TSC (143). All the above studies amongst several others, such as Badache et al.'s (165, 196), Rad and Ameri's (150), Miseviciute and Rudzinskas's (197), concluded that although solar radiation heavily influences heat delivery, the efficiency and effectiveness of the TSC are not significantly affected. A visualization of this statement (Figure 3-10) can be seen in Cali et al.'s (185) real case study where only the days with incident solar energy higher than 1500 Wh/m^2 were considered, as the uncertainty in data below this value was too large.

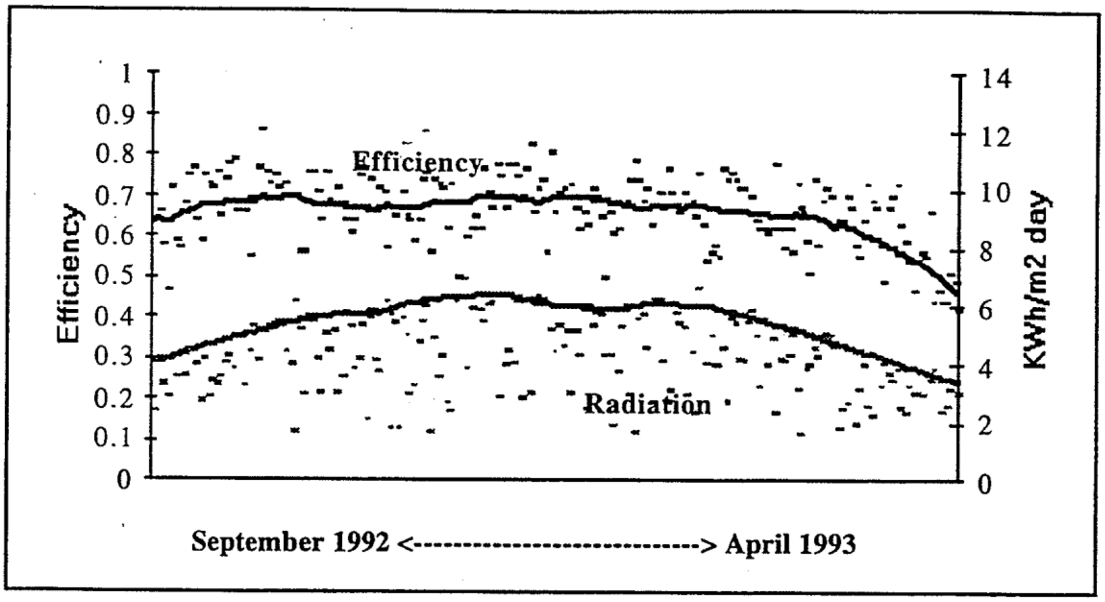


Figure 3-10. Average day efficiency and radiation (185).

3.2.4.2 Ambient air temperature

The outlet temperature of the TSC is strongly dependent on the ambient air temperature, thus it is considered as an essential factor (154). On the other hand, ambient temperature has a minor effect on the temperature rise as discussed by Leon and Kumar (176). In other words, TSC heat delivery is not significantly correlated to the ambient thermal conditions as it is only affected by the heat transfer mechanism causing temperature rise. Li et al.'s modelling in glazed TSCs, indicates a slight reduction from 69.07% to 65.33% in effective efficiency for an ambient air temperature change from 2°C to 20°C. The study explains that this fall in heat delivery is due to an increase in the heat loss coefficient (178). Similarly, insignificant yet negative impact of the increased ambient air temperature on heat delivery is observed in Gholampour and Ameri's study on PV-TSC (198) and Rad and Ameri's study on a two-stage TSC (150). Semenou et al. (199) agree with the above studies indicating that collector's efficiency decreases slowly with the rise of the outside ambient temperature indicating a corresponding increase in convective and radiative heat losses. The study also points out that during sunny days the losses are more noticeable than during cloudy days where ambient air temperature's impact on efficiency is negligible.

In real case studies, ambient temperature is a vital component as it is directly related to the heat demand. Whether a collector can be applied in a particular location is largely dependent on the local ambient air temperature. In the UK climate, temperature rise is beneficial for most of the heating season whereas it can create some overheating during summer. In the event of any unwanted temperature rise, the warm air has to be bypassed to avoid overheating and discomfort. This process requires a control mechanism and will be reviewed in section 3.5.

3.2.4.3 Wind effect

The effect of wind on the TSC performance depends on three characteristics: the incident angle, the turbulence and the wind speed. Li and Karava state that an increase in turbulence intensity would decrease both TSC outlet air temperature and instantaneous efficiency, especially when increasing wind speed and decreasing suction velocity (193, 200). Suction velocity is determined by the mass flow rate and the porosity. Vasan and Stathopoulos studied the wind effect on unglazed TSC and found maximum convective heat losses for winds at 45° angle, reducing TSC effectiveness. They also pointed out that local flow patterns are highly dependent on the immediate surroundings (201). Tajdaran et al. state that if 0° wind is defined as the parallel to the collector wind; for every 10° increase of wind angle, both surface temperature and temperature rise will decrease by 0.28°C and 0.19°C respectively. The benefit of parallel flow was also indicated in Perisoglou (author) et al.'s experimental study where parallel to the panel winds would result in a higher plenum air temperature compared to perpendicular winds (202). Thus, non-flat panels that are impacted by cross winds and turbulence have a disadvantage. Also, the pitch and spacing of the holes is important and related to the wind vector with higher effectiveness values obtained in the case of a pitch arrangement with a lesser spacing in the cross-stream direction of hole rows (155).

Cali et al. (1999) stated that efficiency of perforated collectors could be increased, decreased and drop down when wind velocity is zero, low (1m/s) and high (3m/s) respectively (185). For high wind speeds the impact is negative with a decrease in surface temperature and temperature rise (195). Fleck et al. indicated that the efficiency peaks at wind velocity of about 1.5 to 2 m/s and then drops down with further wind increase (3); this is explained by turbulence and vortex variations and is strongly related to the plate geometry and corrugation. Also, high wind speeds affect the air in the plenum causing reverse flows with significant impact on the TSC performance. For these reasons, Gunnewiek et al. suggest TSC applications for areas with winds below 5m/s (160, 163). Cordeau and Barrington quantified the impact of wind speeds on efficiency stating that a rise from 2m/s to 7m/s would reduce efficiency from 65% to 25%. They also studied the recovery efficiency which describes the back wall heat recirculation, stating that for every 1m/s increase of wind speed, the recovery falls by 5.7% (144). The suction velocity is driven by the flow rate;

the lower the flow rate, the easier it is for wind to disturb the velocity vector across the route to the fan. This raises concerns especially when TSCs installed in a non-urban windy environment and wind site analysis should indicate applicability.

3.2.4.4 Thermo-physical properties of air

The air temperature is related to the thermo-physical properties of air such as density, specific heat capacity, thermal conductivity, thermal diffusivity and dynamic and kinematic viscosity. All these parameters affect the air performance; however, specific heat capacity and density directly affect heat delivery (Equation 3-4, Equation 3-5).

- Specific heat capacity of air is the amount of heat required to change the temperature of one kg of air by one degree. Although it changes with the air temperature, it is relatively constant for ambient temperature ranges with a value of 1.005 kJ/(kg*K) at 0°C, 1.006 kJ/(kg*K) at 20°C 1.006 and 1.007 kJ/(kg*K) at 40°C (203).
- Air density is an important conversion parameter when calculating mass flow rates from volume flow rates. This is the case with TSC systems monitoring where the volume flow rate is calculated through measuring air velocity. Air density is affected by temperature, barometric pressure, which is a factor of altitude, and also by the amount of water vapour in the air. The International Standard Atmosphere (ISA) value at sea level, at 15°C and 100kPa is 1.225kg/m^3, while at 20°C and 101.325kPa is 1.204kg/m^3. Temperature rise, the addition of water vapour to the air as well as high altitude reduce the density of the air.

3.2.5 A summary of the collector’s parameters

The study of the collector is a prerequisite for the understanding of the integrated TSC; thus, this section explored the parameters that affect the technology of the collector prior to any real-life design decision-making process. Table 3-3 below, summarises which parameters are standardised in response to Table 3-1 where the collector related parameters are identified.

Table 3-3. TSC collector parameters standardised summary (continued overleaf)

Parameter category	Collector related parameters	Standardised values
Geometry	Panel thickness	0.8-1.55mm (183)
	Porosity	0.4% (150, 176)
	Perforation pitch	>12mm (150, 176)
	Hole diameter & shape	0.8mm circular less effective but easier to be manufactured (150, 176).
	Surface shape	Flat better than corrugated (161).
	Plenum width	No significant impact between 50-200mm (164) (165) but narrow plenum will increase fan power consumption (165, 182).
Coating thermal characteristics	Absorptivity	The higher the better (176)
	Emissivity	Not so important but the higher the better (178, 185), (176, 186)
	Conductivity	Not so important but the lower the better (162) (178)
	Colour	The darker the better (147, 180, 187)
Heat transfer	Flow rate	Up to 50m^3/h.m^2 efficiency increases From 50-10 efficiency increases slower and > 100 increases insignificantly (185)
	Temperature rise	Increase with radiation (167, 195)
Environmental	Ambient air temperature	Not so important but when increasing slightly reduces efficiency (178)
	Air properties	Specific heat capacity change is insignificant for TSC temperature ranges (203) Higher density (lower altitude and higher humidity) will increase mass flow rate.

Parameter category	Collector related parameters	Standardised values
	Solar radiation	Increases temperature rise especially in low mass flow rates (176)
	Wind (approach) velocity	Efficiency increases up to 2m/s and then decreases with sharp decrease for winds >5m/s (160, 163), (144).

In terms of the geometry, the shorter the pitch and the hole diameter the better the efficiency and effectiveness; however, manufacturing challenges and design parameters such as pressure drop set the limitations of these parameters (150, 176). In order for a fan to operate and transfer the heat, a minimum allowed pressure drop should be considered at 25Pa; thus, the suggested minimum pitch is at 12mm and hole diameter at 0.8mm for a porosity of 0.4%. Manufacturing challenges may also occur for complex hole types such as “x” and “+”; which are found to be slightly more effective than the circular one. The circular hole is widely used as the best option amongst other typical shapes. Also, the triangular pitch arrangement is the most effective as this arrangement allows for a better heat transfer around the perforations. Another parameter that is market driven is the type of cladding which is metallic despite the fact that other materials can have high absorptivity (183). The typical thickness range is from 0.8 to 1.55mm. Three different profile types are available: the tongue and groove planks, the cassette panels and the profiled metal sheeting which is applied in the majority of large installations. Corrugated panels are the least efficient; however, design and cost choices should also be considered. The plenum width has minimal impact on effectiveness and efficiency; it is designed based on suction velocity and construction limitations. Coating materials and colours with high thermal conductivity and absorptivity should be used whereas emissivity is not a crucial factor. Black colour is the most effective; however, other dark colours that are more desirable by the users can also be effective and considered.

Mass flow rate and temperature rise are the two main factors of the heat transfer equation. A flow increase would benefit the heat delivered but compromise the temperature rise. The efficiency increases significantly for flows up to $50m^3/h.m^2$ and then the increase slows down until reaching a plateau for flows over $100m^3/h.m^2$. This is a fundamental sizing challenge as in real installations, mass flow rate should meet comfort priorities such as ventilation needs and desirable temperature rise.

There is a linear correlation between the TSC output air temperature and solar irradiation; the impact is more noticeable for low flow rates. The collector's efficiency decreases slowly with the rise of the outside ambient temperature indicating a corresponding increase in convective and radiative heat losses; the effect is minor making TSC suitable in every climate with a heat demand enough to make the TSC cost effective. Wind has a negative effect on TSC performance when velocity is >2m/s. If there is wind, it is best for it to be parallel to the collector. The suction velocity is driven by the flow rate; the lower the flow rate, the easier it is for wind to disturb the velocity vector across the route to the fan.

There has been a noteworthy development in TSC optimisation over the last 30 years. The geometry and coating characteristics have been optimised; however, real-life site particularities may alter priorities and compromise the collector's performance. The heat transfer and environmental parameters were also analysed - a valuable piece of information in the design decision-making process.

Taking these on board, the study can focus on the TSC as a system and explore if and how this responds to the building-specific requirements.

3.3 Existing design guidance on TSC integration

While reviewing the literature there are very few case studies with adequate supporting data published and only five sources were found with some basic guidance on TSC integration and evaluation: US DoE's Transpired Solar Collectors document from 1998 (204), Cali et al.'s report for the Task 14 IEA (185) from 1999, Hastings's book from 2000 (140), Hall et al.'s Design Guidance on Transpired Solar Collectors in Renovation from 2011 (205) and TATA STEEL's more recent Colorcoat Renew SC Design guide from 2016 (206) which was developed in the UK. It needs to be noted that Hastings's guide addresses solar air systems in general but is not specific to TSCs. Tata steel's guide focusses on a specific product. As no guidance is provided with regard to evaluation and optimisation, this section focuses on the guidance regarding the TSC design presented in these documents.

3.3.1 Design drivers

3.3.1.1 Design intent

the US DoE's (18) states that a minimum ventilation need is required while Cali et al. (185) claim that any application that requires the heating of outdoor air could benefit from a TSC application. Hastings (140) argues that the main design parameter is the necessary ventilation rate, and it can thus be assumed that ventilation provision is the main design intent of such applications. Tata steel implies that the design intent of the use of the specific product in buildings is solar heated air for ventilation and space heating (206).

3.3.1.2 Sizing

According to the US DoE's (18) worksheet, sizing is based on available south-facing wall area and fresh air requirement. No information about sizing is provided in Cali et al.'s (185) and Hall et al.'s (205) reports. Hastings (140) explains that the collector area is determined by the type of the selected collector, the air flow rate, any restrictions on the inlet temperature, the performance prediction from simulation tools and the cost of the collector. Tata steel (206) suggests that the collector design and sizing are initially based on the ventilation requirement or the air change rate of the building and the selection of the TSC flow rate. Other design factors include the internal dimensions of the space to be heated, the thermal efficiency of the envelope's fabric, the actual space heat demand, the orientation of the building and any shading effects and the available wall space for the TSC installation.

3.3.1.3 Simulation

Cali et al. (185) suggest the use of TCFLOW for TSC design, which models the temperature and air flow distributions of unglazed TSC. They also suggest using SIMAIR to predict the annual TSC performance. A lot of details are provided in the publication regarding the use and configuration of these two tools. In Hastings's book (140) the software TrnsAir is presented, which is able to simulate six generic solar air heating systems in combination with a two-zone building model in order to evaluate the system's performance. According to Hall et al. (205), there are two tools typically used to predict the integrated environmental and economic performance of TSCs and these are RETScreen® V3.1 Solar Air Heating Project Model (207) or in the UK the Simplified Building Energy Model (SBEM) 2010 (Version 4.0.a onwards) (208) for Building Regulations Part L compliance. Tata Steel's design guide (206) presents a bespoke software tool called CRAFT (Colorcoat Renew SC Assessment and Feasibility Tool), which can predict the TSC performance in an individual building by performing initial feasibility assessments. No information about simulation was provided in the US DoE's (18) report.

3.3.2 Envelope integration

The US DoE (18), considers TSC applications to be a suitable south-facing wall or a wall within 45° of true south, Locations with short heating seasons should be avoided, as would be multiple-storey buildings (because of possible problems with fire codes) (18). It is also stated that a support grid of perforated vertical and horizontal Z-channels is typically used for the TSC integration to the structural wall. Little descriptive information regarding the envelope integration is provided in Cali et al.'s (185) report and no information in Hall et al.'s (205) report. Hastings (140) includes guidance about the panels, their colour, the coating and the plenum. However, he focusses on a specific product that has specific properties, i.e. SOLARWALL panels. He suggests that panels are made from galvanised steel or aluminium, with aluminium being more economical. Dark shades, for example black or dark brown, should be preferred. A durable and proven paint system should be used for coating, in order to last for a long period without any maintenance. He suggests that the plenum should have a depth that allows an air flow of maximum 3m/s. The depth can be reduced if air is drawn at different points. If there is a canopy at the top of the wall, this should be built as a plenum and should allow a flow rate of maximum 5m/s. Various ways of building integration are offered with regard to the cladding and the canopy; for example, the cladding can be mounted at the same distance from the wall, but at a maximum distance of 300mm; or the cladding can be tapered; or the cladding can have a canopy at the top of the façade (mounted either away from or directly to the wall); or the cladding can be on a canopy over windows and doors, which is a possibility especially if the architect is considering adding an architectural feature along the top of the wall. The US DoE (18) and Hastings (140) argue that costs can be reduced if the TSC integration is considered early on in the design. Tata steel (206) suggests that a south-facing wall (or with an orientation of up to 20° from south) is selected for TSC installation, while an orientation of 45° from south could yield acceptable results. Vertical walls are preferred and shading of the collector from nearby obstructions should be avoided. While a range of collector colours are available, dark colours are suggested to achieve maximum solar efficiencies. The potential profile options offer versatility in terms of the envelope integration and may have different impacts on heated air movements inside the plenum, affecting the TSC performance. Similarly to Hastings (140), Tata steel suggests a vertical air velocity of 3m/s, but they recommend a plenum width of 170mm as an optimal solution. In terms of the dimensions of the collector, the maximum width advised is 30m per outlet or a maximum area of 300m^2. It is claimed that tall and narrow collectors should be preferred as they are more efficient. In addition, the outlet (inlet to the building) should be positioned in the middle of the wall and on the top part of the collector to enable efficient distribution of heated air into the building.

3.3.3 Systems integration

3.3.3.1 Variants and functions

The US DoE (18) highlights TSC should bring fresh air in (without 100% recirculation systems) and absence of a heat recovery system, as it's thought that this function is redundant. Hastings (140) presents three system variations with regard to the heated air distribution: i) the air can be delivered directly to an adjacent space, ii) the air can be ducted to a remote space or iii) the air can be distributed to a central mechanical ventilation system, which then delivers it to different rooms. In this case the TSC acts as a preheater to the ventilation system. In addition, it is mentioned that the TSC system may be connected to a heat storage device if the delivery of the heat to the building needs to be delayed. No variants are mentioned in other guidance documents.

3.3.3.2 Air flow rate

In Hastings's (140) guidance it is claimed that in most ventilation heating designs an air flow rate of 72-97m^3/h per m^2 of collector area is quite typical, while if a higher temperature rise is required, then an air flow rate of 18-36m^3/h per m^2 of collector area is used and if a lower temperature rise is required, then a higher air flow rate of about 126m^3/h per m^2 of collector area is used. In Tata steel's design guide (206) it is argued that higher air flows through the collector deliver a lower temperature rise, but are more efficient in terms of delivered energy per m^2 of the TSC, while lower air flows result to a greater temperature rise, but are less efficient. An airflow of 72m^3/h per m^2 of collector area is recommended in order to achieve good efficiencies and a reasonable temperature rise, while providing a cost-effective collector size. Generally, for most applications an air flow of 70-80m^3/h per m^2 of collector area should be cost-effective and efficient. Further specific guidance is provided with regard to the temperature rise and volume of ventilation air requirements. For example, if a high temperature rise or a low volume of ventilation air is required, then an air flow of 45-53m^3/h per m^2 of collector area is recommended, while if a low temperature rise or higher volumes of ventilation air is required, then an air flow above 100m^3/h per m^2 of collector area is recommended.

3.3.3.3 Controls

In terms of the control strategy, Hastings (140), speaking of solar air systems in general, identifies four options: i) air is continuously drawn through the system, ii) the system is controlled on the inlet temperature, iii) the system is controlled on the irradiation level and iv) a time switch controls the system. Hastings also provides specific steps to select a controller. For example, initially the analysis of the system including number of components that have different thermal status, modes of operation (winter/summer) and further requirements, such as a timer, schedules, etc., should take place. Then the rules of operation should be defined; for example, what should happen, when and for how long (for each operation mode and component). The rules require the installation of a switch, such as a thermostat, a timer etc. Other considerations include the accuracy (<1K), type of sensors (NTC, Pt-100, Pt-1000, semiconductors), range of temperatures (0°C to 80°C), range of adjustable ΔT (1 to 15K) and range of adjustable hysteresis (1 to 10K) among others.

In terms of the selection, placement and accuracy of sensors, certain requirements are presented. The capacity (size) is recommended to be as low as possible, in air collectors the sensor should be placed close to the air flow outlet without touching the absorber, the temperature sensor should be placed at the position of the mean temperature (due to the inhomogeneous temperature distribution often occurring in air channels) and irradiation sensors should be placed close to the collector having similar tilt and azimuth angle.

In terms of operation Hastings suggests that a commissioning test is performed, as no off-the-shelf controllers exist in the market for solar air systems. For this, a controller with an integrated display showing temperature and status is preferred. In case there's no sun, the commissioning test should include a simulation of the operating status by heating the sensors etc. Regarding maintenance, Hastings recommends that the system functions are inspected regularly, especially for dampers and fans, as they have mechanical parts that may fail. He suggests that the design of the system should be kept as simple as possible and the costs of the control system relative to those of the TSC system.

Tata steel's design guide (206) provides four operation modes regarding the specific product, through the use of two dampers (collector damper and summer by-pass damper):

- If the TSC air temperature converges with building set point temperature, the collector damper is fully open and the by-pass damper fully closed.
- If the TSC air temperature is above ambient, but not sufficient to reach set point temperature, the collector damper is fully open and the TSC air is boosted by the conventional heating system of the building (or it is mixed with building's re-circulated air). The by-pass damper is fully closed.
- If the TSC air temperature is higher than the required set point temperature and within the allowable comfort band, then the 'excess' heated air from the TSC can charge the thermal mass of the building fabric or the TSC air can be mixed with cooler air drawn through the by-pass duct. In the former case, the

stored heat is released at a later time. In the latter case, the collector and the by-pass dampers are partially open and regulated to achieve the desired air flow and temperature.

- In the summer the by-pass damper is fully open to supply ambient fresh air as required, while the collector damper is fully closed.

No information about controls is provided in the US DoE (18), Cali et al.'s (185) and Hall et al.'s (205) reports.

3.4 Existing Case Studies; an overview

The TSC collector has been researched and optimised since 1986 (46) and a significant number of TSCs have been installed in a variety of building types. Solarwall® claim that they have installed more than 500,000m^2 of TSC (209). Cali et al.'s (185) report for IEA has been the most comprehensive review so far; however, it was done in 1999, including only four monitored sites, all industrial, with lack of consistency of the parameters explored and very little information on the design. Hollick (152) and Hastings (140) have also reviewed two monitored case studies each including limited information. Bake et al. (179), Shukla et al. (141) and Brown et al. (69) briefly introduced a variety of case studies; however, there is no information on controls, monitoring, performance evaluation or other parameters. A thorough investigation of the existing case studies in the literature will therefore set a baseline of knowledge and gaps.

The case studies were selected using the following criteria:

- The source was considered to be trustworthy, meaning that the case study is published in a platform that was peer reviewed or published by an institute that pursues independent research.
- The source should present information that would facilitate comparison with other case studies. The minimum information is the TSC area, inclination and orientation and a quantitative or qualitative assessment of the performance based on monitoring.

Due to lack of quantitative data, only fifteen case studies met these criteria: eleven on industrial buildings, three residential, and one commercial;. Most of them are in Toronto, Canada, where Solarwall® is based and Colorado US, where the US National Renewable Energy Laboratory (NREL) is based. Only five case studies are outside US; three of them are industrial, in Turkey, Germany and UK (Durham) and two of them residential, in New Zeeland and UK (Oxford); however, the one in Oxford did not address an occupied building (Figure 3-11, Table 3-4).

Figure 3-11. 15 literature TSC building-integrated case studies; map (author).

An overview of the case studies is shown in Table 3-4 where the studied buildings are cited chronologically with a reference to the building use, location, installation year and literature sources.

Table 3-4. TSC building-integrated case studies; overview and sources.

Building name	Building use	Location	Year installed	Author
NREL Waste Handling Facility	industrial	US	1990	Cali et al. (185) NREL (18)
Ford Automotive Assembly Plant	industrial	Canada	1990	Cali et al. (185)
GM Battery Plant	industrial	Canada	1991	Cali et al. (185) FEMP (170)
Utility Co-generation Plant	industrial	Germany	1992	Cali et al. (185)
Bombardier Inc	industrial	Canada	1993	Hastings (140)
US Army Hangar	industrial	US	1995	Hastings (140)
Intek Fabrics Manufacturing	industrial	US	1998	Maurer (210)
BigHorn Home Improvement	industrial	US	2000	Deru (211)
CA Group Roll Mill	industrial	UK	2005	BSRIA (212)
Broiler barns	industrial	Canada	2007	Cordeau & Barrington (144, 213, 214)
PIMSA Automotive production plant	industrial	Turkey	2012	Eryener & Akhan (215)
Wal-mart	commerci al	US	2006	Kozubal (216)
Windsor Housing Authority	residential	Canada	1994	Hollick (152) Hastings (140)
House in Judgeford	residential	New Zealand	2005	Heinrich (217)
Wheatley Campus Retrofit	residential unoccupie d	UK	2009	Lawson & Hall (167, 218)

The full details of the case studies are collated in a 36-column summary table which can be seen in Appendix II**.** In addition to the overview (presented in Table 3-4), the data are considered in categories for Design (A, B and C), Evaluation (D) and Optimisation (E) (Table 3-5). These categories will be used to structure the discussion parts of this chapter (sections 3.5-3.7).

Table 3-5. Content and format of summary table included in Appendix II and broken down in parts in the discussion sections (sections 4.3-4.5)

Case studies	Design			Evaluation	Optimisation
Table Overview	Table A Design drivers	Table B Envelope integration	Table C Systems integration	Table D Evaluation	Table E Optimisation

The data units in the case studies were homogenised by the author to allow the reader to compare and understand the differences between installations. The most critical conversions are the mass flow rate (m^3/h or m^3/h per m^2 of TSC), heat (kWh and kWh per m^2 of TSC) and cost in £ or in £ per m^2 of TSC. An overview of the case studies is presented below, but detailed technical information on design and evaluation (including optimisation) can be found in Appendix I.

3.5 Discussion on case studies design integration

This section will discuss the design drivers and the integration to the building envelope and systems of the literature case studies presented above. Three Tables (Table 3-6, Table 3-7 and Table 3-8) (part of Appendix II) in the beginning of each sub-section will assist to group the parameters to be discussed.

3.5.1 Design drivers

The aim is to understand the reasoning behind the design intent, sizing and the tools used in this process. The discussion that follows analyses the data presented in Table 3-6, which shows an overview of the design drivers including the parameters information for all the case studies.

Table 3-6. Design drivers. Summary table from literature case studies; author.

Building name	Design intent	Ventilation demand linked to sizing/ evaluation	Performed simulation	TSC collector area in building (m^2)
NREL Waste Handling Facility (185)	Unclear	No*	heat transfer modelling	27.9
Ford Automotive Assembly Plant (185)	Retrofit, available area	No	SIMAIR	1877 (237 were monitored)
GM Battery Plant (185)	Unclear/ Retrofit	No	SIMAIR	365 (420 incl. non-perforated)
Utility Co-generation Plant (185)	Retrofit/ Combustion air supply	N/A	N/A	305.6 (343 incl. non-absorbent area)
Bombardier Inc (140)	Retrofit/ ventilation with some heat	No	N/A	611
US Army Hangar (140)	Cost	No	N/A	725
Intek Fabrics Manufacturing (210)	Unclear	No*	TRNSYS	277
BigHorn Home Improvement (211)	Available area, fuel consumption reduction	No	Whole building energy simulation	209
CA Group Roll Mill (212)	Unclear	No	N/A	410
Broiler barns (144, 213, 214)	Unclear	No	CFD	221 (for each of the two barns)
PIMSA Automotive production plant (215)	Unclear	No	RETscreen	770
Wal-mart (216)	Unclear	No	N/A	743
Windsor Housing Authority (140, 152)	Retrofit	No	Energy savings modelling	335
House in Judgeford (217)	Unclear	No	N/A	28.1
Wheatley Campus Retrofit (218)	Unclear	No	N/A	10.4

* Although ventilation demand was not linked to sizing or the evaluation of the system in this case study, this aspect was mentioned in the guidelines as an important consideration to be taken in the design of the system (NREL 2010 (219), Mauer 2004 (210)).

3.5.1.1 Design intent

Many of the buildings under investigation addressed retrofit projects, in which a TSC was installed to repair the south wall, e.g. Bombardier (140), Ford Automotive Assembly Plant (185), Göttingen Utility Co-generation Plant (185), Windsor Housing Authority (140, 152) and Wheatley Campus Retrofit (218). This denotes that the driver behind the sizing was very likely the area of the surface to be repaired, which was indeed the entire wall. Specifically for Bombardier, the aim was to improve the ventilation and air quality inside the building. In the Ford Automotive Assembly Plant (185), the authors argued that the TSC technology was used due to the lower costs and higher efficiency compared to a glazed system. It was installed as a manifestation of system safety and aesthetics. Thus, no consideration of the ventilation demand was made in the sizing of the system, which contradicts the guidance found in the majority of the design guides (e.g. Hastings's (140), Tata steel's (206) and US DoE's (18) guides). In Windsor Housing Authority (140, 152), the improvement of the appearance of the building was of prime importance as was the reduction of the heating costs. No ventilation demand values were presented. In Göttingen Utility Co-generation Plant (185), the TSC was only used as a mechanism to pre-heat the combustion air and not for ventilation purposes.

In the PIMSA building (215), the system was designed to improve the air balance and comfort of the building, while displacing onsite auxiliary heating fuel consumption and recapturing building heat loss; however, no connection has been made between the design intent and the ventilation demand. In the BigHorn Home Improvement Centre (211), the TSC area was as large as possible to minimize the load on other heating systems, so the size of the TSC was informed by the available area on the south façade, without giving due regard to the ventilation requirements of the building. However, the author of this work highlights multiple shading effects in a variety of solar paths, caused by the driver to use the whole south elevation. The rationale behind the use of TSC in the US Army Hangar (140) was that the TSC's cost would be comparable to a conventional gas-heated ventilation system that was initially specified. In the GM Battery Plant (185), the TSC was installed to correct the ventilation problems, but again, no details were provided about the specific problems and associated ventilation requirements.

In the NREL Waste Handling Facility (185), the aim was to provide solar-heated ventilation air to offset some of the heating of the conventional electric heaters. Similarly, in Wal-mart (216), the design intention behind the sizing of the collector was for it to provide both warm air for the ventilation needs of the building and space heating. However, while minimum ventilation requirements have been provided, it looks like the dual function of the TSC (heating and ventilation) was an afterthought, as Kozubal et al. state that the TSC was oversized for ventilation air preheating (216). This is contradicting the statements by Cali et al. (185) who argued about the effective TSC performance without considering the building's real demand.In the Broiler barns case (144, 213, 214) the aim of the study was to measure the performance of the

TSC system and savings in heating load during the monitored period (144), as well as its impact on winter ventilation rate and broiler chicken performance (213); however, the driver behind the sizing of the system was unclear.

In Intek Fabrics Manufacturing Facility (210), the aim was to determine whether TSC was appropriate for the climate in North Carolina, so the ventilation demand was not linked to the sizing as different flow rates were tested; however, it was mentioned that it should typically be linked in practical applications. Similarly, in Wheatley Campus Retrofit (218), the intent was of an exploratory nature, i.e. to investigate the application of TSC to over-cladding of existing concrete or masonry buildings, as it could potentially significantly reduce the heating costs of a building when combined with external insulation. Yet, no information was provided as to how the TSC sizing was decided.

The objective of the CA Group Roll Mill (212) and the House in Judgeford (217) studies was to provide guidance on the installation and monitoring of TSC systems in buildings. In the first case specifically, the aim was to develop a standard monitoring package/process for use in future installations. No further information was provided relating to sizing of the system. In the House in Judgeford (217) the TSC was used to provide heating only.

Table 3-6 illustrates that ventilation demand was not a consideration in the design stage or in the evaluation stage for any of these case studies. It is evident from the information presented that the size of most of these TSC collectors was based on the available area on the solar-facing wall. The readings suggest that the effective provision of warm air for the ventilation needs of the buildings was often seen as an afterthought. It has been thus inferred that ventilation demand was largely omitted as an aspect that could drive the sizing of the TSC system in the initial stages of the design and the evaluation of the system in later stages.

3.5.1.2 Sizing

The collector area across all TSC installations ranged between 10.4 and 1877m^2. In two cases, i.e. the GM Battery Plant (185) and the Göttingen Utility Co-generation Plant (185), there was an additional non-perforated manifold at the top part of the TSC, so the total collector area amounted to 420m^2 and 343m^2 respectively with a manifold area of 13% and 11% respectively. The Wheatley campus test installation (218) included a significant area of dummy panels for aesthetic reasons. NREL recommends cost effective installation at maximum 0.014m^2 per m^3/h of ventilation air needed or 73.4m^3/h per m^2 (18). In the GM Battery Plant (185) case study one of the proposed modifications after monitoring was to match the TSC size to the fresh air and heating requirements of the building. However, in most of the case studies the sizing process was dominated by the maximum available solar facing envelope area with lack of further plausible design intent. This contradicts recommendations found in some of the design guides, e.g. Hastings's (140), Tata steel's (206) and US DoE's (18), who claim that sizing should be based on the ventilation requirements of the building and the available wall space for the TSC installation among others.

3.5.1.3 Simulation

In some of the studies, it is mentioned that simulation took place; however, it is used mostly as an evaluation rather than a design tool. For example, SIMAIR was used in two industrial buildings (Ford Automotive Assembly Plant (185) and GM Battery Plant (185)), which is also one of the two tools recommended by Cali et al.'s design guide (185) and RETscreen, which is also mentioned in Hall et al.'s design guide (205) was used in another one (PIMSA Automotive production plant (215)) to predict the energy savings. In another industrial building (Intek Fabrics Manufacturing Facility (210)) TRNSYS was used to look at the potential for TSC installation in warmer climates than where they are typically installed. The same tool was used for the energy savings prediction of the Wheatley study (218). Whole building energy modelling was performed in the BigHorn Home Improvement Centre (211), but no specific information is provided for any TSC modelling. For the NREL Waste Handling Facility building (185), modelling was performed to estimate the heat transfer contribution through the concrete wall to the TSC efficiency. In one of the residential buildings (Windsor Housing Authority (140, 152)), simulation was performed to estimate the annual energy savings. Lastly, in Broiler barns (144, 213, 214) CFD simulations were used to establish TSC configurations to optimize heat recovery and minimize flow reversal. It is therefore apparent that different approaches to address different aims were employed in some of the case studies, but none specifically relating to the sizing of the TSC. Other recommended tools found in the design guides are TCFLOW (in (185)), TrnsAir (in (140)), SBEM (in (205)) and CRAFT (in (206)). In any case no guidance on TSC system design modelling was found.

3.5.2 Envelope Integration

When the collector is designed and installed on a building's facade, the shape, colour, orientation and panel's characteristics play a key role on the performance thus have to be taken into consideration in the design stage. Table 3-7 presents the envelope integration-related parameters summarised for all the literature case studies. The parameters are then discussed considering both the case studies and the analysis of the collector's technology.

Table 3-7. Envelope integration. Summary table from literature case studies; author.

Building name	Inclination	Orientation	Surface shape	Colour	Porosity	Hole diameter	Plenum width (mm)
NREL Waste Handling Facility (185)	vertical	south	corrugated	black	2%	N/A	N/A
Ford Automotive Assembly Plant (185)	vertical	south	flat	black	1% and 2%	N/A	N/A
GM Battery Plant (185)	vertical	south	flat	black	2%	1.6mm	150
Utility Co-generation Plant (185)	vertical	south-east	possibly corrugated	dark brown	1%	N/A	100
Bombardier Inc (140)	vertical	south	flat	custom dark olive-green	N/A	N/A	220
US Army Hangar (140)	vertical	south	flat	dark bronze	N/A	N/A	250
Intek Fabrics Manufacturing (210)	vertical	south	corrugated	black	0.60%	1.6mm	200
BigHorn Home Improvement (211)	vertical	south	N/A	dark bronze	N/A	N/A	N/A
CA Group Roll Mill (220)	vertical	south	possibly corrugated	dark/black	N/A	N/A	N/A
Broiler barns (144, 213, 214)	vertical	south-east	corrugated	black	1%	N/A	N/A
PIMSA Automotive production plant (215)	vertical	south	N/A	dark grey	N/A	N/A	N/A
Wal-mart (216)	nearly vertical	south	flat	dark grey	N/A	N/A	N/A
Windsor Housing Authority (140, 152)	vertical	south	corrugated	dark brown	N/A	1.5mm	250
House in Judgeford [19]	vertical	north	corrugated (metric)	black	1%	N/A	N/A
Wheatley Campus Retrofit (218)	vertical	south	flat (cassette)	grey	0.22%	N/A	30mm/ 140mm

The **inclination** was vertical or nearly vertical in all building cases, as suggested in Tata steel's (206) design guide. In most cases the **orientation** of the TSC panels was solar facing or nearly solar facing, as also recommended in US DoE's (18) and Tata steel's (206) design guides; in two cases (industrial buildings), the orientation was south-east due to the initial footprint of the building envelope. Shading had a performance impact in some case studies such as the house in Judgeford (217). Kutscher claimed that tilted TSC would perform slightly better than the vertical ones (155); however, only the TSC in the Wal-mart building (216) was slightly inclined and no horizontal or roof-integrated applications were found in the literature.

Regarding the TSC panel surface type, there was a mix of flat and corrugated panels used in the industrial cases and all had a rectangular outline. Flat panels were selected for the Wheatley campus building (218) (residential) where a cassette type was used. In section 3.2.1 it was mentioned that flat panels are more effective and in some applications they may be more attractive; however, no such correlations were made in the case studies literature.

The predominant collector colour is black, while dark grey, dark brown and dark bronze colours have been used, which agrees with the recommendations provided in Hastings's (140) and Tata steel's (206) design guides. A custom dark olive-green colour was used in one industrial building and grey was used in one of the residential building cases (Wheatley campus retrofit (218)). Dark colours were used in agreement with the absorptivity analysis presented in section 3.2.2.

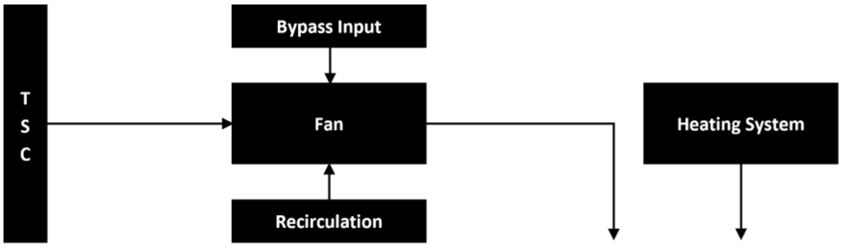
Little information was provided with regard to the hole diameter. This was 1.6mm for two industrial applications and 1.5mm for one residential one. Specifically for one industrial application, the spacing of the holes was 16.5mm on the horizontal axis and 20 mm on the vertical one. However, this is not such a dominant factor in comparison to porosity (section 3.2.1). Collector's porosity ranged between 0.22% and 2%. An interesting combination of 1% and 2% was used in the Ford Automotive Assembly Plant (185); 1% porosity was used near the fan and 2% further away to achieve even airflow distribution across the entire collector. No porosity parameter was provided for the commercial building. It seems that more recent installations have lower porosity to increase efficiency as seen in the collector's technology analysis in section 3.2. This is something that can be even more effective when temperature rise is a priority thus flow rate decrease and pressure drop allow low porosity. No information about hole diameter or porosity is provided in the design guides.

Plenum width ranged from 150mm to 250mm for industrial applications, while for one residential application a width of 250mm was used. All agree with the maximum recommended plenum width of 300mm in Hastings's guidance document, while no case study used the recommendation of 170mm by Tata steel (however, it should be noted that this recommendation relates to a specific product). Two different cavity widths were tested in the Wheatley building (218) and this was the result of the presence or not of an insulation layer; 30mm width was tested when insulation was applied and 140mm when no insulation was applied.

3.5.3 Systems Integration

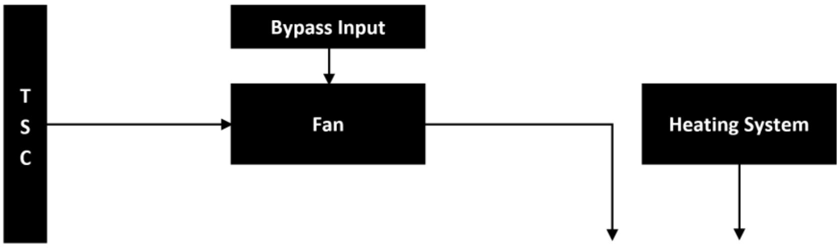
The integration of TSC into the building services is a crucial part of the design decision-making process. The collector can be integrated to a fan (DHV), with or without the presence of a separate auxiliary heating system or can be integrated into the HVAC system. In both cases, there are two supplementary yet important functions, the summer bypass and the recirculation connections. All these, as well as the design intent, sizing and envelope integration drive the air flow rate which is fixed and varies within a range (or can’t be fixed and varies). Finally, the choice of controls and operational scheduling is a vital component of the effective TSC system. Figure 3-12 and Figure 3-13 visualise the main TSC variants used in the literature case studies for both DHV and PHV systems and Table 3-8 summarises all the parameters related to systems integration to facilitate the following discussion.

I.



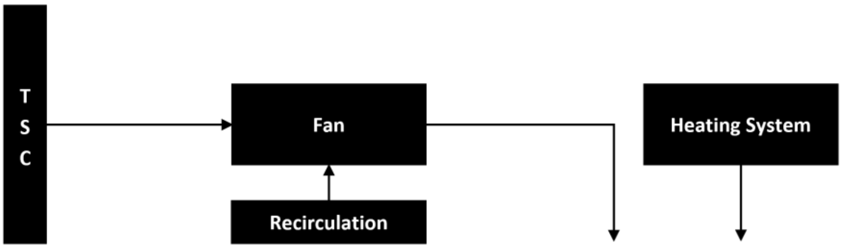
- Ford Assembly Plant
- General Motors (GM) Battery Plant
- CA Group Roll Mill

II.



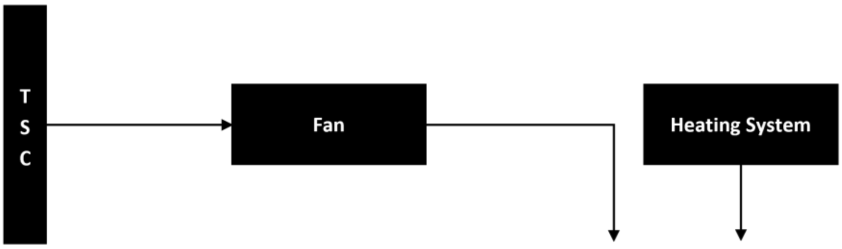
- Broiler barns

III.



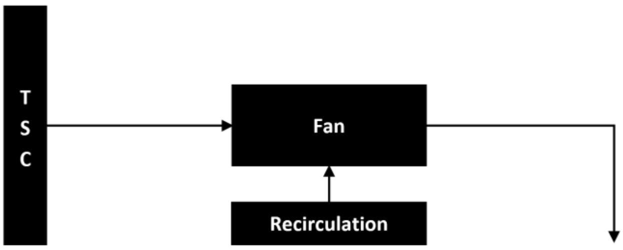
- Intek Fabrics Manufacturing Facility *(heating system implied)*

IV.



- BigHorn Home Improvement Centre
- House in Judgeford (Heating system no info)
- Wheatley Campus Retrofit (no aux heating system used in testing)

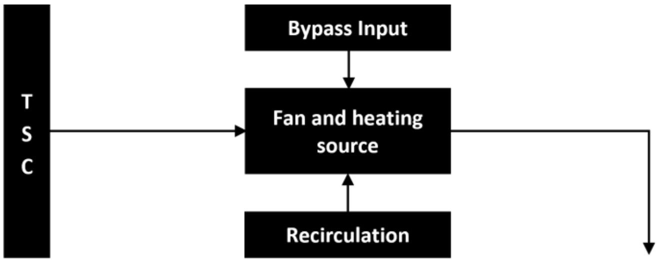
V.



- Bombardier Inc. (No pre-heat, Heating source N/A, Recirc N/A)
- U.S. Army Hangar (No pre-heat, Heating source N/A, Recirc N/A)

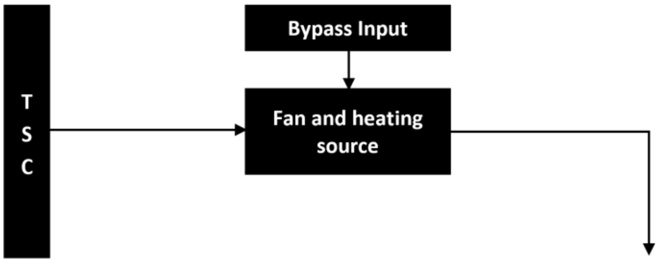
Figure 3-12. DHV TSC systems. A schematic overview to group variants and functions of building integrated TSC systems of the reviewed literature case studies; author.

I.



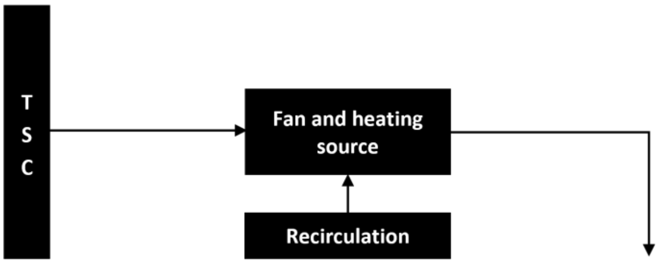
• PIMSA Automotive production plant

II.



• NREL
• Windsor Housing Authority (Recirc N/A)

III.



• Wal-mart (no info about by-pass)
• Göttingen Utility Co-generation Plant (not a ventilation system – feeds an air combustion boiler)

Figure 3-13. PHV TSC systems. A schematic overview to group variants and functions of building integrated TSC systems of the reviewed literature case studies; author

Table 3-8. Systems integration. Summary table from literature case studies; author (continued overleaf).

Building name	Air flow rate (m^3/h per m^2 of TSC)	TSC integrated to HVAC system	Auxiliary separate systems	PHV or DHV	Bypass overheating	Recirculation	Controls
NREL Waste Handling Facility (185)	183	Yes (electric heater)	No	PHV	Yes	No	Yes: electric heater based on TSC and room T. Bypass based on external T
Ford Automotive Assembly Plant (185)	119	Yes (ventilation only)	Gas heaters	DHV	Yes	Yes	Yes: for recirculation and bypass (bypass damper used at 18°C)
GM Battery Plant [3]	162	Yes (ventilation only)	Steam heaters	DHV	Yes	Yes	Yes: for recirculation and bypass (bypass damper used at 18°C)
Utility Co-generation Plant [3]	27.5 - 70	Not a ventilation system	No	PH	No	Yes	Yes: recirculation when solar <100 W/m^2
Bombardier Inc (140)	117	No	No	DHV	N/A	Yes	Yes: fans driven by occupancy patterns and recirculation by outside air
US Army Hangar (140)	50 - 148	No	No	DHV	N/A	Yes	Yes: regulator dampers would mix recirculated air driven by external T
Intek Fabrics Manufacturing (210)	51.5 - 52.7	No	Possibly**	DHV	No	Yes	Yes, but no summer bypass
BigHorn Home Improvement (211)	N/A	No	Gas fired radiant floor system	DHV	No	No	Yes, destratification fans ware also included
CA Group Roll Mill (220)	45	No	Gas heater	DHV	Yes	Yes	Yes: algorithms depending on scheduling and T sensors
Broiler barns (144, 213, 214)	42 - 57.2	No	2 gas heaters	DHV***	Yes	No	Yes: for the bypass, fans and gas heaters to follow broiler T protocol
PIMSA Automotive production plant (215)	82.8	Yes (6 AHUs)	N/A	PHV	Yes	Yes	Yes: 24 automatic damper controllers

Building name	Air flow rate (m^3/h per m^2 of TSC)	TSC integrated to HVAC system	Auxiliary separate systems	PHV or DHV	Bypass overheating	Recirculation	Controls
Wal-mart (216)	28 - 104	Yes RTUs & 2 AHUs	No	PHV	No	Yes	Yes
Windsor Housing Authority (140, 152)	69	Yes 6 gas heaters	No	PHV	Yes	N/A	Yes: dampers for bypass at 20°C ambient T
House in Judgeford (217)	23.5 - 79	No	Probably yes but no info	DHV	No	N/A	Yes, but no recirculation/ preheat/ bypass mentioned
Wheatley Campus Retrofit (218)	41.5 (20.7)*	No	N/A	DHV	No	N/A	No

<u>Notes:</u>

PHV: Pre-heat ventilation, DHV: Direct-heat ventilation, PH: Pre-heat only, T: Temperature. The hyphen (-) is used to denote ranges.

* The air flow rate is mentioned to be 41.5 m^3/h per m^2 of TSC, but 5 years extrapolation use the value of 20.7 m^3/h per m^2.

** Auxiliary separate systems are implied, as recirculation and modelling are mentioned, hence the value in this cell is ‘possibly’.

*** This system is classified as DHV, but auxiliary heating system was placed just after TSC outlets.

3.5.3.1 Variants and functions

The TSC generic system was introduced in Figure 1-3 (section 1.3.5) and all the variants explored in the case studies are summarised in Figure 3-12 and Figure 3-13. Only four case studies integrate TSCs in an air heating system (PHV) and there are no studies on how a TSC would impact the effectiveness of such systems. For DHV systems, the building's heating demand is served by an auxiliary system that is not directly connected to the TSC or the building is not serviced at all which is only possible in some industrial buildings for the UK climate. Seven TSC systems include a summer bypass function and all of them but one were industrial, which raises concerns, as commercial and residential buildings would face significant overheating issues with the presence of air solar systems in the summer. Nine of the buildings have recirculation function which raises concerns if polluted air is recirculated. Thorough flow and damper adjustments are needed to keep the fresh air ventilation demand up to recommended levels while benefitting from heat recirculation and destratification. Recirculation is criticised after the Covid-19 era and even banned by HVAC organisations (221). An effective alternative is to exchange heat rather than recirculate air mass and there are no studies found on the integration of TSC to MVHR units. Further to the variants above, Hastings's (140) design guide mentions that the TSC system may be connected to a heat storage device if the delivery of the heat to the building needs to be delayed.

3.5.3.2 Air flow rate

The air flow rate for all applications ranged between 20.7 and 183 m^3/h per m^2 of TSC, which correspond to a residential (218) and an industrial (185) application respectively. The lowest air flow rate that was applied in the industrial context was 42 m^3/h per m^2 of TSC for the Broiler barns (144, 213, 214) where temperature rise seemed important. Early industrial applications (e.g. Ford Automotive Assembly Plant (185), GM Battery Plant (140), Bombardier Inc (140)) had a flow rate above 100m^3/h and utilised porosities of 1% or higher. In residential context where temperature rise was the dominant aim, lower flow rates were used from 20.7 to 79 m^3/h per m^2 of TSC, generally respecting NREL recommendation for maximum flow rate at 73.4m^3/h per m^2 (18). For commercial applications multiple flow rates were tested from 28 to 104 m^3/h per m^2 of TSC. Considering the recommendations provided in Hastings's (140) and Tata steel's (206) design guides (see section 4.1.3.2), the variety of flow rates can be explained based on the requirement of higher or lower temperature rise in each application. In most of the cases the flow rates were chosen based on the potential heat delivery in combination with the available solar facing area available rather than ventilation needs. This was pointed out in Maurer's (210) statement that choosing the optimum flow rate for the TSC system is dependent on required ventilation rates. Lowering flow rates and increasing TSC size to maximise temperature rise was not studied for DHV systems where drafts of cold air can decrease comfort.

3.5.3.3 Controls

There are two main categories of controls in TSC applications. The first one refers to the control of the flow and is associated with both DHV and PHV systems. The second one refers to the control of the heating system (extra power) that is associated with PHV systems or DHV systems working in conjunction with separate auxiliary heating systems.

The control of the flow is associated with the flow source and rate. Through the use of dampers the flow can be drawn via the TSC, the recirculation or the summer bypass, or in some cases can be mixed from the TSC and recirculation to ensure some fresh air income. Tata steel's design guide (206) provides four operation modes, through the use of two dampers (collector damper and summer by-pass damper). The rate can be regulated by the fan speed and this will have an impact on both the heat and ventilation delivery. In Table 3-8 it can be seen that some bypass dampers' activation is driven by ambient temperature at 18°C or 20°C which would imply a lack of heat demand. Recirculation is used when TSC cannot deliver air at desirable temperatures and is controlled by outside temperature air (Ford Automotive Pant (185)), TSC delivery temperature (CA Group Roll Mill (212)) or solar radiation (Utility Co-generation Plant (185)). In addition to the reservations on recirculating polluted air, the temperature used for control is not related to the room temperature and its stratification. In Wal-mart case study (216), a design problem was presented, when the monitoring results showed that although in January there was higher incident solar radiation on the TSC, there was 25% less delivered energy. This happened largely because the AHUs would be forced to reduce the air flow or even shut it off when the ambient air was below freezing due to the presence of internal water coils, which constituted a design problem. This would happen even though the air delivered by the TSC could be above 0°. As a result, the TSC system had been underperforming due to the non-effective utilisation of the solar resource and more specifically due to implementation and control strategy issues. For example, the air velocity through the TSC could be raised up to 0.03m/s if the preheated air flow was maximised when solar resource was favourable. Another recommendation was related to the effective distribution of ventilation air, which could enable the immediate zone temperatures to rise higher during the day and preheat the building during the night.

The control of the heating system needs information of the heat demand which can be given by the room temperature and a predetermined temperature set point and the output of the TSC to check if there is enough heat delivery to supply the space in order to reach the set point or if more power is needed. An example of this application can be found in the NREL West Handling Facility (185) and the CA Group Roll Mill (212); in the latter, no extra heat is required as long as the TSC delivers at a temperature that is higher than the room temperature plus 2°C. This extra boundary of 2°C is used presumably to ensure temperature rise in the space up to the set point despite any duct distribution and stratification losses. More specifically for the CA Group Roll Mill case study (212), in terms of the control system, three temperatures were considered: outside temperature (T_{out}), inside temperature (room temperature) (T_{room}) and temperature in the TSC duct (T_{TSC}). The following algorithm was continuously run:

If $T_{room} < 18$°C and $T_{amb} < 16$°C and $T_{TSC} > T_{room} + 2$°C from 07:00 to 19:00, then solar heated air is delivered through the TSC.

If $T_{room} < T_{TSC} < T_{room} + 2$°C, from 07:00 to 19:00, then solar heated air is delivered through the TSC and recirculated air.

If $T_{room} > 18$°C and $T_{amb} < T_{room} - 2$°C, then fresh air was delivered (using bypassing system).

If $T_{amb} \geq 16$°C, then fresh air or recirculated air was delivered (using bypassing system).

In addition, the room temperature set point between 19:00 and 07:00 is 14°C.

Specifically for the House in Judgeford (217), the TSC used a heating system control algorithm to deliver space heating energy (see red part in Figure 3-14), which was as follows:

If $T_{duct} > T_{in}$ and T_{duct} > set point, then activate fan;

If T_{in} > set point, then stop fan (set point was usually set at 20°C but could be adjusted by the user).

A few case studies used scheduling to ensure fresh air delivery during occupancy. In Bombardier Inc (140), fresh air would be provided only during occupancy hours. In CA Group Roll Mill (212), TSC would provide during the day assisted by the auxiliary system if needed; however, the set point was reduced at 14°C during the night. In the broiler barns (144, 213, 214) the flow rate and delivered temperature was adjusted due to seasonal breeding scheduling. In large modern buildings such as PIMSA (215), the TSC was connected to the holistic control strategy of a BMS.
Control systems that focus on the heat delivery rather than ventilation needs would stop if delivered temperature is low. Temperature sensors are the dominant control instrumentation; however, there is a lack of information on the positioning and integration to the controller – the only information provided on this is in Hasting's design guidance (140), where he also provides recommendations on operation and maintenance of the control system. Another challenge for the control mechanism is to quantify the potential TSC delivery temperature for zero flows. When the driver is TSC delivery temperature, the control mechanism needs a flow to sense, meaning that for zero flows but sunny days (for example in the morning) the TSC may have a potential that is not captured by the TSC delivery temperature sensor. This is something that is not investigated in the literature.

3.6 Discussion on case studies evaluation

This section discusses the performance evaluation of the building-integrated systems in the case studies literature. The summary Table 3-9 below (part of the table presented in Appendix II) gathers a collection of important evaluation elements for each building, including monitoring aspects, Key Performance Indicators (KPIs) and Supplementary Performance Indicators (SPIs) that are analysed in sections 3.6.1, 3.6.2 and 3.6.3 respectively. The discussion in section 3.7 focuses on outputs and optimisation, including lessons learnt from the existing case studies' exploration.

Table 3-9. Evaluation. Summary table from literature case studies; author (continued overleaf).

Building name	Monitoring period (months)	Data acquisition interval	Key Performance Indicators	Supplementary Performance indicators	Heat savings (kWh/m^{2}a)	2020 Cost (£/m^2 of TSC)	Cost includes
NREL Waste Handling Facility (185)	14.5 (2 periods)	N/A	Total heat savings % of heat supply TSC cost and payback	Efficiency vs incident solar Efficiency vs wind speed Back wall impact	513	230	Materials, installation, design and supervision labour
Ford Automotive Assembly Plant (185)	9	N/A	Total heat savings % of heat supply TSC cost	Meteorological data validation Efficiency vs incident solar Efficiency averages Fan energy consumption Active solar heat collected Night-time recaptured heat Destratification savings Radiant heat loss Passive solar heat and T gains	389.9	122	Panel supply, installation, labour
GM Battery Plant (185)	36	15 min	Heat delivered Total heat savings TSC cost and payback	Active solar heat collected Efficiency Efficiency vs air flow Fan energy consumption Weather data verification Back wall recaptured heat	656*	230	Panel supply, installation, ducts, fans, labour and upgrade
Utility Co-generation Plant (185)	7.5 (2 periods)	5 min	Heat delivered Total heat savings TSC cost	Efficiency vs suction velocity Variation of daily temperatures. Room recirculation heat Heat losses and gains of back wall Heat losses and gains of ducts TSC cost / kWh/m^{2}a	250	272	Investment costs, incl. additional cost of TSC over conventional façade, air duct, control system

Building name	Monitoring period (months)	Data acquisition interval	Key Performance Indicators	Supplementary Performance indicators	Heat savings (kWh/m^{2}a)	2020 Cost (£/m^2 of TSC)	Cost includes
Bombardier Inc (140)	12	N/A	Heat delivered Total heat savings	Destratification savings	705**	N/A	N/A
US Army Hangar (140)	N/A	N/A	Heat delivered Total heat savings TSC cost	Destratification savings	810***	185	Project costs (no further details provided)
Intek Fabrics Manufacturing (210)	0.8	15 min	Total heat savings % of heat supply TSC cost	Efficiency Air flow Pressure drop Efficiency and T_{rise} vs solar Stratification T variations Efficiency vs modelled efficiency Efficiency vs plate and ambient T	1 - 2.1 kWh/m^2/day	241 (collector was 141)	Panel supply, shipping and miscellaneous costs, equipment independent of the collector
BigHorn Home Improvement (211)	30	N/A	Whole building energy demand/consumption	N/A	N/A	N/A	N/A
CA Group Roll Mill (220)	12	5 min	Heat delivered % of heat supply	Stratification Destratification CO_2 savings T variations	193.1	N/A	N/A
Broiler barns (144, 213, 214)	24	5 min	Heat delivered Total heat savings TSC cost	Efficiency Efficiency vs wind speed	185	209	Investment cost (no further details provided)
PIMSA Automotive production plant (215)	6	N/A	Heat delivered Total heat savings Cost savings	N/A	N/A	N/A	N/A
Wal-mart (216)	2	15 min	Heat delivered	Efficiency Heat delivered vs incident solar Collected energy utilisation	15 kWh/m^2/month (avg)	136 (target)	Installation cost target

Building name	Monitoring period (months)	Data acquisition interval	Key Performance Indicators	Supplementary Performance indicators	Heat savings (kWh/m^2a)	2020 Cost (£/m^2 of TSC)	Cost includes
Windsor Housing Authority (140, 152)	N/A	N/A	Heat delivered Total heat savings (predict) TSC cost	N/A	584 (predicted)	92 more to conventional cladding	Cost of TSC over conventional cladding
House in Judgeford (217)	N/A	3 min	Heat delivered Power output	Temperature variations Efficiency Solar	N/A	N/A	N/A
Wheatley Campus Retrofit (218)	N/A	15 sec	Heat delivered % of heat supply	Air leakage and conduction losses of back wall Fan energy consumption Temperature variations vs solar	104 (predicted)	N/A	N/A

* The study reported a heat displacement breakdown of 473.1 kWh/m^2a from active solar heat and 182.9 kWh/m^2a from recaptured heat

** Additional destratification savings of 758 kWh/m^2a were reported

*** Additional destratification savings of 533 kWh/m^2a were reported

3.6.1 Monitoring and instrumentation

The performance of the TSC system was evaluated as a whole with the exception of the Ford Assembly Plant (185) where only 13% of the enormous collector were evaluated, the CA Group Roll Mill (212) where only about 18% of the total TSC area was monitored and the Judgeford house (217) where its collector was evaluated separately. Only the CA Group Roll Mill (212) presented and followed a relatively elaborate 3-stage monitoring process, which included (a) the production of a building energy performance report, (b) the development of a payback period model based on the effect of the TSC installation on energy costs and (c) the development of a monitoring standard procedure. As part of this process, gas and electricity consumption data from the last five years were analysed and the data for the last year (2005/2006) were normalised against weather changes based on historic degree days. This data served for comparison with monitored data in 2006/2007 which are presented in along with the energy savings and delivered energy in Table 3-10.

Table 3-10 Overall TSC contribution [203].

Month	2005/6 consumed (kWh)	2006/7 consumed (kWh)	2005/6 dd	2006/7 dd	2005/6 kWh/dd	2006/7 kWh/dd	Saving in kWh/dd compared to 2005/6	TSC Energy delivered (KWh)
Apr	64754	40000	223	221	290	181	38%	9396
May	41357	6709	152	147	272	46	83%	4776
Jun	6700	1023	66	58	102	18	83%	1626
Jul	0	62	38	26	0	2	0%	902
Aug	1729	85	45	37	38	2	94%	1438
Sep	9948	52	69	34	144	2	99%	2892
Oct	37541	13980	102	102	368	137	63%	7661
Nov	74563	45855	345	306	218	120	45%	25075
Dec	75316	36855	345	306	218	120	45%	25075
Jan	90721	56930	358	274	253	208	18%	4428
Feb	96076	44976	306	281	314	160	49%	2310
Mar	100751	49796	353	264	285	189	34%	9616

Total	**599456**	**295913**	**2345**	**1975**	**2545**	**1266**	**50%**	**79191**

The monitoring period for the building cases ranged from 24 days (for an industrial building) (210) through several months (2 months for a commercial (216) and 9-14.5 months for industrial buildings (140, 185, 212)) to several years (3 years for an industrial building (185)). Regarding the interval used for data acquisition, this ranged from as low as 15 seconds (218) to 15 minutes (210). The 15-sec interval was used for the Wheatley test residential building (218), while the 15-min one was used in industrial (185) and commercial buildings (216). In one residential building a 3-min interval was used (217), while for many industrial buildings an interval of 5 min (144, 185, 212) was used. Again, no justification was given for interval or duration choice but It can be argued that to assess a solar heating system a monitoring period of at least one heating season will give appropriate data if weather and occupancy is representative. In addition, it can be argued that monitoring transient phenomena may require shorter intervals whereas quantities that can be averaged or summed may allow for longer intervals.

In terms of temperature sensors, a variety of thermocouples and PT100s were used, with minimum information on the type, response time, accuracy and wiring. The flow was measured via fan speed or balometers, or, in some cases, more accurately via flow velocity or pressure difference meters.

In two case studies, i.e. Ford Assembly Plant (185) and GM Battery Plant (185), the monitored solar radiation and ambient temperature values were compared to the Typical Meteorological Year (TMY) historic values for Toronto, but no action was taken after deriving the results.

There is little information on energy meters for heating systems. Fan energy consumption was monitored or taken from the specifications; however, in some case studies such as Gottingen case study (185) it was argued that the fan’s energy should not be considered as for a low-pressure system the fan’s power with or without TSC would be similar. Local or in situ weather stations were used and in some cases a comparison/verification between these two was performed without further explanation. Such comparisons may assist in data extrapolation and replicability conclusions if they follow appropriate methodology such as Degree Days normalisation (as seen in Chapter 2.1.2.2 and further analysed in Chapter 8). It was argued that vertical placement of pyranometers would be a better fit for vertical TSCs to allow direct comparisons and easier application to efficiency equation (212).

Monitoring challenges were observed, including data loss, fault detection, importance of sensors location and occupancy disruption; however, they were not addressed or explained how they got addressed. In addition, a variety of other potential challenges such as accessibility limitations, cost, accuracy, data synchronisation, data manipulation, wired/wireless transmission and analysis were not discussed, and no guidance was presented. Information on the instrumentation, yet without sufficient reasoning is presented in Intek Fabrics Facility (210) and the CA Group Roll Mill (212), which will inform part of the monitoring approach of this work. For example, in Intek Fabrics Facility (210) the use of thermocouples for surface and plenum temperature measurements and thermistors for air temperature measurements at the fan inlet from the wall monitoring was suggested, as well as an anemometer for outdoor wind speed and a pyranometer to measure the horizontal solar radiation. A velometer was used for air velocity measurements in the distribution duct and two air flow measuring stations were installed downstream from the fan outlet and coupled with two differential pressure transmitters to determine outlet air flow. Despite the use of extensive monitoring equipment (see table in Appendix II), there is a generic monitoring comment in the source on low quality measurements because of instrumentation fault positioning, high uncertainties and TSC construction and controlling mismatches, so these are aspects that need to be considered in effective TSC design and evaluation. In CA Group Roll Mill (212) a calibrated pyranometer was placed on the vertical TSC plane to measure solar radiation and thermocouples were installed in the TSC plenum and the delivery duct for temperature measurements. Temperature sensors were used to study stratification. In both studies a logger was used to log data every 15 (210) and 5 minutes (212) respectively.

Further information is provided for the House in Judgeford (217), where wiring communication was used in the monitoring equipment and the data logger. It was shown that monitoring via wired communications is time-consuming and difficulties were encountered in fault detection. In addition, the data-logger was noisy because it was placed inside the house and was not capable of operating with backup batteries. Type-T thermocouples and an additional reference temperature sensor were used, which were connected to the logger, for temperature monitoring. The study concluded that careful consideration should be given regarding the optimal placement of the room temperature probes, so that they represent the average temperatures. Any proximity to electrical appliances that produce heat, windows, fan outlets and similar sources that could influence the measurements should be avoided. Fan speed was measured by using the 0-10V signal from the controller and was transformed into actual airflow through the use of mathematical equations. The solar radiation was monitored using a calibrated small solar cell at each TSC panel.

Lastly, in the Wheatley study (218) a weather station was placed on the roof. Data was captured every 15sec and were downloaded regularly. Thermocouples were installed to capture the temperature at specific points to investigate the impact of the materials and the air temperature change.

3.6.2 Key performance indicators

There are several evaluation metrics used in the investigated building cases with different naming, units, monitoring approach and different or lack of definition. This lack/variability of definitions was a major challenge in grouping and for inter-comparisons. A prime example of this is the term “TSC heat delivery” which has varying meanings as the delivered temperature was measured in different locations or without giving location information. Delivered temperature was measured in the cavity, duct or after the mixing box (adding recirculation); or simulated and referred as the panel’s “collected energy” with or without the recaptured heat from the back wall. This lack of consistency also applied to many more parameters and a lot of time, effort and inevitable assumptions were used from the author to gather comparable and consistent information (Table 3-9). Specifically for the CA Group Roll Mill case study (212), the delivered energy (Equation 4-1) by the TSC was calculated using the heat transfer equation analysed in section 2.1.2.4.

$$Q_{del} = \dot{m}_{tot} C_p (T_{duct} - T_{room}) \qquad \textit{Equation 4-1}$$

Where Q_{del} is the heat delivered through heat transfer

$\dot{m}$ is the mass flow rate of the medium

C_p is the specific heat capacity of the medium

T_{duct} is the duct temperature and

T_{room} is the room air temperature.

It is important to note that the temperature difference being considered is now the difference between the room temperature and the duct temperature, whereas previously it was the difference between the ambient outdoor temperature and the temperature of air leaving the fan and entering the space. This equation is used to calculate the actual heat delivery assuming that the TSC is replacing a system that recirculates air. If recirculation is not considered, then T_{amb} should be used because 100% of the air would be delivered from outside.

Moreover, In Kozubal et al.'s (216) (Wal-mart study) the collected energy was higher than the delivered energy, due to the fact that top-up energy was required to heat the incoming air to reach a temperature equal or higher than the current indoor one, which was not counted in as delivered energy. This is an important consideration, as, energy collected from the TSC when the air flow rate is higher than the ventilation rate, needed to be delivered above return air temperature in order to counterbalance gas use. So under the existing heat strategy, only about 60% of the collected energy was utilised during the two monitored months, which means that the system can be economically ineffective. This is demonstrated in Figure 3-14, which shows that when the TSC matches the ventilation demand, all the heat delivery is useful (blue part). For ventilation rates above ventilation demand, there are two cases: if the delivered temperature is higher than space temperature, then heat delivery is useful; otherwise, it is just collected energy that doesn't offset gas use (216) and creates cold drafts.

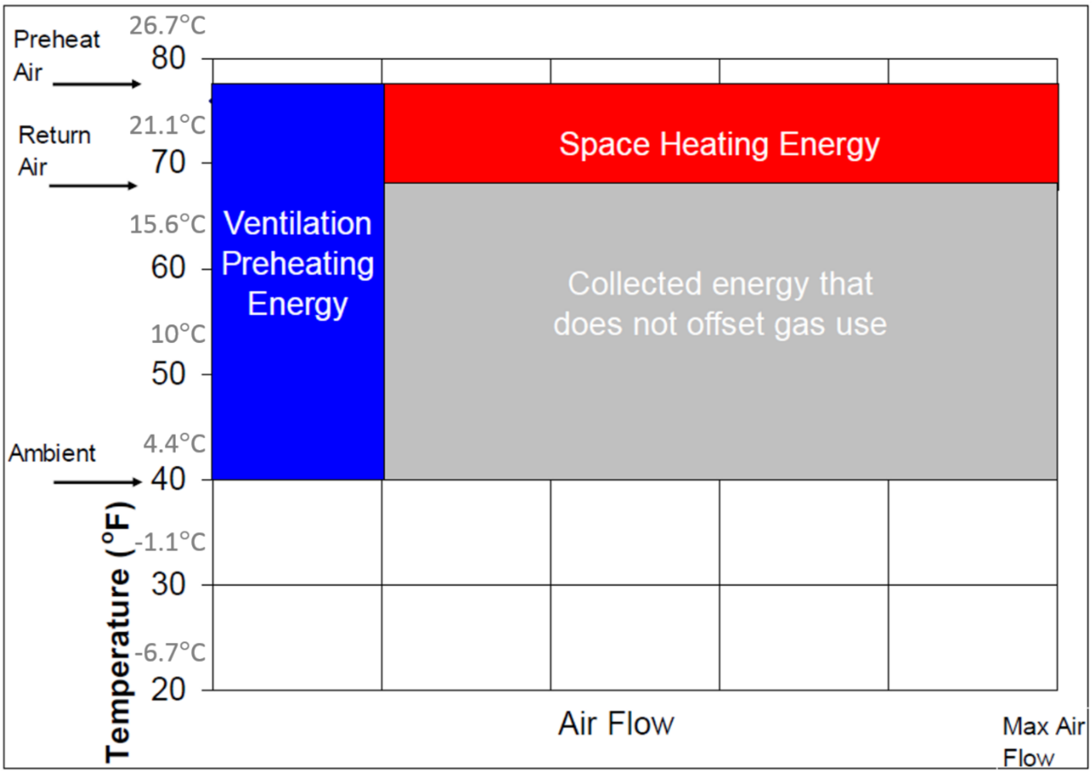


Figure 3-14. Example of delivered energy portion (red and blue) of total collected energy for a given preheat temperature. The rectangle areas are proportional to energy. Adapted from Kozubal et al. 2008 (216).

In the Wheatley building (167) the annual produced energy was estimated by multiplying the average daily heat production by an assumed period of 150 days for annual yield, which provided an energy yield of 104 kWh/m^{2}a. However, it was not clarified how many days were analysed to obtain the average the authors based the annual yield on.

Some of the researchers would evaluate the TSC as a system whereas others would break it down and monitor or simulate specific quantities and variables. Performance evaluation is correlated to the desirable output metrics and this varies for different audiences. As this work aims to primarily assist the installation and evaluation of TSC in buildings it is important to establish Key Performance Indicators (KPIs) to reflect TSC impact to the building. This approach perceives TSC as a holistic system with a specific cost and payback time resulting to heat savings and reduction of conventional heat supply. In addition, many interesting metrics are used to break down the technology, understand insights and explore optimisation possibilities; thus, supplementary Performance Indicators (SPIs) are also established and are discussed in the following sub-section.

The measured annual total heat savings is defined as the conventional heat displacement or the total useful heat delivery to the building based on Equation 3-4 in 3.1.2. However, very few researchers comment on what is useful and correlate usefulness to fresh air requirements or actual heat demand. Pearson (CA Group Roll Mill study (212)) alters the heat delivery equation replacing ambient temperature by room temperature when TSC is replacing a recirculation system. Kozubal et al. (216) (Wal-mart study) in a similar approach suggests that for flows above ventilation needs, the room temperature should be used for temperature rise calculations. This leads to the conclusion that without establishing ventilation needs, it is impossible to effectively design or evaluate TSCs. An interesting finding is mentioned in BigHorn Centre case study (211) were the author in a qualitative evaluation approach states that the TSC was not performing for a variety of reasons with the most crucial being the lack of airtightness as the warehouse had at least one large overhead door continuously open which could be the case in many industrial and commercial sites. Moreover, the low temperature and low velocity warm air that was delivered through the fans near the ceiling, would not affect the occupied part of the space, so it is believed that the thermostatically controlled ceiling fans were not effective either (211).

The total heat savings were normalised per square meter of TSC for one year; however, some of them include recirculation benefits and some do not. They ranged from 100 to 810 kWh/m^2 and by comparing this to flow rates from Table 3-8, a strong relationship is identified which is expected according to the analysis in 3.2.3. Also, as seen in Table 3-9, TSC applications in maritime climates seem to deliver less energy in comparison to colder and drier climates such as US and North America mainland. The proportion of savings of the total annual heating supply was discussed in few cases. It was about 21% and 26% for two industrial buildings, while for another one the authors claimed 34-62% per month. It was also predicted that the savings could be about 20% in the case of the Wheatley test building (218). In the case of Ford Automotive Assembly Plant (185) and Windsor Housing Authority (140, 152), the contribution of the TSC to the fresh air heating requirements for the monitored periods amounted to 5-20% and 28% respectively. It has to be noted that some of the authors use the term requirements and some the term supply without a clear definition. In this study the monitored heat is the heat supplied and the modelled one is the required one (or heat demand).

As far as **cost** is concerned, the information provided is not always consistent as to whether the given values address the TSC as a panel or as a system, including design, installation of panel and ventilation equipment, controls and commissioning. The average cost from all cases studies normalised for 2020 and for British currency[6] is approximately at £200/m^2 whereas operational and maintenance cost accounts for a small fraction of this (lower than 5% annually) and fan consumption can be neglected for low flow TSC systems that are add-ons to ventilation systems. The larger the installation the lower the investment per area with Ford Assembly Plant (185) TSC (1877m^2) cost being 40% cheaper at £122/m^2 of installed TSC. The cost values, especially for installations that were performed at the early technology stages, e.g. the one in the GM Battery Plant study (185) (which cost £230/m^2 of installed TSC), should be treated with care, as such values may be higher than typical installations as design and installation procedures had not been tested and well-documented (170) at that time. The latest studies (170, 222) on cost indicate that the absorbing plate accounts for approximately half of the cost whereas fixing and flashing accounts for another 25% and installation and other costs for another 25%.

Although in many cases the TSC could cover the maximum south-facing area available, oversizing may not be necessarily cost effective (210, 219). Kozubal et al. (216)recommends a TSC system size based on efficiency and ability to deliver a significant amount of thermal energy, which could lead to economic benefits claiming at least a 10% internal rate of return for central and north U.S. climates with a cost

[6] Note that costs related to USA or Canadian historic reference was converted to USD 2020 or CAN 2020 cost accounting for inflation using https://www.usinflationcalculator.com/ and https://www.bankofcanada.ca/rates/related/inflation-calculator/ and then converted to GBP using an exchange rate from https://www.xe.com/, accessed at 12/05/20.

target of £136/m^2 (216). However, no information on how to optimise and design such a system is given. The payback time varies significantly in the literature with the most optimistic figure being 1 year; however, payback estimations were based in historic energy and TSC costs and would depend on the conventional heating medium. For example, in the GM Battery Plant study (185), a payback time estimation was carried out based on a potential steam system that could replace the TSC system and produce the same amount of energy. It was found that the payback time for the TSC would be 1.3 years, which could be reduced to 1 if the exhaust fans were located at the ceiling (as occurs in most industrial buildings – in this particular case study the exhaust fans were located at head height). By using averages for cost and heat savings from Table 3-9 and for a current (2022) end user electricity price in UK (£0.32/kWh) it can be argued that for £200/m^2 installation and annual TSC savings at 200kWh/m^2, the payback would be approximately three years. This is a very broad estimation as potential savings such as destratification savings were not included, environmental conditions were not considered and an expensive heating medium (1:1 electricity to heat) was used.

3.6.3 Supplementary Performance indicators

There is a wide range of quantitative explorations in addition to the KPIs that are summarised in Table 3-9. Some of the evaluation indicators intend to break down the heating contribution of each part of the system including destratification benefits. Other indicators aim to correlate variables such as solar radiation, wind speed and temperatures with TSC performance indicators such as efficiency and effectiveness. Another group of supplementary indicators relate to different control settings.

TSC annual destratification savings were demonstrated separately in the two industrial buildings (Bombardier Inc (140) and US Army Hangar (140)) with the highest heat delivered values (705 and 810 kWh/m^2), amounting to an extra 758 and 533 kWh/m^2 respectively. For the GM Battery Plant (185), where an annual heat delivery of 656 kWh/m^2 was demonstrated, 473 kWh/m^2 came from the TSC collector and the rest were recaptured. It is unclear if destratification refers to recirculation through a damper or through forced circulation caused by the fan or for both. In any case, changes in stratification can be measured by vertical temperature mapping with the fan on and then off (185). In CA Group Roll Mill (212) the beneficial effect of TSC in destratification was also demonstrated by averaging temperatures from sensors in different heights.

It is essential to point out that there is little information regarding the fresh air delivery during recirculation mode. Some examples include “on-off damper” meaning that mechanical fresh air would stop when heat is recirculated. Whereas others include variable dampers meaning that the fresh air would be reduced. If fresh air was a design priority its mass flow rate should not be compromised by the presence of recirculation. This was identified as a challenge in some case studies (e.g., Intek Fabrics (210)) but it was not addressed. Redesigning, resizing or complex controls and distribution system would be needed to maintain desirable room temperature and keep fresh airflow rate when recirculation air is used.

Other supplementary benefits of TSC were quantified such as back wall heat recapture for day and night (through heat or/and air leakage), TSC surface heat gains, collector passive insulation heat savings, duct gain/losses and CO_2 savings (212). Some researchers visualised the break downs in weekly, monthly or annual heat balance bar graphs. However, a thorough analysis is needed to understand the physics of each component. For example, ducts are a constant heat recirculator if they are inside a serviced area whereas if they are outside both losses or gains should be considered constantly depending on ambient temperature around the duct. In Intek Fabrics (210) although there was no monitoring of the radiative and convective heat losses, these could be correlated with the heat effectiveness and collector’s design parameters through laboratory tests (as presented in Duffie and Beckman (223), Kutscher (153), Kutscher et al. (154), Kutscher (155), Cali et al. (185), Van Decker et al. (173)). Moreover in the same study, as there was no pressure drop data through the collector and the plenum, it was calculated by using previous studies (224).

Temperature variations were also used as an SPI for some case studies ((217, 218, 220)) and specifically in the CA Group Roll Mill (212) in order to present the TSC performance graphically, temperature variations and energy delivery were presented. Furthermore, the authors of the Wheatley study (167) calculated the potential saving in the conductive heat loss through the façade by using Equation 4-2:

$$Q_c = U_{ocf} \bullet A \bullet (T_d - T_{out}) \qquad \textbf{\textit{Equation 4-2}}$$

Where U_{ocf} is the U value of the over-clad façade (W/m^2 K) and

T_{out} is the outside or external temperature (°C).

Using Equation 4-2 the authors calculated the daily saving in conductive heat loss to represent about 2% of the heat delivered by the TSC and adding the savings by reducing air leakage to that, it was shown that the total reduction can amount to about 5% of the heating energy produced. Additionally, by using specific building dimensions, the savings in heating energy were estimated to be about 20% of the total heating demand of the building. Moreover, the fan energy consumption was calculated and was found to be about 7% of the TSC heat energy production. The assumptions for this estimation included five years of operation running at half the maximum flow rate.

As far as the evaluation of TSC efficiency is concerned, in the NREL case study (185) it was suggested that it is performed weekly or over longer periods of time. In addition, in this case study only the days with incident solar energy higher than 1500 Wh/m^2 were considered, as the uncertainty in data below this value was too large. Another interesting finding from the House in Judgeford (217) was that two adjacent and identical walls had a large difference in the evaluated efficiency (15% vs 54%). This might be seen as an odd finding; however, the ducting length and most importantly the flow rate they used differ, so ducting and specifically its length was found to be a key factor affecting the heat delivery. Shading effects were also a crucial factor decreasing efficiencies and should be studied extensively. Approaching case study efficiency as instantaneous / short term led to values over 100% due to the envelope and panel thermal storage phenomena. This is a limitation when a real building is measured and some of the case studies would average efficiency data and use solar radiation and wind speed acceptable ranges to eliminate external parameters and measure efficiency components more accurately. However, there was a lack of justification on selected ranges. Also, researchers did not discuss measuring approaches during transient phenomena (e.g. clouds) that demand extreme instrumentation synchronisation and thermal mass assumptions. Amongst others, problems in controls, reduced flow rates and shading effects would cause efficiency and heat delivery reduction; yet, in many studies, efficiency was comparable to lab case studies.

3.7 Discussion on case studies Outputs and Optimisation

In terms of whether **optimisation** of the system through simulation or in real life was undertaken to improve the TSC performance, there were a few cases for which this applies. This is shown in Table 3-11 accompanied by some lessons learnt from each site, which is also part of Appendix II.

Table 3-11. Optimisation. Summary table from literature case studies; author.

Building name	Optimisation through simulation	Optimisation in real life	Lessons learnt (related to the scope of this study)
NREL Waste Handling Facility (185)	No	Improvements to the data acquisition system	▪ Best sizing for ≤ 73.4m3/h per m^2 of TSC ▪ 9 years payback
Ford Automotive Assembly Plant (185)	No	Installed higher capacity fans	▪ Destratification and back wall recaptured have major impact
GM Battery Plant (185)	No	Replaced fans, motors and ducts to improve airflow	▪ Absorber cost is less than half of the total cost
Utility Co-generation Plant (185)	No	More sensors installed	▪ There are significant night time gains
Bombardier Inc (140)	No	No	▪ Recirculation assists T rise but compromise fresh air
US Army Hangar (140)	No	No	▪ Recirculation assists T rise but may compromise fresh air
Intek Fabrics Manufacturing (210)	No	No, but initial measurements were taken to optimise the flow monitoring equipment	▪ Activation T sensor should be placed in the plenum ▪ Much instrumentation info
BigHorn Home Improvement (211)	Yes (no specific info)	No	▪ High-ceiling low flow heat does not heat occupancy ▪ No shading and open doors
CA Group Roll Mill (220)	No	Proposed modifications	▪ T rise equation is dependent on ventilation demand ▪ Lots of instrumentation info ▪ Match TSC size fresh air demand
Broiler barns (144, 213, 214)	No	No	▪ Desirable room T drives flow rate settings and T rise
PIMSA Automotive production plant (215)	No	No	▪ Weather has a huge impact on TSC performance
Wal-mart (216)	Simulation of improvement estimated heat delivery increase from 15 to 74 kWh/m^2/month	Proposed modifications	▪ When air flow is higher to the ventilation needs, only delivery above room T is beneficial
Windsor Housing Authority (140, 152)	No	No	▪ Include TSC in initial design ▪ Potential roof implementation
House in Judgeford (217)	No	Proposed modifications	▪ Complex monitoring requires very detailed planning
Wheatley Campus Retrofit (218)	No	No	▪ Back wall can contribute a total of 5% to the total heat delivery

Four of the industrial applications performed real-life optimisations on the TSC system or monitoring. In the Ford Assembly Plant (185), a higher maximum airflow was achieved in the TSC by tightening the fan belts and installing higher capacity fans. In the GM Battery Plant (185), after two years the TSC system was modified slightly to improve airflow by replacing the fans, motors and ducts. In the NREL Waste Handling Facility (185) improvements to the data acquisition system were made. In the Göttingen Utility Co-generation Plant (185) more sensors were installed to investigate the heat transfer through the building in more detail and flow rates were reduced to enhance temperature rise. For the BigHorn Home Improvement Centre (211) many aspects were said to have been optimised in terms of the building's operation and control sequences, yet no specific information was provided. The low performance of the TSC as explained in 4.3.2 could lead to further optimisation actions.

In the Intek Fabrics Manufacturing Facility (210) initial measurements were taken to optimise the flow measuring equipment and control; the TSC activation temperature sensor was placed in the plenum to avoid cold air delivery. This led to the assumption that probably the sensor was in the delivery duct prior to the optimisation. For the commercial application (Wal-mart (216)) the authors proposed modifications in the control strategy and performed simulations to estimate the improvement on the TSC efficiency and the delivered energy. Amongst others, they suggested to improve zoning and increase of flow rate (surface velocity up to 0.03m/s) when solar availability is high. They predicted a rise from 15 to 73.4 kWh/m^2/month if the proposed changes were implemented. Another recommendation was related to the effective distribution of ventilation air, which could enable the immediate zone temperatures to rise higher during the day and preheat the building during the night. An estimation for payback improvement was also made in the GM Battery Plant case study (185), where the change of the exhaust fans' location from head height to ceiling was proposed. In addition, other proposed modifications included the optimisation of the orientation based on the building's heating requirements, the utilisation of the high temperature air produced in summer.

For the rest of the buildings no optimisation either through simulation or in real life was undertaken. Some authors (including where the case study had been previously optimised) provided recommendations on how the TSC system or the monitoring system could be improved as an outcome of their evaluation. The Judgeford house (217) monitoring system would work better if it was wireless or there was provision for wire integration, and if the logger was quieter, had a better capacity and power autonomy. A larger TSC in the Windsor building (140, 152) would perform better which could have been possible in the building design stage or if the roof was utilised (subject to snow restrictions). It was suggested that CA Group building would perform better if the TSC wall had a different orientation, summer TSC heat delivery was somehow utilised and last but not least, the TSC was sized according to fresh air and heating requirements of the building. As an outcome of the evaluation stage, further suggestions from the Wal-mart case study (216) point out that energy collected from the TSC when the air flow rate is higher than the ventilation rate, needed to be delivered above space air temperature in order to counterbalance gas use. This last one is a significant challenge that very few studies deal with and mostly as an afterthought despite that it significantly affects both the design and evaluation methods and results. In addition, there is a further gap on bypass controls installation and optimisations.

4 Literature conclusions and research gap

This section summarises the literature review findings (from Chapters 2, 3 and 4) and presents the research gap linked to the design and evaluation as a result of the literature analysis and case studies' in-depth investigation.

4.1 A summary of space heating and ventilation

Space heating accounts for the highest energy consumption in EU domestic buildings, holding a share of 70% of the total end-use energy (93) (95). Heating and ventilation requirements should be considered when a heating system that delivers air is to be integrated in a building.

Spatial, seasonal and socioeconomic deviations have been indicated to affect monitored real temperature (76-80). CIBSE guides are typically used in the UK to suggest comfortable temperature ranges and ventilation rates – which are also included in UK building Regulations for both domestic and non-domestic buildings (87, 136) - for different spaces and seasons based on the activity taking place in the space. Therefore, a range of 11 to 14ºC is recommended for industrial buildings, while a range of 21-23ºC is recommended for offices in winter and 22-25ºC in summer.

While space heating can be modelled by using historic weather data, it can also be modelled by using normalised monitoring data to enable comparability of case studies and monitored years. In the case these data are unavailable, benchmarks can be used to quantify space heating requirements. Moreover, standards such as the Passivhaus one are available to indicate best practice (114).

When a supplementary heating system such as a TSC is included in the design, the specification of design heating demand reduction the real heating delivery displacement are of utmost importance. Among the mechanical ventilation systems, which are increasingly used in domestic and non-domestic buildings, the MVHR is considered to be the most effective one with cost and system balancing to be challenging (118, 121).

4.2 A summary of the collector's parameters

Different parameters that affect the technology of the collector were explored. Most of the collectors' parameters are standardised (table 3-3) and will be used within the framework development (Chapter 6).

Regarding geometry, while shorter pitches and hole diameters mean higher efficiency and effectiveness, the suggested minimum pitch is 12mm and hole diameter at

0.8mm for a porosity of 0.4% due to manufacturing challenges and design parameters (150, 176). Circular holes are very common, and the triangular pitch arrangement is the most effective as this arrangement allows for a better heat transfer around the perforations. Complex hole geometries, such as “x” and “+” are found to be slightly more effective than the circular one, but manufacturing challenges may occur. In terms of the type of cladding, profiled metal sheeting is applied in the majority of large installations and the typical thickness ranges from 0.8 to 1.55mm. Corrugated panels are the least efficient. The plenum width, which is designed based on suction velocity and construction limitations, has minimal impact on effectiveness and efficiency. Regarding coating, materials and colours with high thermal conductivity and absorptivity should be used. Black colour is the most effective, but other dark colours may as well be considered. Moreover, the back wall’s thermal characteristics are more accurately evaluated in real life applications, instead of in laboratory test rigs.

Mass flow rate and temperature rise are the two main parameters of the heat transfer equation and are inversely related. The efficiency presents a sharp increase for flows up to $50m^3/h.m^2$, which then decelerates until reaching a plateau for flows over $100m^3/h.m^2$. This is a critical challenge when it comes to TSC sizing in real installations, as the mass flow rate should meet ventilation requirements and desirable temperature rise.

There is a linear relationship between the TSC output air temperature and solar irradiation and the impact is more noticeable for low flow rates. Despite the presence of convective and radiative heat losses, these are minor and make the TSC suitable in every climate with a heat demand enough to make the TSC cost effective. The presence of wind is not preferred, but if there is, it is best for it to be parallel to the collector.

While the collector’s geometry and coating characteristics have been optimised over the past 30 years, site constraints may have an impact on priorities and affect the collector’s performance. The above parameters are important to be considered before one focuses on the exploration of the TSC as a building-integrated system.

4.3 A summary of building integration aspects

The following table (Table 4-1) summarises the main gap identified in the literature in relation to the integration of a TSC system in response to the table where the main integration parameters are identified. Opposite to collector’s parameters (Table 3-2) most of the integration parameters has not been standardised.

Table 4-1. Building-integrated TSC system parameters accompanied by standardised values and gap.

Parameter category	Integrated system related parameters	Standardised Values / Gap
Design Drivers	Design intent Sizing driver (heating and/or ventilation) Simulation	Unclear in most of the cases Maximum available area / Ventilation requirements but not defined RETscreen, TRNSYS, minimum info
Envelope integration	Size Colour Shape Inclination Orientation Shading Hole Size Actual plenum width Back wall	Various and not well reasoned Dark colours Corrugated and flat, Rectangular only Vertical only Facing the sun No information 1.5mm minimum info 100-250mm with no further info No info
Services integration	Variants Functions Air flow rate Controls	Mostly DHV, no domestic Recirculation and bypass Various but optimised from 20.7 to 79 m^3/h per m^2 (18) Temperature sensors and dampers regulators, minimum info
Commissioning	Performance Gap Optimisation	No info Minimum info but measurements & monitoring informed optimisation decisions

The Table above (Table 4-1) indicates that a series of important information is missing when designing TSC systems. TSC performance is contingent on site and context which means a standardized feasibility study for each application is a prerequisite for an effective design.

4.3.1 Design driver

In most of the building cases ventilation demand seems to not have been considered at all, which contradicts the guidance found in the majority of the design guides (e.g.

Hastings's (140), Tata steel's (206) and US DoE's (18) guides). Other drivers for TSC installation were presented instead; i.e. repair of the walls, lower costs than conventional systems, aesthetics, and solar facing availability. However, as TSC systems' primary function is to provide ventilation air heating, the ventilation demand of a building is of utmost importance in order for the system to be appropriately sized. NREL recommends cost effective installation at maximum 0.014m^2 per m^3/h of ventilation air needed or 73.4m^3/h per m^2 as a rule of thumb (18). NREL's ventilation rule of thumb case could define the minimum area needed to cover ventilation needs; however, the collector's technical characteristics and heat demand also need to be considered including indoor and ambient temperature including future weather projections.

Simulation was used to predict energy savings or to analyse heat transfer in some case studies (e.g. Ford Automotive Assembly Plant (185), GM Battery Plant (185), PIMSA Automotive production plant (215), NREL Waste Handling Facility building (185), Windsor Housing Authority (140, 152)), but it was not used specifically for sizing of the TSC and none of the case studies provide any guidance for modelling in the design stage of the TSC. Some simulation tools are also recommended in the design guides, but no guidance on TSC system design modelling was found.

4.3.2 Envelope integration

Only vertical applications are investigated in the case studies and shading impact was highlighted as an issue, particularly in BigHorn (211). No inclined or horizontal TSCs were evaluated in the literature. Only rectangular panels (with the exception of BigHorn (211), which reached into an apex) were tested and there is a lack of performance or aesthetical reasoning behind the selection between corrugated and flat panels. Dark colour choice seems to follow absorptivity physics and recommendations in the design guides. However, choice of porosity is not explained in the case studies and no information about hole diameter or porosity is provided in the design guides, which is probably because in real-life applications porosity is a fixed characteristic of the panel available for purchase (which was also the case in Tata steel's (206) and Hastings's (140) design guides).

4.3.3 Systems integration

There is a lack of case studies for TSCs integrated to commercial, institutional and residential buildings as only one commercial was studied, two occupied residential and no institutional ones. Also very few studies refer to PHV TSCs that preheat the air for an air heating system. Recirculation is driven by the heat benefits without adjustments to match the fresh air needs. Also, recirculating polluted air is a high-risk method for a variety of buildings especially in the COVID-19 era. Alternatives such as the integration of TSC with heat recovery units and heat pumps have not been studied.

There is a lack of exploration regarding overall flow rates and flow rates per TSC area for TSC applications, although recommendations in ranges have been provided in Hastings's (140) and Tata steel's (206) design guides. For DHV systems, low flow rate would decrease efficiency but increase the temperature rise and comfort, as mentioned in Hastings's (140) and Tata steel's (206) design guides; however, cost impacts have not been explored.

The majority of the control systems focus on the heat delivery rather than ventilation needs using temperature sensors with no guidance on the location and control integration. There is a lack of reasoning and guidance on how to select both temperature input and set points. Another challenge for the control mechanism is to quantify the potential TSC delivery temperature for zero flows which is something that is not investigated.

4.3.4 Monitoring and instrumentation

A series of choices have to be made in order to monitor a variable quantity and TSC performance depends on many intermittent and frequently changing factors. Literature (e.g. (185)) indicates appropriate instrumentation, data logging, data transmission, sampling intervals and monitoring duration (among others); however, there is a lack of evidence to support the choices. TSC systems require a bespoke approach to deal with challenges and limitations in order to facilitate replicability and enhance decision making. Researchers (210) mentioned the importance of correct positioning of sensors; however, very few provide the relevant information. In the literature, e.g. in the case studies presented in (185) and (140), monitoring was only used for evaluation; however, author's studies (51, 225, 226) have provided evidence that monitoring can be useful in the design, control and commissioning process. There is a significant gap here as more detailed monitoring guidance would help to address a variety of technical details and assist evaluation as well as design.

4.3.5 KPIs and cost

Researchers set a series of performance indicators depending on their priorities; but from the TSC building integration perspective, heat delivery and payback are key indicators for evaluating the effectiveness of building energy technologies. TSC heat delivery has not been clearly defined in the literature; some studies correlate TSC delivery to heat demand but not to ventilation needs. This is the essential criterion to define as ventilation needs would define if heated fresh air is useful below or above room temperature. Two studies (212, 216) have both used room temperature as an indication of control but ventilation needs are not defined. Cost analysis also lacks consistency with limited information on what is included in the TSC cost. Cost is a dominant factor that should play a key role in the design stage and sizing; however, none of the studies included cost-based design guidance. In addition, cost or payback intercomparisons are challenging due to variability of parameters. Heat savings (kWh/m^2a) are related to heat demand, mass flow rate, controls, orientation inclination etc. on the top of geography. A normalisation method should be applied to allow comparison of different TSC systems.

Supplementary performance indicators refer to the breakdown of TSC heating contribution such as back wall recapturing and destratification. There is a definition issue with supplementary benefits such as destratification as a simple fan would in any case de-stratify with or without TSC presence. Also, recirculation algorithms seem to impact fresh air flows which is something that is identified but not tackled in the literature. Another challenge identified related to efficiency calculations; in an uncontrolled environment, intermittent phenomena and heat transfer inertia affects instantaneous measurements that input to the efficiency equation.

4.3.6 Optimisation

Very few cases addressed optimisation iterations on the design of the system, and even fewer were monitored after optimisation was performed to verify improvements. Across the board, control is optimised for maximum heat delivery rather than temperature rise or ventilation needs. It is, therefore, believed that this area and especially optimisation on the system controls needs further investigation, as this will allow for improved performance of these systems in real life applications. Also, commissioning was not discussed as an opportunity to adjust the system and ensure design targets.

4.4 Research gap summary

Efforts have been made to document current practices and provide guidance with regard to the integration of TSC systems in buildings from the literature, including case studies (140, 144, 152, 167, 185, 210, 211, 213-216, 218, 220, 227) and current design guides (140, 167, 185, 204, 206). Very little information was found regarding a clear justified strategy on design and TSC sizing. While some high-level information including design considerations is provided in two of the five design guides (Hastings's (140) and Tata steel's (206) guides), these address a specific product in each case, i.e. SOLARWALL in Hastings's (140) and Colorcoat Renew SC in Tata steel's (206)), so cannot be applied generally for TSC. There is also a lack of detailed published guidance and parameters such as the effect of dampers and ducting, TSC variants, TSC add-ons and collaborative systems have not been adequately explored or reported by researchers. Consideration should be given to the systematic design and sizing of the TSC system, so that ventilation requirements are met, while useful heat is delivered. A clear correlation to the heat and ventilation demand of specific building types and co-existing systems to TSC sizing and flow rate is missing. Collaboration between TSC and innovative systems such as MVHRs and exhaust heat pumps has not been considered. Occupied residential and commercial buildings and their needs are barely discussed and institutional buildings are not discussed at all. The lack of diversity in the building types addressed was also evident in all design guides, which seemed to focus on industrial applications. Moreover, there is a lack of a systematic review on building integrated TSC case studies especially in the UK. Although TSC collectors' characteristics are compared in the literature, TSC systems are not.

In addition, researchers used a variety of methods and instrumentation to monitor and evaluate the performance of TSC. Information is fragmented and limited evidence supports the selection of equipment and techniques. Key performance indicators differ throughout all case studies, making inter-comparisons extremely difficult. Performance evaluation data are limited and sporadic, whereas some analysis comes from commercial sources which introduces an uncertainty to the clarity and traceability of the results. It should also be noted that no information on monitoring and evaluation is provided in the design guides.

Therefore, this thesis aims to provide a systematic methodology regarding the design and commissioning of building integrated TSC, which will culminate into a framework. Taking on board all the literature findings, recommendations, lessons learnt and gaps, the framework will be enhanced by research on ten new experimental case study buildings in the UK introduced in Chapter 5. Moreover, based on the literature findings and the research on the ten new experimental case studies, the thesis suggests a framework to monitor and evaluate a building integrated TSC for new build and retrofit projects.

5 Methods and experimental case studies

This Chapter describes how this study was designed and carried out. It includes the methodology followed to develop the TSC design and evaluation framework that was applied to new experimental case studies. Ten new experimental case studies and an experimental roof TSC kit are introduced. The author was involved in all the cases studies enabling the construction of the framework. The Chapter summaries the case studies parameters and the author's contribution. It also describes the tools that contributed to completion of the objectives set in the introduction of this study (section 1.1).

5.1 Methodology

This section demonstrates the design process for this research work. Starting from the main question "how to design and evaluate TSCs", the author defines the system as a heating and ventilation system and initiates an investigation and quantification on heating and ventilation building demand. This is followed by a review of the existing technology and building implementation to identify the performance gap in response to those heating and ventilation priorities. Table 3-3 and Table 4-1 identify what is done so far and what is missing which leads to the need for further standardisation on the integration of the technology. A need for a framework that would prioritise integration parameters and will also introduce an evaluation method is established through the literature critique. New experimental case studies are then introduced to allow the author to develop and apply the proposed framework (see Figure 5-1 below). Framework and case studies are linked as a narrative but not chronologically allowing for the framework to evolve through different case studies and vice versa. This non sequential order allows interactions between pre-design, design and a post-design phase which is a fundamental proposition for the "research by design" methodological approach (228).

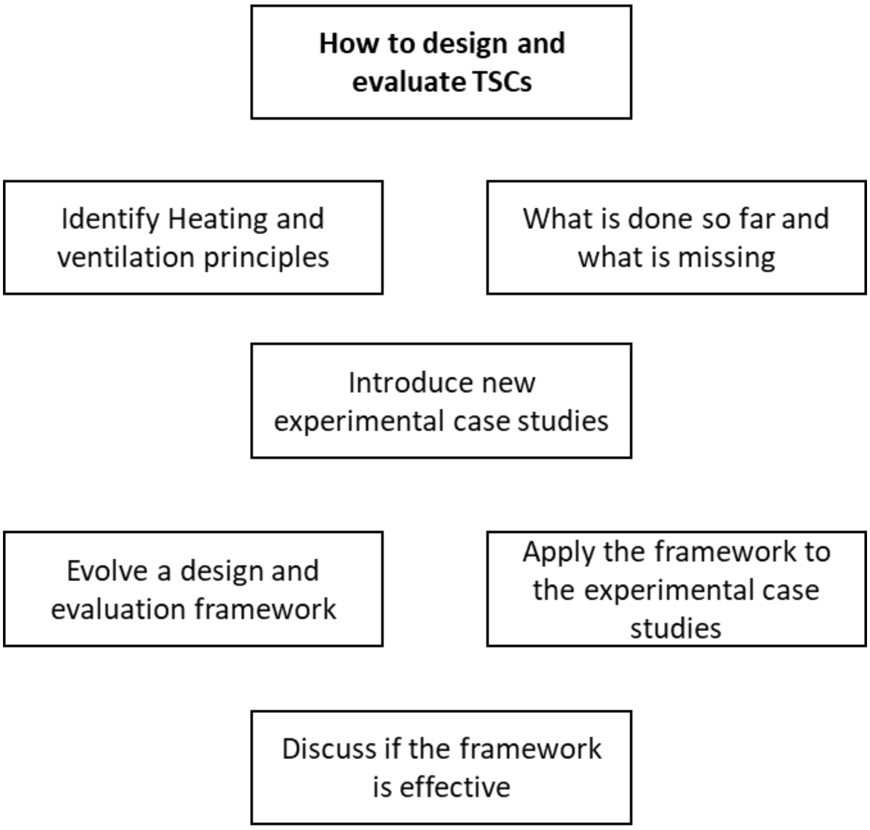


Figure 5-1. Basic study flow, author.

In more detail, after the critical analysis of the existing literature case studies, new unpublished experimental case studies are introduced to facilitate the development of a framework - a process to effectively design and evaluate building integrated TSCs. The framework is initiated by the existing literature and enhanced by the experimental case studies.

The structure of the thesis is introduced in Figure 1-5. In Figure 5-2 and Figure 5-3 a more detailed flow diagram of the study is visualized. It indicates the steps taken (vertically) and the development of the context (horizontally). Colours are used in these figures to indicate parts of the study.

In the Introduction, the aim, questions and context of the research are presented. The context addresses background information on the UK building stock, low carbon buildings and building integrated renewable energy technologies, as well as aspects associated with the TSC design, such as heating and thermal comfort and ventilation. The thesis overview is also included.

The literature review section includes a review of the building heating and ventilation demand, a review on the TSC technology and of building integration case studies. It aims to identify the research gap through the assessment of evidence about TSC design and evaluation in response to the heating and ventilation demand. It is split into three parts (Figure 5-2); the first one addresses heat and ventilation demand for different types of buildings (shown in yellow), the second one addresses the characteristics affecting the performance of the TSC collector, e.g. geometry, coating, heat transfer, environmental (shown in grey) and the third one presents the analysis of the existing design guides and assesses the design, evaluation and optimisation of integrated TSC systems in 15 case study buildings (shown in orange).

The methods used in this study include literature review (A), interactions with stakeholders (B), mathematical analysis (C), case study modelling (D) and case studies monitoring (E) (the two latter through the introduction of 10 new experimental case studies). The methods will be presented in section 5.2. and will be further developed through the framework.

The objectives shown in three different shades of green (Figure 5-2) are addressed by using the methods (letters A to E). The first objective is addressed by assessing the literature review (Chapters 2 to 4) and identifying the well established processing and the missing processes towards composing the framework.

New experimental case studies (Figure 5-3) are introduced (Chapter 7) to respond to the other two objectives, the development of the framework.

The second objective is addressed in Chapter 6, which deals with the framework development. The design part of the framework begins with a feasibility study and then evolves design and building integration process to conclude with a commissioning and optimisation procedure; stages that were identified within the literature and corresponding gaps. The evaluation part sets the performance indicators and then develops an instrumentation, data processing and analysis study to respond to the indicators. The framework development stage is further explained in Chapter 6.

The third objective, in which the design and evaluation framework is applied in buildings with varying demand, envelopes and systems, was dealt with in Chapter 7. The 10 new experimental case studies (blue Figure 5-3) were used for this purpose however one of them, the residential IV, was used as the main narrative in applying the framework.

The discussion (Chapter 8) examines the framework and its application in response to the literature. The methodology here is to discuss the challenges in developing and applying the framework and compare the process with the literature and the gaps identified in Chapter 5. It the end of the discussion, a detailed flow chart of the framework and a concise design framework is presented as an output of this discussion.

The conclusions (Chapter 9) review how the objectives have been met through this work. In addition, an overview of the outputs and achievements, challenges and lessons learnt as well as future work are presented.

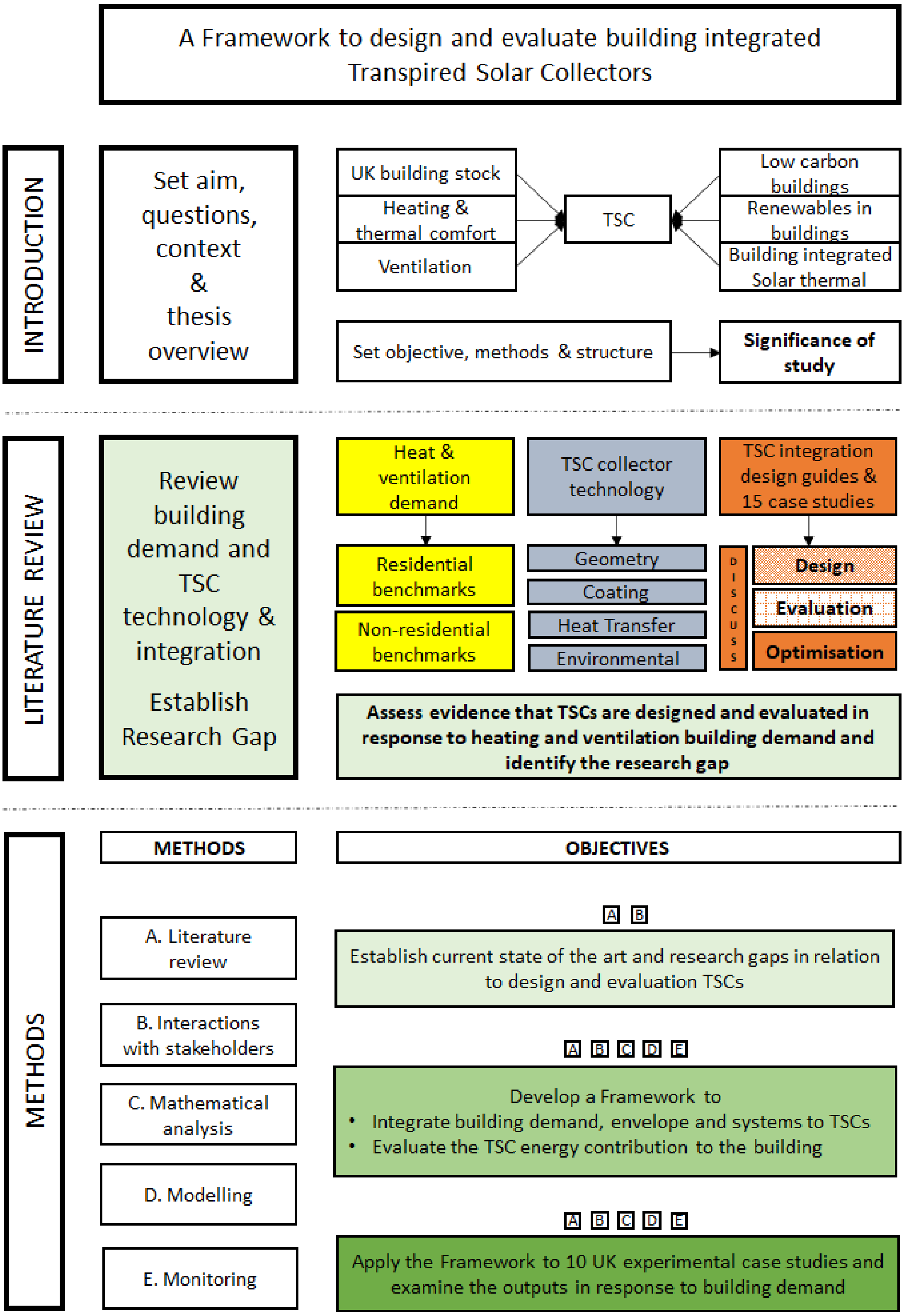


Figure 5-2. Thesis structure - flow diagram of the study, author (continued overleaf)

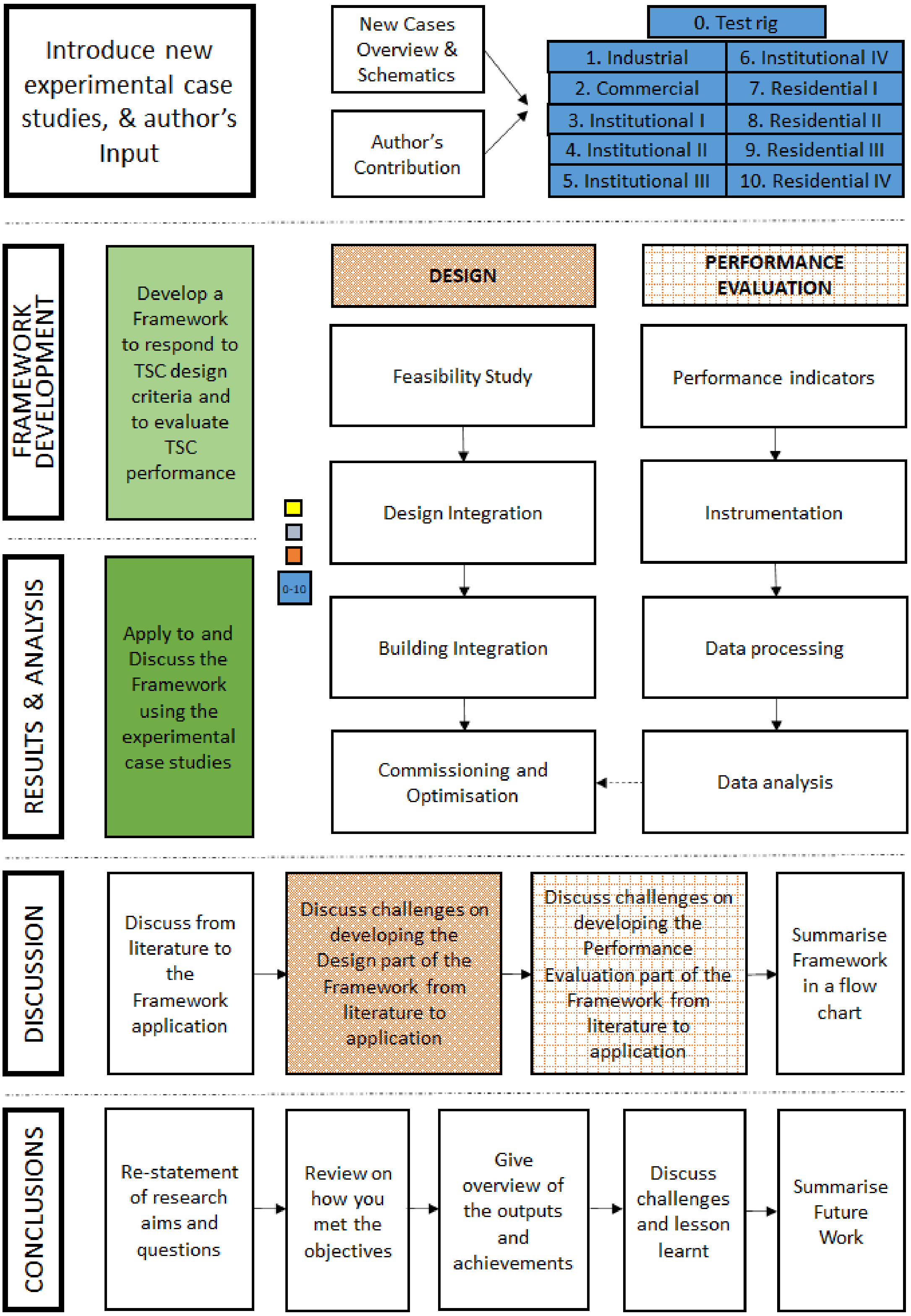


Figure 5-3. Thesis structure - flow diagram of the study, author

5.2 Methods and tools

Focussing on the methods and experiment presented in Figure 5-3, Figure 5-4 shows the five methodological approaches used in this work and their relationship with the objectives. Each objective (green boxes in the figure) relates to one or more methods used. The methods and tools used will be explained in this section.

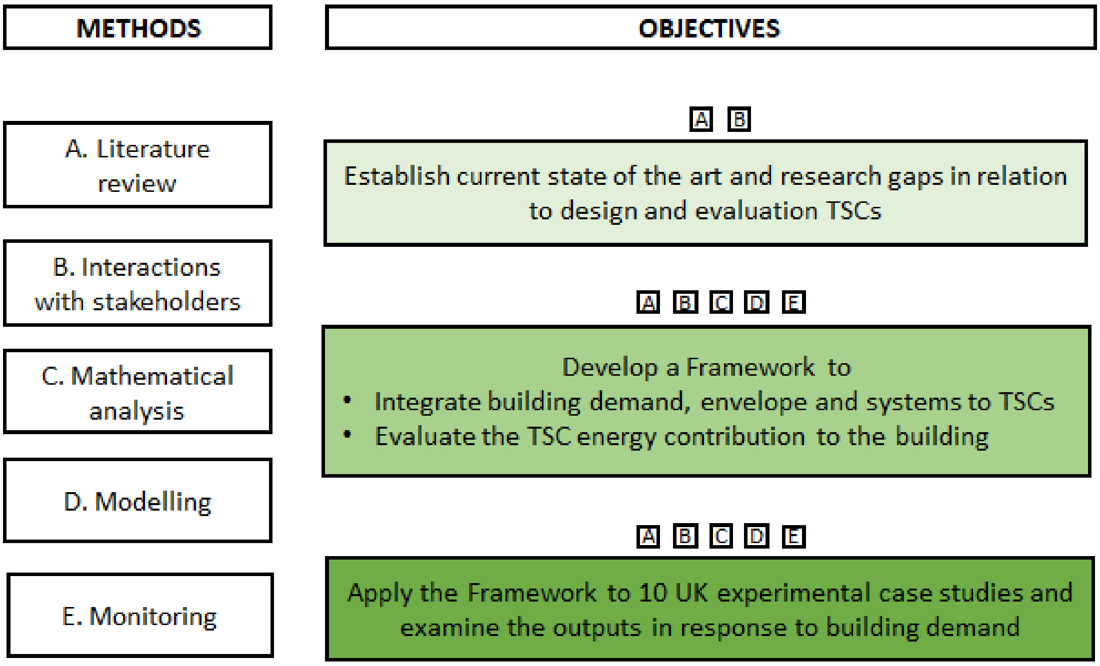


Figure 5-4. Excerpt from the study's flow diagram (Figure 5-3); relationship between methods and objectives, author.

5.2.1 Literature review

A literature review can be described as a systematic way of collecting and synthesizing previous research and information. An effective and well-conducted review as a research method creates a firm foundation for advancing knowledge and facilitating theory development (229). By integrating findings and perspectives from many empirical findings, a literature review can address research questions (230). The outcomes of the literature review are related to this research work as they facilitated:

- The establishment of the current state-of-the-art and research gaps in relation to design, evaluation and optimisation of TSCs
- The development and application of the framework.

Literature was used to set the context of the study and to narrow down the focus in the introduction. From UK building stock, heating and ventilation and need for low carbon buildings (demand side) to low carbon technologies, policies and solar thermal envelop applications and finally TSCs (supply). Then objective 1 was addressed in Chapters 2&3. This included gathering benchmarking information for a variety of buildings regarding heat and ventilation demand and comfort (Chapter 2), exploring the principles of the TSC technology and the development of the panel was also assisted by literature sources and finally exploring existing TSC guidance and literature case studies (Chapter 3) to include robust scientific evidence and filter non peer-reviewed marketing resources.

Literature fed into the second objective (framework development) both indirectly and directly. The literature case studies set the starting point of the framework and the initiation of the experimental case studies. Also, the framework includes a variety of supplementary literature resources to strengthen the development of the design and evaluation processes. Literature also contributes to further Chapters as a natural continuation of the knowledge sequence. Table 3-3 and Table 4-1 summarise the literature findings and gaps in terms of parameters of the TSC technology and integration.

The main search tools used were Google scholar and Cardiff University library. Google search was also used for commercial products, definitions, conversions and supplementary work. Some specific scientific libraries were also used, i.e. Science Direct, Elsevier, Scopus, Web of Knowledge and ORCA (Online Research Cardiff) which is the digital repository of Cardiff University’s research outputs. The published material came from international sources (English language used) such as books, reports, governmental standards, guides and resources, journal papers, workshop and conference proceedings, doctoral theses, scientific magazines and newspapers articles, specification manuals and brochures, audio-visual material as well as company and institutional websites. The acquired material followed a confidence hierarchy starting from highly ranked peer-reviewed journal articles. Sources from well-established laboratories (e.g. NREL) were prioritised and recognised authors in the field were ranked first. British standards and CIBSE guides were used for two reasons; the first one that they are globally known sources with significant international applicability; the second reason is that the experimental studies introduced are all in the UK. However, the aim of the framework is to be applicable globally, thus specific benchmarks were used as indicative and exemplary.

5.2.2 Communications and interactions with stakeholders

Research by design should allow for unexpected explorations in order to identify best fitting solutions for a design problem (228). A vital tool in such exploration is the stakeholders engagement (231) in order to extract information in the beginning and apply resolutions later on. The author had the opportunity during the initial stages of this work to visit some literature case studies or/and communicate with the authors and get insights to the research methods, challenges for both the design and evaluation stages (CA Group Mill (212) and Wheatley campus (218)). Most importantly the author was part of all the research teams designing, installing, and evaluating the experimental case studies introduced in Chapter 5. The involvement is stated in the "author's contribution section" (section 5.6). The author had the opportunity to interact with the design stakeholders, the panel's manufacturers, TSC modelling programmers, TSC designers and architects, installation managers and installers, service and control engineers, monitoring and instrumentation consultants, sellers and manufacturers and commissioning and handover team. The author was part of regular meetings relating to site selection, design, installation and research. Also, the author had communications with policy makers (RHI), IEA annex teams and IEA SHC Task teams.

In addition, the author had multiple communications with the building owners, managers and selection[7] of occupants in all the experimental case studies. Semi-structured interviews were performed with the focus on occupant comfort. In addition, data such as bills, EPCs and systems specifications were shared following GDPR protocols. Thus, no occupants' names, addresses or other traceable information is communicated in this work.

5.2.3 Mathematical analysis

The focus on TSC systems requires investigation of the relationship between variables and outputs which had not previously been explored. As an example, the correlation between demand and TSC supply or the effect of heat transfer when combining a TSC with an MVHR. This requires the identification of important variables and the development of the mathematical description through defining appropriate algebraic formulas. This is a mixture of physics and mathematics that is included in parts of the process development and is also considered in the results section (Chapter 7). This method includes modification of existing known equations analysed in Chapter 3 to represent a variety of systems and case studies by introducing alterations or limitations to these mathematical expressions. For example, heat transfer equation includes temperature rise; however, this variable is differently defined in different contexts. Defining application limits to equations is a tool used to

[7] Selection referred to commercial, industrial, commercial and multi-residential case studies where occupants vary. Regarding the houses, the author has interacted with all the occupants.

facilitate design parameters such as thermostats and set appropriate performance indicators to enable comparable outputs.

Data transformation is another mathematical analysis approach which is widely used in the literature, framework and result sections. This includes offset correction, extrapolation and interpolation, unit conversion, normalisation, averaging, annualising, or daily, monthly or seasonal data association, use of standard deviation, regression, uncertainty estimation etc. (232). Heating degree days normalisation techniques is used to normalise weather dependent data sets. The method will be further explained in Chapter 6. Data series transformation is used when large quantities of raw data are used. This include techniques such as data grouping, data cleaning, gap treatment and data synchronisation (233). More information for specific data processing is included in the framework development in Chapter 6.

5.2.4 Modelling

The modelling tools widely used to simulate TSC performance are RETScreen and Swift; other tools such as SBET and HTB2 can also be used but are not widely known or commercial.This study suggests the modelling tool Swift for simulating the performance of building integrated TSC. The tool has been introduced in section 3.1.3, accompanied by evidence of its advantages (171, 172). Swift is a freeware, allows for manual weather data set input, and is highly configurable as explained in section 3.1.3. It can also be noted here that an additional technical benefit of Swift over RETScreen is that it includes summer bypass simulation with desired temperature control (234) which is important for climates in which overheating is possible. The tool is used to calculate TSC heat delivery on a monthly basis using a variety of parameters, weather data and variables such as total TSC area.

The tool has been recently improved after suggestions from researchers (67, 141, 172). In earlier versions, the weather data set available included only USA and Canada weather files; however, current version allows for manual input of weather data sets. Latest versions also include a better response of the delivered heat to the ambient temperature changes. Swift has the capacity to automatically distinguish the heating period based on HDD, according to which the bypass dampers can be modulated to achieve an optimum TSC system efficiency. It also allows the user to change the TSC geometry and outputs, duct length, fan type flow, set point temperatures, etc. It also includes some TSC variants and control scheduling. Another advantage of Swift is that it is an open source and free software.

Swift has some limitations including that the default TSC products are the Solarwall products; however, the TSC products used in the experimental case studies have very similar thermal characteristics and geometry; in any case, the tool allows alteration of some thermal properties if known. Another limitation is that the software is designed for simple heating/ventilation systems designed for industrial use. There are ways to imitate domestic use; however, the software does not include MVHR's and HPs. Also, TSC orientation can be only set at a 45^o step: North, North-East, East, South-East, South, West-East, West and North-West which would have a slight impact if real orientation different. Although Swift allows dynamic (hour-to-hour) modelling for Canadian sites, it only simulates monthly averaged weather data for anywhere else. A step-by-step guidance on the tool use and parametrisation is included in the framework Chapter 6. Design Builder[8] and Energy Plus[9] are introduced in Chapter2 and will be suggested in the framework. Simulation results from HTB2[10] (Simulation software developed in WSA, Cardiff University) are also shown in the result Chapter in comparison to Design Builder outputs.

5.2.5 Monitoring

A key method to evaluate a system is to identify appropriate quantification and measuring techniques and create an experimental process to get reliable outputs. Monitoring was used to assess the actual performance. The "why, what and how to monitor" process is visualised in Figure ***5***-***5***. This approach is based on author's work on buildings' and systems' monitoring (225, 226). The diagram applies to a variety of building monitoring exercises and was used as a monitoring flowchart for this work. This process will be used in the TSC design, for information gathering, and evaluation framework accompanied by technical information and the application of this will be seen in the results section.

Referring to Figure ***5***-***5***, the initial stage considers "why" a quantity should be monitored, as all the monitoring parameters are determined by the cause. The next

[8] Design Builder by DesignBuilder Software Ltd is a simulation software to assess environmental performance of new and existing buildings.

[9] EnergyPlus™ by U.S. Department of Energy and other organisations, is an open-source whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings.

[10] HTB2 by WSA Cardiff University, is a software suite intended for the general purpose simulation of the energy and environmental performance of buildings.

step deals with “what” to monitor and refers to the KPIs and SPIs already grouped and discussed in Section 3.6 and Table 3-9. The third stage refers to “how” to monitor; it starts from breaking down appropriate equations into variables that can be measured.

The next “how” step is to choose appropriate instrumentation including sensors, loggers and a system to collect data. An analysis of the instrumentation parameters is included in the framework section. Extensive programming was used by the author in this stage for data logging and transmission to enable an automatic and reliable data capturing and collection. Campbell Scientific was the main logging platform used in all the experimental cases studies and Loggernet CRBasic was the programming platform used to control signals and sensors and manipulate data logging, grouping and transmission. A combination of SQL and PHP programming was used in the server side, however the author had minimum involvement as there was an existing server set up in WSA.

The installation of the equipment is the next monitoring step, and a monitoring plan facilitates this process indicating instruments and position. The use of existing data regarding the site, building, occupants and services is another step needed to give monitoring data some context. The analysis involves several mathematical techniques in order to create and visualise outputs which is the last part of the “how” process and is directly related to “why” and “what” as it aims to respond to the preselected indicators.

To develop suitable instrumentation that will measure TSC performance, the author used an experimental testing rig. Techniques were tested and optimised; for example, the position of the velocity meter within the ducting was tested in response to the turbulence flow within the ducts. Also the distribution of the temperature within the cavity was assessed and corelated to the external wind (202).

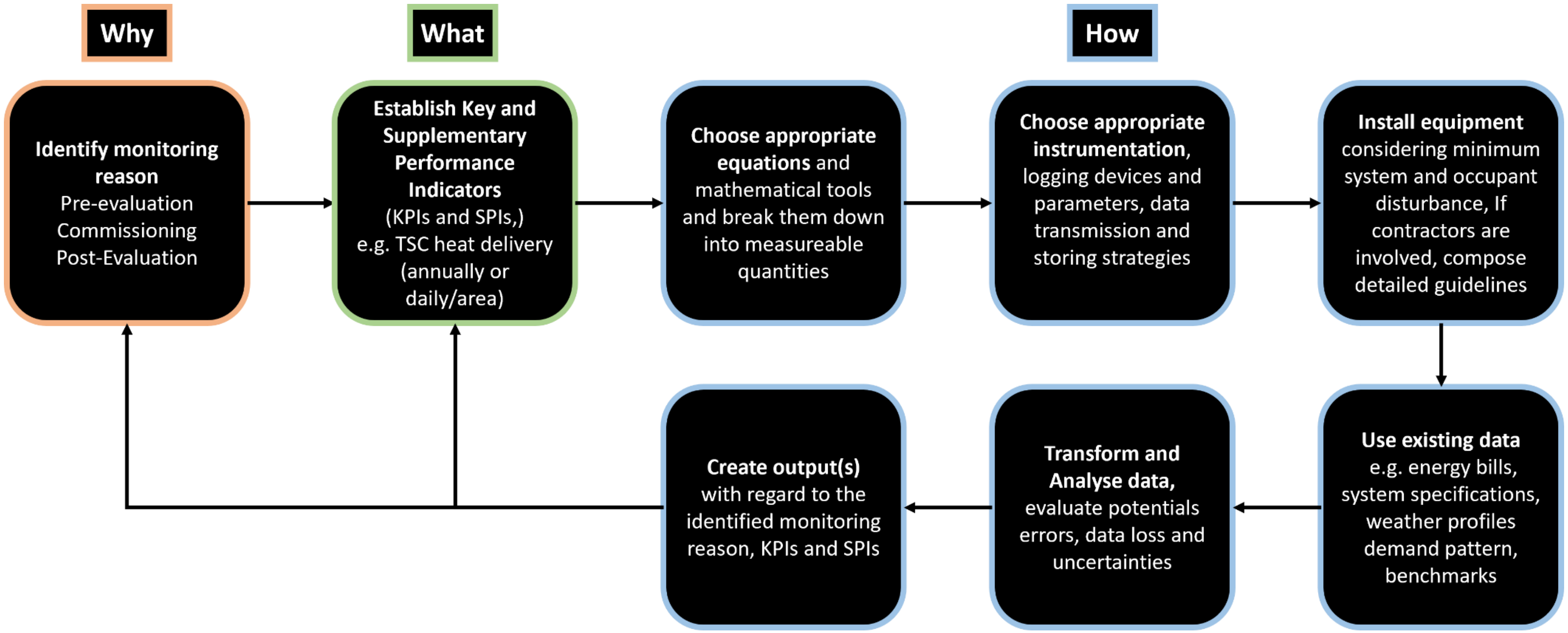


Figure 5-5. ***Monitoring process followed in this work responding to why, what and how to measure, author.***

5.3 Cardiff University Bute roof rig

Initially, an experimental testing rig was installed on the flat roof of Bute Building, Welsh School of Architecture, Cardiff, to understand the heat transfer principles in practice and evolve the monitoring strategies and instrumentation, which would then be developed for the experimental case studies. A portrait, a square, a landscape and an inclined experimental module were placed vertically, facing south. All four collectors (Figure 5-6) have the same absorbing area (1m^2); which is similar to other prototype studies in literature (196, 235-237). Three variable speed fans were placed behind the TSCs in order to draw air through a ducting system, while all the collector's parameters were kept exactly the same in order to facilitate comparisons.

Figure 5-6. TSC test rig, Bute building roof at Cardiff, Wales; author

Data were collected for all the TSCs together using synchronized data loggers. Amongst other, a variety of air velocity and temperature sensors where tested. A meteorological station was also placed to capture wind speed, wind direction, solar radiation (vertical and horizontal) and rain. Measurements were collected for different flow rates under stable solar radiation conditions (clear sky) and during windy and non-windy days. Furthermore, the mass flow rate and the pressure inside the cavity was kept similar for all the collectors for each set of measurements. Traceable techniques and high-quality instruments were used to minimise data errors and uncertainties. The aim was to test a variety of monitoring techniques, sensors, logging devices and strategies, control mechanisms and other design and evaluation parameters in order to be able to apply effective processes to the ten experimental case studies and facilitate the framework formation (Chapter 6) and application (Chapter 7).

5.4 Experimental case studies

The collector's parameters have been standardised and will be used in the Framework. Opposite to collector's parameters, most of the integration parameters has not been standardised and the new experimental case studies introduced in the section were used to develop and test the framework. These studies are summarised in Table 5-1 were building type, installation position and construction year are mentioned. They were all building integrated TSCs with real occupancy and demand; one of them is industrial, one is commercial, three are institutional and four are residential.

Table 5-1. Summary of experimental case studies, author

No.	Experimental case study name	Short name	Building use	Roof/Wall installation	Year installed
1	**SEDA Ltd. Blackwood, production hall**	SEDA factory	industrial	Roof	2015
2	**B&Q store Cyfarthfa, retail store**	B&Q store	commercial	Roof	2014
3	**Lampeter School, main hall**	Lampeter hall	institutional	Roof	2015
4	**Lampeter School, cloakrooms**	Lampeter cloakrooms	institutional	Roof	2015
5	**Glan Clwyd School, theatre**	Glan Clwyd theatre	institutional	Roof	2015
6	**Glan Clwyd School, corridors**	Glan Clwyd corridors	institutional	Wall	2015
7	**Saxon Court residence, corridors**	Saxon Court	residential	Wall	2015
8	**Rhondda House (terraced)**	Rhondda mid-terraced	residential	Roof	2016
9	**Solcer house (detached)**	Solcer house	residential	Wall	2016
10	**Rhondda House (end-terrace)**	Rhondda end-terraced	residential	Wall	2019

Figure 5-7 represents the locations of the experimental case studies on a map of Wales, UK. They were all funded by WEFO projects and they are in Wales's convergence areas (dark grey) which are areas that EU supported with structural funds between 2014 and 2020. In Appendix III, each study is introduced with project details and a brief overview of the building and the TSC integration. Each case study is accompanied by photographs and a visual representation of the system (similar to the ones in Chapter 3 – Figure 3-12 and Figure 3-13). This information feeds into the design and evaluation analysis (Chapter 6 & 7).

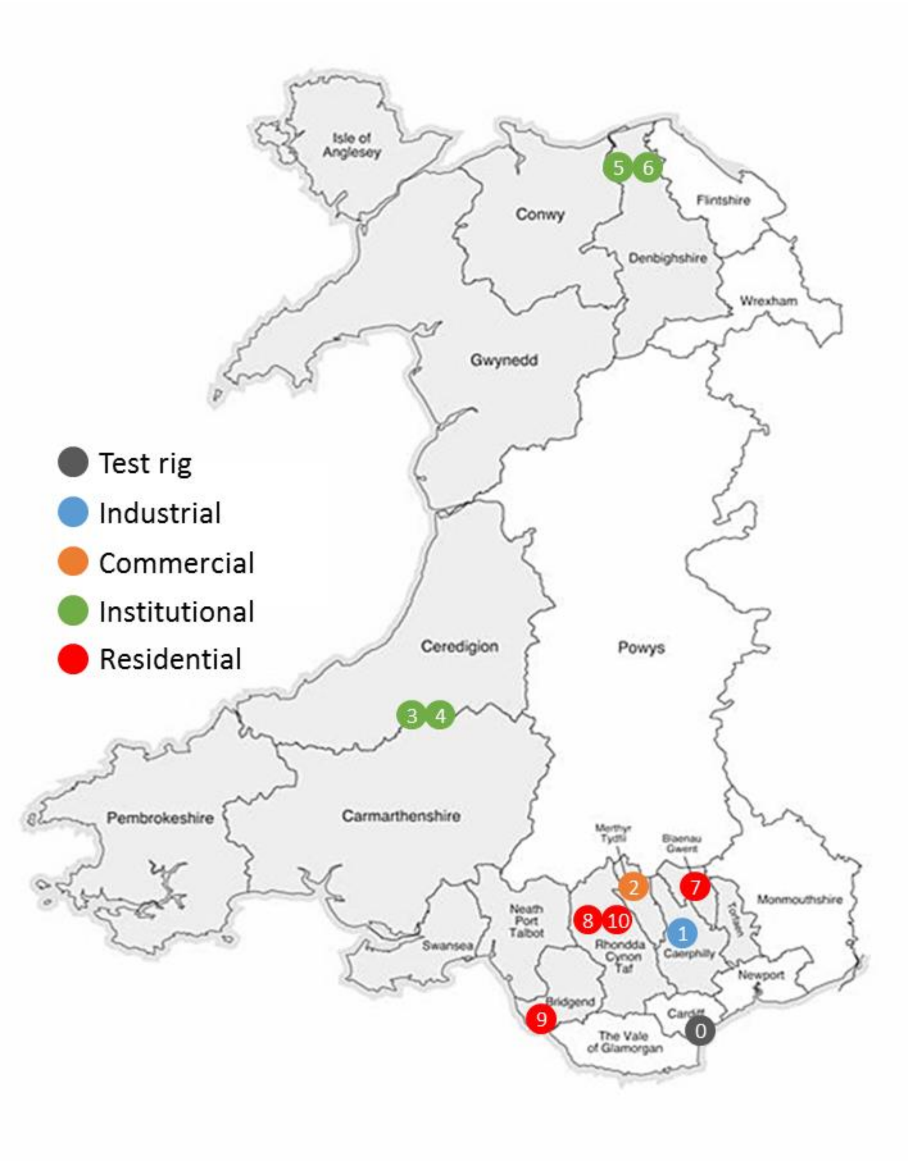


Figure 5-7. Experimental case studies in Wales's convergence areas; author

There are five main reasons that new experimental case studies were used in addition to the literature cases studies analysed in the last Chapter:

a. The author was actively involved in all of them and has knowledge of the design, intention, building, challenges and limitations.
b. The author had full control of the evaluation process including choices in KPIs, SPIs, monitoring plan, instrumentation, raw data capture, data analysis and visualisation.
c. They all informed and benefitted from the framework that is analysed in the next Chapter (Chapter 6).
d. The selection of new case studies intends to fulfil gaps identified in Chapter 4 regarding the lack of diversity in building use, as institutional and residential

buildings are here analysed; also, more and different systems (MVHR, Heat pumps, new controls etc.) are used. The diversity of building types, floor areas and use of different systems responds to a lack of TSC information on several building sectors (research gap identified in Section 4.4).

e. All case studies were selected to represent a widely used building stock in the UK. Some are representative on a more global scale.

5.5 Systems integration for the experimental case studies

Different configurations of the TSC system have been used in the experimental case studies. Using Figure 3-12 and Figure 3-13 from Chapter 3 as a base, it can be seen that regarding DHV systems most of the configurations have also been used in the experimental case studies. More specifically, the configurations including an auxiliary heating system were used, while configuration V was not used. As for PHV systems, only configuration I, where a bypass input and recirculation are present, has been used. A new configuration was also implemented in two case studies (Glan Clwyd School, Theatre and Solcer house), where the MVHR feeds into the heating source (HVAC or heat pump) which then supplies the building with warm air. Also in Rhondda end-terrace house, the TSC, includes a summer bypass and feeds into an MVHR unit. This variety further enriches the analysis and research undertaken in this work and adds to the discussion on applicability of TSC. Similarly to Figure 3-12 and Figure 3-13, Figure 5-8 and Figure 5-9 below visualise the main TSC variants used in the experimental case studies for both DHV and PHV systems (the unused configurations that used in Chapter 3 appear faded).

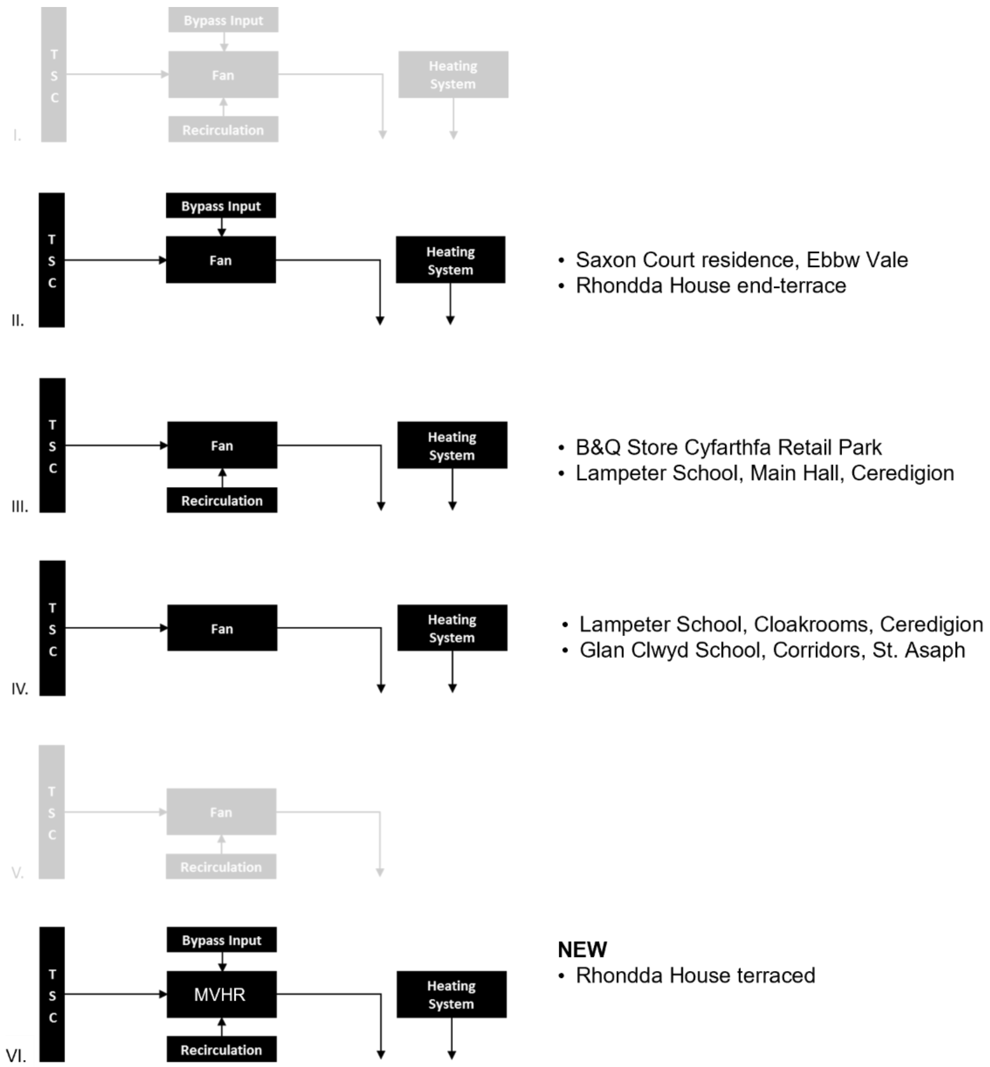


Figure 5-8. DHV TSC systems. A schematic overview of variants and functions of building integrated TSC systems in the experimental case studies; author.

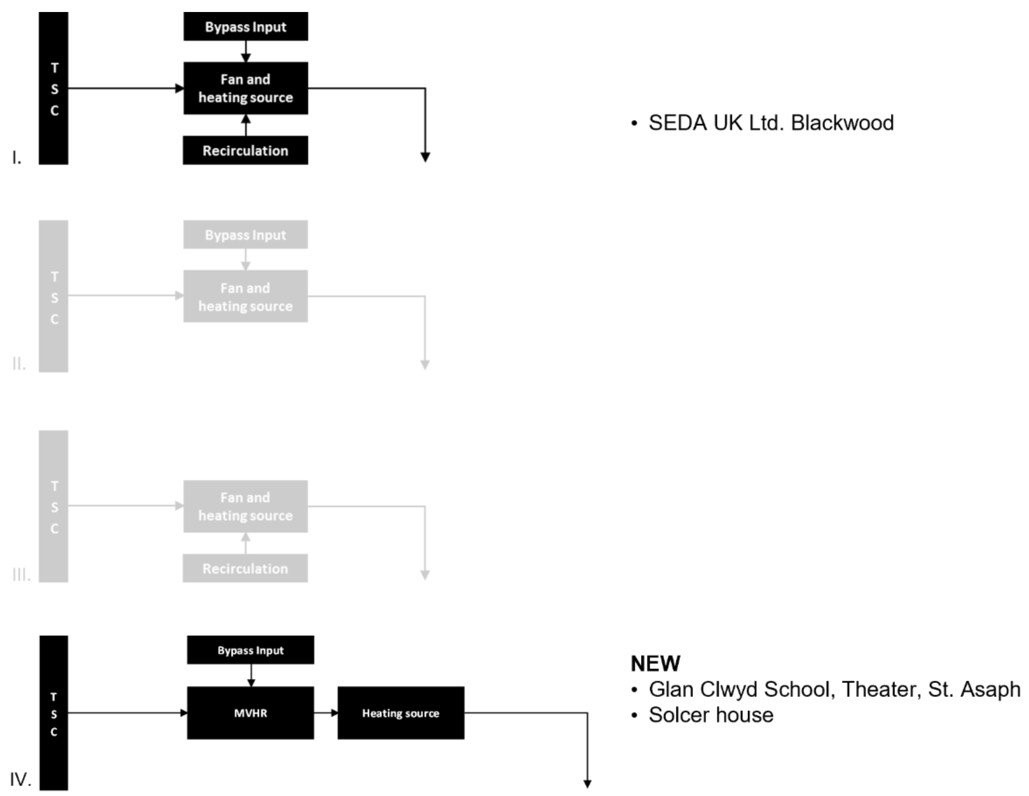


Figure 5-9. PHV TSC systems. A schematic overview of variants and functions of building integrated TSC systems in the experimental case studies; author.

5.6 Author's contribution

All the projects were part of European Funding projects from supported by WEFO. The rig and the eight first installations were part of the SBED project and the last two are outputs of two LCBE projects. The author was involved as a research assistant, research associate or PhD researcher in all the projects. An overview of the author's contribution can be seen in Table 5-2 for every experimental case study introduced in this Chapter.

The author was part of the selection team for all the buildings; 34 buildings were considered and only eight were used based on feasibility, innovation, replicability and time and resource constraints. The author was not part of the Solcer house site selection, which is the only new building in the list. The design of the systems was led by the project's architects and contractors with the exception of the test rig and the Rhondda end-terrace house where the lead designer was the author. In any case, the author was part of the conversations and interactions and has a good insight of the design decision-making process for each case study.

Also, the author led, was part of the team, or closely monitored all the commissioning and optimisation actions following the installation of the TSCs. The author led the evaluation in every project, setting KPI's after the background research (explored in Chapter 4).

Table 5-2. Author's contribution in different stages of the experimental case studies; author

No	Experimental case study name	Site Selection	Design TSC	Commissioning Optimisation	Evaluation
0	**Cardiff University, Bute roof rig**	Yes	Yes	N/A	**Yes**
1	**SEDA Ltd. Blackwood, production hall**	Yes	No	No	**Yes**
2	**B&Q store Cyfarthfa, retail store**	Yes	No	No	**Yes**
3	**Lampeter School, main hall**	Yes	No	No	**Yes**
4	**Lampeter School, cloakrooms**	Yes	No	No	**Yes**
5	**Glan Clwyd School, theatre**	Yes	No	No	**Yes**
6	**Glan Clwyd School, corridors**	Yes	No	No	**Yes**
7	**Saxon Court residence, corridors**	Yes	No	Yes	**Yes**
8	**Rhondda House (terraced)**	Yes	No	**Yes**	**Yes**
9	**Solcer house (detached)**	No	No	**Yes***	**Yes**
10	**Rhondda House (end-terrace)**	Yes	**Yes**	**Yes**	**Yes**

No = Not active contribution, but thorough understanding as part of the team
Yes = Active contribution as part of a team
Yes = Leading or solo
*Together with Dr Ester Coma Bassas

A closer look at the author's contribution on the evaluation of each case study can be seen in Table 5-3 where the evaluation is split in the experimental design, monitoring plan, instrumentation and data analysis. The author led the monitoring plan in all of the case studies and was part of team for instrumentation selection, procurement and installation. The author independently and individually analysed the raw data for every experimental TSC case study introduced; thus, all the products of this work are exclusive intellectual property of the writer.

Table 5-3. Author's contribution in the evaluation stages of the experimental case studies; author

No	**Experimental case study name**	**Experiment design**	**Monitoring plan**	**Instrumentation**	**Data Analysis**
0	**Cardiff University, Bute roof rig**	**Yes**	**Yes**	**Yes**	**Yes**
1	**SEDA Ltd. Blackwood, production hall**	Yes	**Yes**	Yes	**YES**
2	**B&Q store Cyfarthfa, retail store**	Yes	**Yes**	Yes	**YES**
3	**Lampeter School, main hall**	Yes	**Yes**	Yes	**YES**
4	**Lampeter School, cloakrooms**	Yes	**Yes**	Yes	**YES**
5	**Glan Clwyd School, theatre**	Yes	**Yes**	Yes	**YES**
6	**Glan Clwyd School, corridors**	Yes	**Yes**	Yes	**YES**
7	**Saxon Court residence, corridors**	Yes	**Yes**	Yes	**YES**
8	**Rhondda House (terraced)**	Yes	**Yes**	Yes	**YES**
9	**Solcer house (detached)**	Yes	**Yes**	Yes	**YES**
10	**Rhondda House (end-terrace)**	**YES**	**YES**	**Yes**	**YES**

Yes = Yes, as part of a team including some of the following: Dylan Dixon, Huw Jenkins, Dr Simon Lannon
Yes = Leading the team
YES = Solo

6 Development of a framework to design and evaluate a TSC

This Chapter aims to develop a framework as guidance to assist future TSC integration; from the conceptual design to implementation and commissioning and for future performance evaluation of the building integrated TSC system. It is acknowledged that every TSC project has unique characteristics and adjustments may be needed, for this reason flexibility has been built in. Although the design process is linear and should be considered in its entirety, the remainder of the framework can be applied in parts. The framework can be followed in different depths depending on the TSC project. The author's aim is to cover the fundamental parameters and apply this process in experimental case studies in the next Chapter.

This section describes the framework developed within this work that incorporates the design and evaluation of a TSC system. These areas of investigation are priorities set by the research gap identified in the conclusions of the literature review (Chapter 3), where the lack of coherent documented guidance for the application and evaluation of TSC is evident.

The proposed design process aims to enhance the compatibility of TSC to contribute to the heating and ventilation demand of buildings in conjunction with other traditional or novel heating and ventilation systems as identified within the research gap (Chapter 4). The proposed evaluation method aims to systematically assess the contribution of the applied TSC systems to the heating and ventilation demand. Adding to the literature review, a selection of new case studies already introduced in Chapter 5 were used to gather the experience and discuss a design - evaluation framework. The process was evolved and validated through the development and optimisation of the case studies. Chronologically, from the first case study (B&Q) to the most recent (Rhondda end-terraced), the framework was transformed and revalidated by using existing literature and experience on site and through stakeholders.

Moreover, the study develops a monitoring approach aiming to assist in both the design and the evaluation stage. In the design stage, monitoring is a pre-evaluation tool to assist to the site analysis for new buildings and retrofits and quantify site, building and occupancy parameters. Also, monitoring is used to ensure good performance through effective controls and settings in the commissioning-optimisation process. In the evaluation stage, monitoring is the main tool for a holistic approach to TSC assessment that responds to the investigation priorities for research and optimisation purposes. The monitoring process proposed in this study include monitoring techniques and instrumentation that ensure robust and traceable results and apply to all the variants of experimental TSC applications grouped earlier in this study in Chapter 5.

The development of the framework is based on evidence collected and discussed from existing design guides and literature case studies (Chapter 3) and evidence collected and analysed from experimental case studies (Chapter 5). Findings from the literature review in building's heating and ventilation demand (Chapter 2) as well as in TSC technology (Chapter 3) are used to support the framework. Further literature is related to specific technical stages such as feasibility study, sizing, controls, instrumentation, data analysis etc. In addition to literature, as seen in the methodology of this thesis (Chapter 5), the framework is informed by interactions and communications with stakeholders; a source that aims to address practical challenges and limitations. Also, mathematical tools were used in a variety of steps such as in data normalisation, manipulation, and analysis and in the establishment of appropriate equations and algorithms.

The principles followed in the design framework have their foundation in the literature case studies discussion (sections 3.5) where the focus was split into design drivers, envelope integration and systems integration. Although these three elements remain critical, a thorough guidance demands a linear approach where the envelope and systems exploration are also considered in the early stage and in association with the design intent and a feasibility study. Thus, the sections presented in Figure 6-1, ensure a design timeline that makes sequential sense and could work as a checklist incorporating steps aiming for a methodical TSC design.

The evaluation framework also has its foundation in the literature case studies where components of evaluation methods were proposed. The evaluation framework routes arose from the Welsh School of Architecture science lab where the author leads the building and systems monitoring works. Similar evaluation frameworks were already applied to assess a variety of building integrated energy systems. A summary of the methodological approach is explained in the methods section (6.2) and the framework was adjusted for TSC evaluation through experimentation, primarily in the WSA test rig and further developed through the rest of the experimental case studies introduced in Chapter 5. The titles of the framework sections are seen in Figure 6-1.

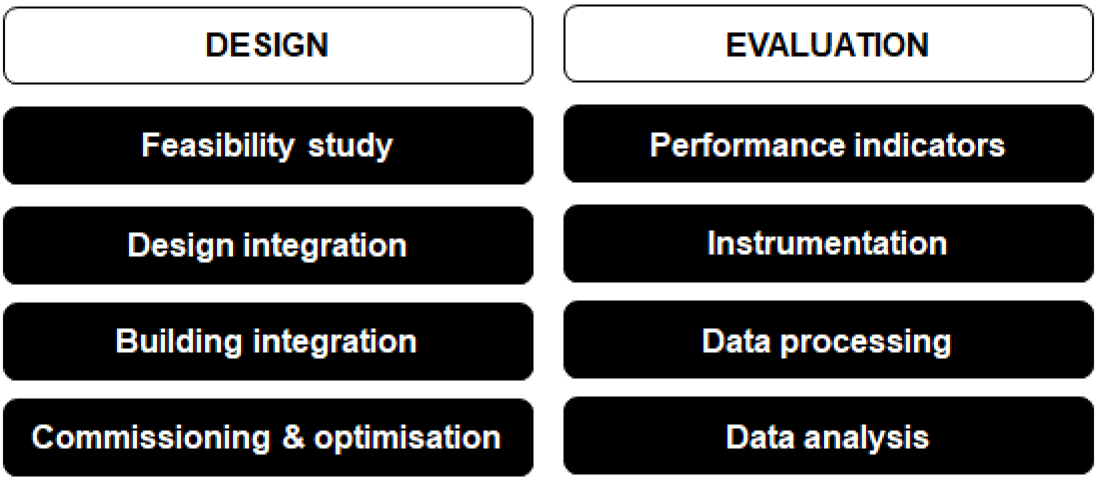


Figure 6-1 TSC design and evaluation framework sections, author. For clarity, the topics are presented in consecutive sections but in practice design and evaluation activities are closely interlinked.

6.1 TSC Design

There are a series of design challenges in integrating a TSC on a building façade and to an HVAC system. This section aims to overcome these challenges by presenting a step-by-step process that starts from a feasibility study; then moves forward integrating the TSC into design, and to the building and concludes by commissioning the system (Figure 6-2).

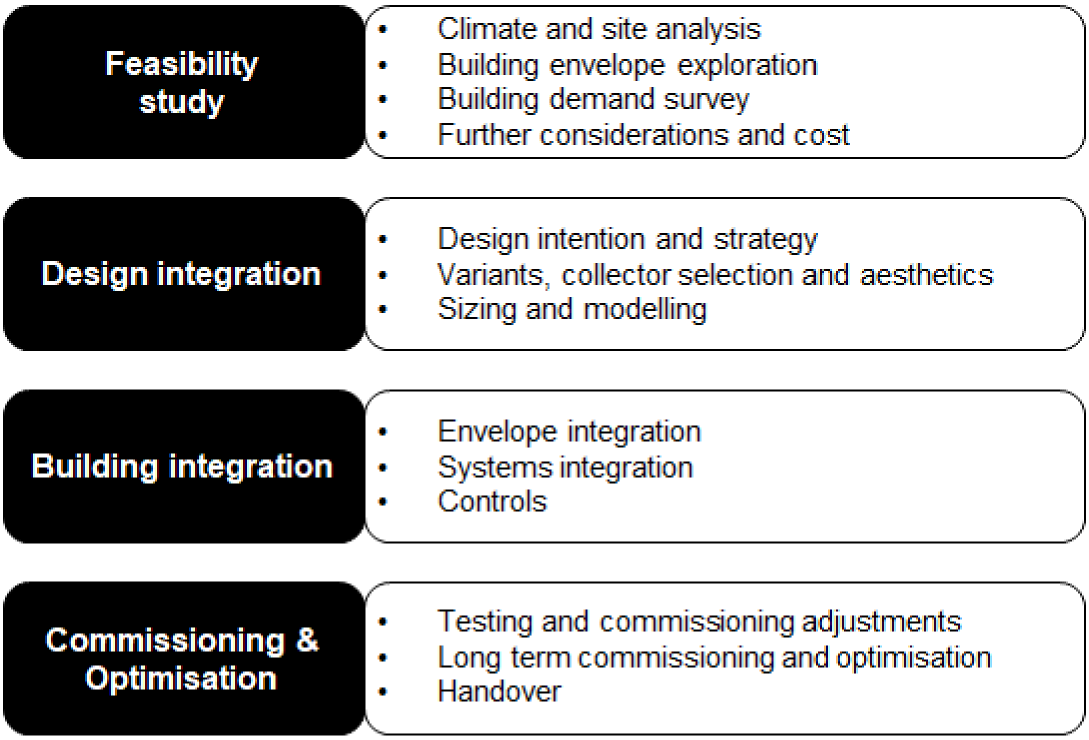


Figure 6-2 Stages for TSC Design, author.

6.1.1 Feasibility Study

The investigation begins by assessing the feasibility of a potential TSC installation. This can be split into three major consideration categories summarised in a site-building-demand exploration exercise: 1) The site should be investigated to determine if the landscape and climate are appropriate to get the TSC benefit. 2) The building envelope should be explored to clarify if and where it can host the technology if a retrofit or should be designed to optimise the technology if new. 3) The building ventilation and heating demand should be studied to make sure that a system providing heat and ventilation is needed.

6.1.1.1 Climate and site analysis

The site analysis is the stage that the context, landscape, shading from surrounding obstructions and local weather are explored while considering limitations of the TSC technology. The limitations can include (but are not limited to) lack of solar availability or lack of heating demand due to climate before considering the specific building, envelope and systems. The architectural context is important as commercial TSC are additions to the envelope skin and despite surface and colour variability, they do not match in every architectural context. A survey or analysis of the neighbouring context such as the study by Drozynski et al. (238), could assist in specifying if TSC would be consistent with the surrounding environment and public perception.

If heating is not needed or the site has no access to solar, then the TSC is not an appropriate technology. A study on the climate and microclimate is needed to establish the heating season duration. This can be quickly done by classifying the climate with tools such as the Köppen-Geiger Climate Classification system (239). The classification indicates a breakdown of average external temperatures that can be compared with Tables 2-2 and 2-3 for climates requiring heating. Tables 2-2 and 2-3 are derived from CIBSE Guide A (87); however, similar guides can be obtained for other climates or/and countries. For further analysis ambient temperature data can be collected from meteorological data platforms, such as the 25-year CIBSE historic data and can also be used to calculate heating degree days according to section 2.1.2.2 and guides such as the CIBSE *TM41* (240) which translates into Equation 6-1. Alternatively, heating degree days libraries such as the BizEE (241) can be used.

$$D_d = \frac{1}{24} \cdot \sum_{i=1}^{24} f(T_b, T_{e,i}), \qquad f(T_b, T_{e,i}) = \begin{cases} T_b - T_{e,i}, & if\ T_b > T_{e,i} \\ 0, & if\ T_b \leq T_{e,i} \end{cases} \qquad \text{Equation 6-1}$$

Where D_d is the heating degree day from mean degree hours

T_b is the base temperature of 15.5ºC was used (242) (also analysed in section 2.1.2.2) and

$T_{e,i}$ External temperature from historic or current data (ºC)

To further understand the local weather profile, a monitoring station can be installed onsite. The monitoring station records several weather variables, with the outdoor air temperature a focus for the case study. External temperature data can be collected from the site or from data bases from nearby weather stations. The historic weather data libraries that are suggested in this study are the CIBSE 25 years historic data (243) and the PVGIS-SARAH2 16 years historic data (free) (244). For both new builds and retrofits, monthly averaged weather data from a year of on-site monitoring using a weather station on site can be compared with historic data from the area (245). When pre and post retrofit weather data are normalised for historic, comparisons are more accurate.

Solar availability is an important factor in exploring solar thermal potential. It is related to building envelope inclination and orientation, which are discussed in the next section (6.1.1.2), but a brief exploration of the sun path is suggested in the site analysis level. In section 3.2.4.1 it is established that although solar radiation heavily influences absolute heat delivery, the efficiency and effectiveness of the TSC are not significantly affected as seen in Figures 3-9 and 3-10. The impact of solar availability and solar path can be carried out using software tools such as the *Daily average irradiance* tool in JRC PVGIS (244). This allows exploration of both vertical and horizontal solar potential for an average winter and summer day. It is essential to consider shading issues related to low sun angles in winter for the UK.

The exploration of the topographic horizon of the natural landscape can be done by meteorological tools embedded in solar modelling tools such as JRC PVGIS (244) or PVSyst (246) or autonomous climatic tools such as Meteonorm Software (247). The PVGIS is a freeware and recommended by the author to quantify solar availability on different planes as the user can choose the *Use terrain shadows* feature and horizon calculations will include local hills or mountains that may block the sun path during some periods of the day with a 90m accuracy. The above tools and calculations do not take into account shadows from nearby objects such as houses or trees. In this case the user can upload horizon information (PVGIS) or design obstacles (PVsyst). The author recommends logging the nearby trees and surrounding buildings by using tools such as Google Maps and Google Earth and by visiting the site and using photography, navigation and dimensional instruments. Such information can later feed modelling tools to increase accuracy of the modelling exercises for both new builds and retrofits. Future weather projections are becoming more important due to climate changes. There are tools that can be used to generate such data Meteonorm Software (247) however projections should consider lifespan of TSCs (10-20 years).

6.1.1.2 Building envelope exploration

Following the initial investigation of the context, a closer look to the architecture of the envelope for both new and existing buildings is recommended. Some buildings or facades have special architectural or/and historic interest and alterations are forbidden or highly controlled. In the UK such buildings are called *listed* and considered to be of national importance and therefore worth protecting. A list of such buildings can be found in governmental sources such as Historic England (248) and National Historic Assets of Wales (249). It is highly unlikely that TSC can be approved by the corresponding authorities to be attached to listed buildings or facades.

Solar panels are subject to normal building regulations, which involves checking that the roof can support the extra load and the installer should run the feasibility check. When retrofitting, planning permission should be considered. In the UK, planning permission is not required for installation of solar technologies as far as:

- The system is installed in such a way that the effect on the external appearance of the building and the amenity of the area is minimal.
- When no longer needed, equipment should be removed as soon as reasonably practicable.
- The system cannot be higher than the highest part of the roof (excluding any chimney).
- The system cannot protrude more than 0.2 meters beyond the plane of the roof slope.

Planning permission is required when TSC is installed on flat roofs as the system needs to protrude more than 0.2m above the roof slope or when the site is in a conservation area or the building is listed (250).

Researchers from Cardiff University (238), found that almost half (47.1%) of 130 questionnaire respondents presented an opinion that domestic TSCs are suitable in terms of sustainable energy generation and their energy saving potential. However, the same study found that most of the participants disagreed with the suitability of the appearance of the device on an existing structure. The majority of the respondents suggested that modern buildings might be more in-tune with the aesthetic of the presented TSCs; in particular factories and shopping centres. Interviews from the same study presented similar themes but with more explicit details. People were more willing to present their dissatisfaction with the aesthetics in cases of domestic TSCs. Although the interviewees were negative in this instance, they did have a positive attitude towards renewables. They commented that “[They] would like to install something that was sustainable but not as obtrusive or obvious” and “the devices help make the environment more liveable and friendly […] aesthetics is not my personal concern here”. The above findings highlight that envelope exploration is highly linked to design integration and a separate study on the integration and aesthetics is required - as seen in section 6.1.3.

During the building envelope exploration, orientation, inclination, and area availability are examined accompanied by a structural feasibility study. This is combined with the site analysis to identify maximum usable installation area and quantify solar availability. Google Maps (251) and Google Earth (252) through photography and aerial photography are useful tools to identify envelope parameters, whereas trigonometry can be used to calculate slopes in existing buildings in situ and in drawings. Careful quantification of inclination, orientation (degrees) and available installation area (m^2) increase the accuracy of the simulation process. Depending on the solar angle, solar thermal collectors can be installed in vertical or/and inclined surfaces. However, when studying optimal inclination for maximum solar availability the centre of interest is the heating season rather than the full year yield as with PVs. For the UK, the heating season is broadly defined from October to April as explained in Chapter 2 (80, 87); however, a further investigation of microclimate may alter the definition of heating season. There are several tools which can be used to calculate solar availability for different locations, inclinations and orientations such as HTB2/Virvil Sketchup (253), PVSyst (246), Climate Consultant (254) etc. This study suggests JRC PVGIS (244) for such studies as the tool is free, easy to use, includes landscape shading and adjustment of various parameters. The results are visualised on screen and downloadable. Solar potential can be quantified for existing facades for retrofits or prioritised within the design for new builds.

Further exploration of the microclimate is also important as there are parameters that can affect the envelope such as prevailing winds and water presence. Wind metrics can be found in PVGIS TMY/EPW files or the Global Wind Atlas (255). Cross winds can reduce temperature rise and disturb flow as discussed in 3.2.4.3; this was also verified through experimentation using the TSC test rig. It is not recommended to install TSCs when winds are above 5m/s whereas low winds of 2m/s could be beneficial (see section 3.2.4.3) which demand a detailed exploration/monitoring of the local winds. Also, increased ambient moisture may impact envelope materials and prevent internal moisture decrease through ventilation. Also, from conversations with manufacturers (TATA Steel), salty air can lead to TSC edge corrosion thus installation in coastal areas is not recommended.

Both CIBSE (103) and ATTMA standards (123, 124) set maximum air permeability targets in order for mechanical ventilation to be effective. Although a SAP Assessor will generally set a design air permeability target of between 5-10$m^3/(h.m^2)$@50Pa, ATTMA benchmarks for mechanically ventilated dwellings are 5$m^3/(h.m^2)$@50Pa (normal) and 1m^3/(h.m2)@50Pa (best practice) (123, 124). ATTMA TSL1 and TSL2 includes specific best practice and normal levels for a variety of buildings shown in Table 6-1. Airtightness targets for various building types

Table 6-1. Airtightness targets for various building types

Building Type	Best Practice $m^3/(h.m^2)$@50Pa	Normal levels $m^3/(h.m^2)$@50Pa
Naturally ventilated dwellings	5.0	7.0
Mechanically ventilated dwellings	1.0	5.0
Naturally-ventilated offices	3.0	7.0
Mixed mode offices	2.5	5.0
Air conditioned / low-energy offices	2.0	5.0
Factories / Warehouse	2.0	6.0
Superstores	1.0	5.0
Schools	3.0	9.0
Hospitals	5.0	9.0
Museums and archical stores	1.0	1.5

Air tightness testing can reveal issues such as infiltration through cracks, poor window sealing etc., that need to be addressed prior to mechanical ventilation installation. A blower door test is suggested following BS EN 13829 and ATTMA TSL1 protocol to determine air permeability values. When external and internal temperatures are different, thermography testing could reveal unwanted infiltration during over pressurising or under pressurising of the building. Draught anemometers can also assist to identify windows and door air gaps and sealing condition. In this study FLIR cameras and TESTO 405NTC telescopic anemometers were used.

6.1.1.3 Building demand Survey

The building demand survey is performed to identify if the building needs ventilation and heat. This breaks down to two different studies: the ventilation demand study and the space heating demand study; the ventilation comes first as it impacts the heat demand study.

6.1.1.3.1 Ventilation demand survey

The ventilation demand is determined by benchmarks and regulations discussed in section 2.2.2. Appropriate ventilation rates in l/s, m^3/h or ACH should be selected based on specific needs. Building and room type and use should be considered in conjunction with special requirements such as occupancy variations. The main sources to determine the ventilation needs in this study were the Building Regulations Part F (122) and CIBSE Guide A (87), as well as semi structured interviews with building tenants, owners and managers. Indicative values for the UK context were discussed in tables 2-5, 2-6, 2-7 & 2-8. For both new builds and retrofits, tenants, owners and managers can assist to explore scheduling as there are building types that do not require ventilation all the time (e.g., schools, or retail), or where a boost mode may be needed (to address smells or extra moisture). Whereas some building types may require doors/windows to be opened frequently or for long periods. In these cases, ventilation can still be useful especially when heated air is supplied through mechanical ventilation to match the total building infiltration rate through the openings. This technique is based on the marginal over-pressurization where sufficient ventilation is provided, which prevents cold air entering through infiltration (as discussed in Chapter 2). This is not however recommended for domestic buildings where TSC require need for mechanical ventilation. Cho et al. (256) discuss the infiltration rate for different buildings with and without a porch. As an example, the study calculates that a $2300m^2$ retail shop may have up to 1420l/s air infiltration rates through door openings during peak time without a porch area and up to 940l/s with a porch.

The ventilation rate is the dominant TSC design parameter and provides a safety net against potential marketing tendencies for costly oversizing. This is because the ventilation rate will later determine sizing through the suggested flow rate per square meter of TSC as discussed in 2.4.3 and 2.4.4 and Chapter 3. If a ventilation system is already installed, monitoring the existing performance is a good practice to compare reality vs design. This can be done by using existing mechanical drawings and specs or/and instruments such as balometers that can measure the existing volume flow rates. However, the existing ventilation rate may not be appropriate and should be reconsidered following the references discussed above.

6.1.1.3.2 Heating demand survey

Climate analysis as discussed in 6.1.1.1 has already given an indication about the local weather and if heating may be required; however, to quantify heating needs, a good understanding of the building is needed. Both desirable temperature range and indicative heating demand for different buildings and spaces were discussed in section 2.1 and summarised in tables 2-2, 2-3 and 2-4 for the UK climate. Indicative heating demand values demonstrated in table 2.4 could be a starting point; however, this information is irrelevant to a unique building and for a different climate. Space heating demand is a study of heat losses and gains or in other words of heat balance. Heating demand (Equation 6-2) is exactly that amount of energy, which is necessary to maintain the desired room temperature by balancing the excess of losses compared to the gains. Equation 6-2 is a simplified heat balance equation based on CIBSE Guide A (87). Losses could be through conduction or infiltration/ventilation whereas gains could be from the sun or internal activities. The heat balance equation assists to quantify the maximum peak load (kW) which determines system sizing and the space heating demand (kWh) which is the energy needed to heat a space within a duration of time. A simplified version of the heat balance equation is shown below.

$$H_d = H_{TL} + H_{VL} - H_{IG} - H_{SG} \qquad \textbf{Equation 6-2}$$

Where H_d Heating demand (see definition above) (W)

H_{TL} Envelope transmission heat losses (W)

H_{VL} Ventilation and infiltration heat loses (W)

H_{IG} Internal heat gains from living beings and appliances (W)

H_{SG} Solar heat gains through building envelope (W)

The components of the equation above are dynamic, meaning that the approach to calculate heat demand should be based on dynamic data such as hourly data (dynamic model). A non-dynamic approach could be applied using representative or extreme conditions of the balance (steady state model) assuming typical or real scheduling. If an EPC exists, monthly and annual space heating demand is presented based on SAP or SBEM steady state model calculations discussed is section 1.3.4.1. If an EPC is not available, SAP calculations can be produced to enumerate heat demand based on static information. SAP calculations however may result to major error in estimating demand as they do not consider occupancy and dynamic weather (SAP2012). Alternatively, dynamic modelling such as HTB2, Design Builder and similar, discussed in the same section, can be used for more detailed data, complex systems and non-typical occupancy patterns. Identifying heating system(s), heated space(s) and occupancy scheduling is a prerequisite when studying heating demand. Also, a variety of data are needed to inform the modelling tools such as meteorological (irradiation and ambient temperature), dimensional, occupancy, envelope infiltration and ventilation (flow rates) and envelope heat transmission. All the above parameters were discussed previously in this framework and literature except the envelope transmission. The envelope transmission can be written down as a heat transfer equation and Equation 6-3 presents that based on CIBSE Guide A (87).

$$H_{TL} = \left(\sum U_X A_X\right) \times \Delta T \qquad \textit{Equation 6-3}$$

Where H_{TL} is the envelope transmission heat losses (W)

U_X is the U value of each envelope element (W/m^{2}K)

A_X is the respective area of each envelope element (m^2)

ΔT is the temperature difference between outside (ambient) and inside (desired) (K)

The area of each envelope component (walls, roof, floor, windows and doors) is dimensional information, and the ambient temperature is a meteorological input. The desired temperature is vital information discussed in Chapter 2. In some UK models such as SAP, the desired temperature is 21°C whereas in others it is 20°C (Passivhaus standard). In CIBSE the desired temperature range is different for different spaces and building uses (table 2.2 and 2.3), whereas dynamic adaptive models (257) can also be used to identify the desired temperature range. For existing buildings, questionnaires, temperature thermostatic set points and air temperature variations monitoring can be used to identify a customised desired temperature. It is crucial to identify if the monitored temperature is the desired one as parameters such as fuel poverty, bad servicing and overheating can create a mismatch between desired and real temperature.

U values can be determined theoretically by following design specifications and U value index (258) or experimentally by U value testing (259).

The above data can now be entered to the heat balance equation by using steady state modelling methods such as SAP/SBEM or more sophisticated dynamic modelling such as Design Builder and HTB2 as discussed in section 2.1.

In existing buildings, space heating delivered can be monitored whereas heat demand cannot be monitored as this is a calculated expected value. The mismatch between modelled and monitored performance is called performance gap. The aim is to reduce the performance gap to produce robust modelling data for a post retrofit scenario of technologies such as TSCs by understanding the reasons behind this. A key reason is the occupancy patterns (profile). If the model is not calibrated for specific monitored occupancy patterns, default benchmarks heating profiles could be used such as the average UK profile in Yao and Steemers study (260) presented in Figure 6-3.

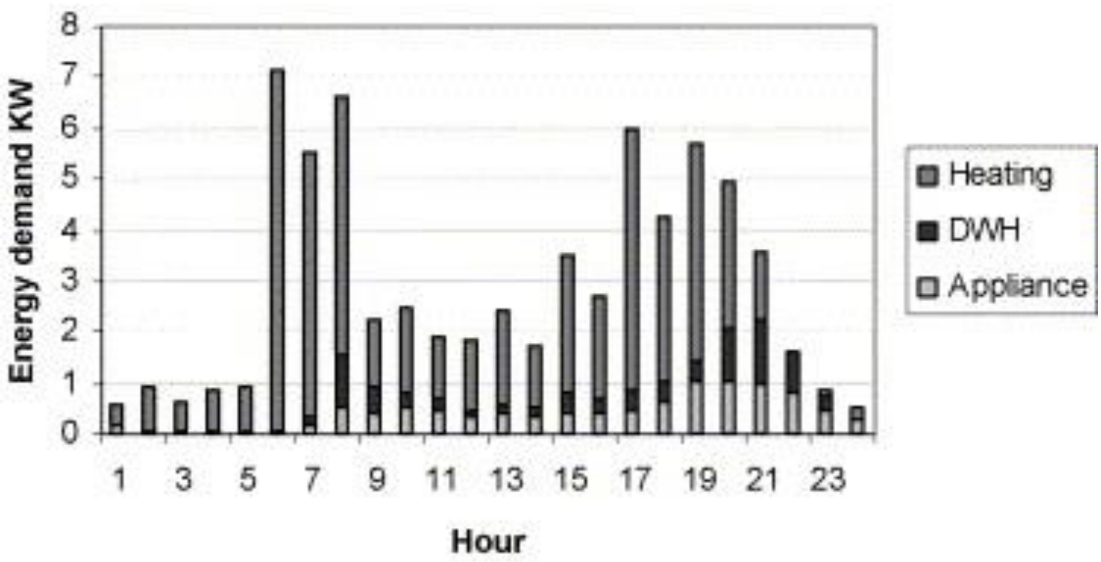


Figure 6-3 Energy-consumption break down in January for an average size UK household (260).

There are two techniques to measure heat delivered in a house; the first one, the co-heating test is irrelevant to the occupants as it is performed in an empty house. The second one is based on heat meters and monitoring the actual space heating delivered during real time occupancy. The co-heating test is a pseudo-steady-state test, where the amount of energy required to maintain a constant indoor temperature is measured and the total heat-transfer rate is calculated (261, 262). Heat delivery monitoring can be done by installing heat meters to the output of space heating mediums such as circulation pipes in wet systems or supply ducts in AHU. In this study, heat meters were installed in the space heating radiator circulation of boilers and ASHP air supply; further information will be provided in the instrumentation section (6.2.2). Space heating delivery monitoring values may need to be normalised for historic weather data especially when compared to modelling heating demand. This can be done by the use of HDD and simple ratio-based normalisation, meaning that the monitored space heating delivery is multiplied by a HDD factor which is the ratio of Historic HDD divided by monitored HDD (101). Also, as mentioned above, the delivered heat monitoring should be accompanied by indoor temperature monitoring to investigate if the desired comfort was achieved.

Another interesting parameter to consider is that the consumer will pay for the space heating delivery. If gas or other fossil fuels are used to deliver space heating, replacing the boilers should be considered. When replacing part of the fossil fuel consumed with renewables (TSC), an investigation on the gas spent for space heating is required. A realistic rather than a boiler’s nominal efficiency should be consider as an Energy Saving Trust report (263) highlights that field trial found that the average efficiency was 83% for combi boilers, which is significantly lower than the SAP rated efficiencies. With HPs emerging into the markets, when replacing HPs space heating delivery with TSC, the measured or nominal seasonal COP of the heat pump should be considered to calculate energy (usually electricity) consumed to deliver that space heating.

In this study, both modelling and monitoring methods were used to determine the space heating demand/delivery and additional data were collected to understand and reduce the performance gap. An important design decision is who to design for; the existing occupants/users, similar occupants/users or the UK average occupants/users? This will determine which profile to trust and if modelling or monitoring is more appropriate. This will be further discussed in the design integration – intentions section (6.1.2).

6.1.1.4 Cost and further feasibility considerations

Further data collection on the building systems can facilitate preliminary and feasibility studies.

Examples of the types of information gathered are existing or designed PV areas, heating and ventilation system types and strategy, ducting, risers, suspended ceilings, access and structural details. If there is an existing HVAC system (already built or designed), the exploration identifies if the system would work in conjunction with the TSC. The fan power consumption can be measured before and after to determine any increase in power consumption due to the TSC pressure drop. An investigation of the area that potential PVs may need to be determined, based on design prioritisation, TSC feasibility and sizing constrains. A study of moisture and damp issues for retrofits can be used to determine local ventilation flow rates and inlet/outlet positioning. Structural details of the fabric to be used for TSC can facilitate design detailing. Also, if an in-depth structural survey or structural support is needed, this may incur an additional cost.

A semi-structured interview with existing (or future) occupants assists in communicating the technology, including benefits and limitations as suggested by a study co-authored by the author of this thesis (238).

Deadlines should be considered; the feasibility to run design and construction of a non-mature bespoke technology needs to be considered in the decision-making process especially if performance evaluation and optimisation work is included.

The market may use theoretical pricing based on business-as-usual know-how; however, all the projects followed in this study had a completely different final cost which was considerably higher to the quoted one due to the bespoke R&D nature of projects. Cost will be considered in sizing but a basic cost analysis should be considered in the feasibility stage and shared with the clients. In order to briefly quantify maximum cost in early stages the following parameters should be collected:

- Desired volume flow rate, based on ventilation demand exploration and acceptable flow rates (167, 218, 219, 264). When dividing maximum ventilation need by minimum acceptable TSC flow rate per m^2 ($15m^3/h$ (219, 264)), the maximum TSC area will be determined.
- TSC cost and payback, normalised in today's prices. Extra costs such as structural implications, interviews, design, bespoke TSC shapes, system and envelope integration, finishing, logistics, risks and delays should also be considered.
- TSC average efficiency to calculate the heating output. TSC efficiency should respond to the selected minimum acceptable TSC flow rate from manufacturers' data such as the one in Wand et al.'s study (193). Efficiency will convert determined annual solar for TSC area to potential minimum annual heating output. The heating season output can be used for space heating. The non-heating season output can be used for storage.
- Cost benefits for heating displacement. Existing or reference heating systems with their conversion factors should be considered to calculate cost of the displaced energy. Ofgem price caps (265) can be used for current energy prices in the UK.

- Solar availability for potential TSC area based on total solar available for heating season (e.g. from PVGIS, (244)) and envelope exploration; to be used in the TSC efficiency equation.

An example of the estimation guide described above, can be found in the corresponding results section 7.1.1.4. A cost analyses will follow in the sizing section (8.1.2.3) and in applied at 7.1.2.3.

6.1.2 Design Integration

The feasibility study informs design decisions, and a good design is the basis of good implementation. The TSC integration into design is an exploration of why, what and how much:

- Why do we use a TSC? Is the performance the main driver? Should aesthetics be an important factor?
- What are the variants and collectors' parameters that go with different facades and HVAC systems?
- How much area should be installed and how this can be optimised through modelling tools?

This section aims to help the designer to respond to these questions.

6.1.2.1 Design intention and strategy

To discuss the TSC strategy, a full services strategy should be understood. In whole building retrofits TSC is discussed in conjunction with other systems, thus a holistic retrofitting approach using the feasibility study should be analysed before TSC parametrisation.

The selection of appropriate TSC systems in terms of aesthetics, variants, alterations, and systems that work in conjunction to them is a fundamental step in design and a prerequisite for sizing and implementation. The designer together with the client need to decide and weight priorities as the TSC needs to:

- Respond to the feasibility study, corresponding to het and ventilation demand
- Fulfil building integration aesthetic criteria
- Work with innovative building services and singularities

The very first step is for the designer to identify the design intention. Aesthetics could be the dominant reason to use all of the sun-facing façade as seen in existing case studies (Table 4-4) and questionnaires (159, 238). The main driver of this research is to reduce space heating delivered by fossil fuels and match the ventilation demand.

When aesthetics leads the collector selection and sizing, a compromise on heating delivery and ventilation may occur.

Ventilation can be matched by adjusting the total TSC volume follow rate. The parameter to consider is the flow rate per TSC area ($m^3/m^2/hr$). TSC heating delivery is defined in Equation 3-4 with two main contributors, the mass flow rate and the temperature rise. Experiments with the WSA test rig showed (Figure 6-4) that by increasing the mass flow rate up to approximately 100-120m^3/h per square meter of TSC, the heat delivery is increased, and the efficiency is maximised, but the temperature rise is decreased to 7°C. The inverse relation between flow rate and exit air temperature is studied in section 3.2.3 and is also visualised in TATA design guide (206). In DHV systems as defined in 1.3.5, temperature rise is a major design driver otherwise unwanted cold draughts may occur.

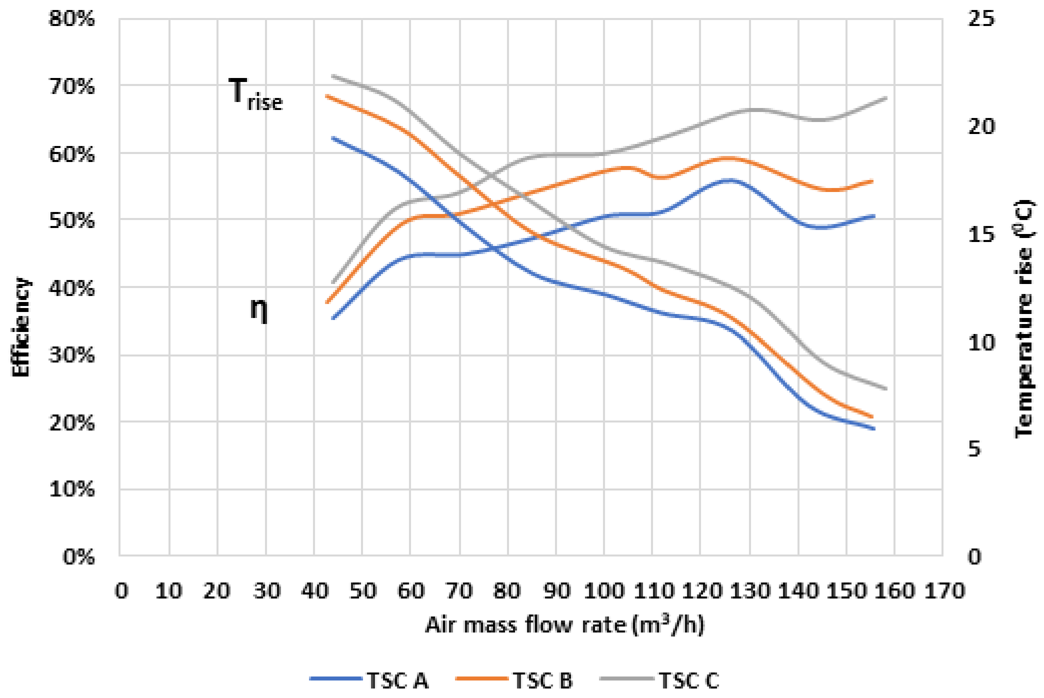


Figure 6-4 TSC performance using the WSA Bute building roof test rig for three different TSC dimensions (A, B, C) The graph indicated the relationship between air mass flow rate, temperature rise and efficiency be using averaged data for different climate conditions. Data sets used in Perisoglou and Dixon study (202), author.

The fundamental principle of any system that delivers heat is to fulfil the heat demand. In the building services world heat demand translates into a room/building temperature set point that activates or deactivates a heating system through a simple or sophisticated thermostat. When an HVAC system is used to deliver heat and ventilation, fresh air volume flow rate control to fulfil the designed ventilation demand is required in addition to a thermostat. Figure 6-5 visualises a break down of HVAC delivery in response to heat and ventilation demand

A. HVAC fulfils the ventilation and heat demand, the thermostat will stop or lessen the heating element when current room temperature reaches set point, The flow rate is kept at ventilation demand ensuring no extra fresh air is coming. This status ensures an effective performance of the HVAC where all the delivery fulfils the demand.
B. HVAC delivers in higher flow rate but does not create discomfort as delivery is above current room temperature. The thermostat will stop or lessen the heating element when current room temperature reaches set point. This status ensures an effective performance pf the HVAC unless extra ventilation rate cause unwanted drafts which could be the case especially in residential applications.
C. HVAC delivers in higher flow rate and at a temperature below the current room temperature that would create more heat demand. This status is not effective.
D. HVAC delivers in higher flow rate and at a temperature that causes room temperature to exceed set point temperature crating overheating. This status is not effective.
E. HVAC fulfils the ventilation demand but delivers at a temperature that causes room temperature to exceed set point temperature crating overheating. This status is not effective.

From the above, the TSC can assist in status A and B. It has to be considered that status B would require more sophisticated controls and also the daft risk needs to be assessed in design and commissioning.

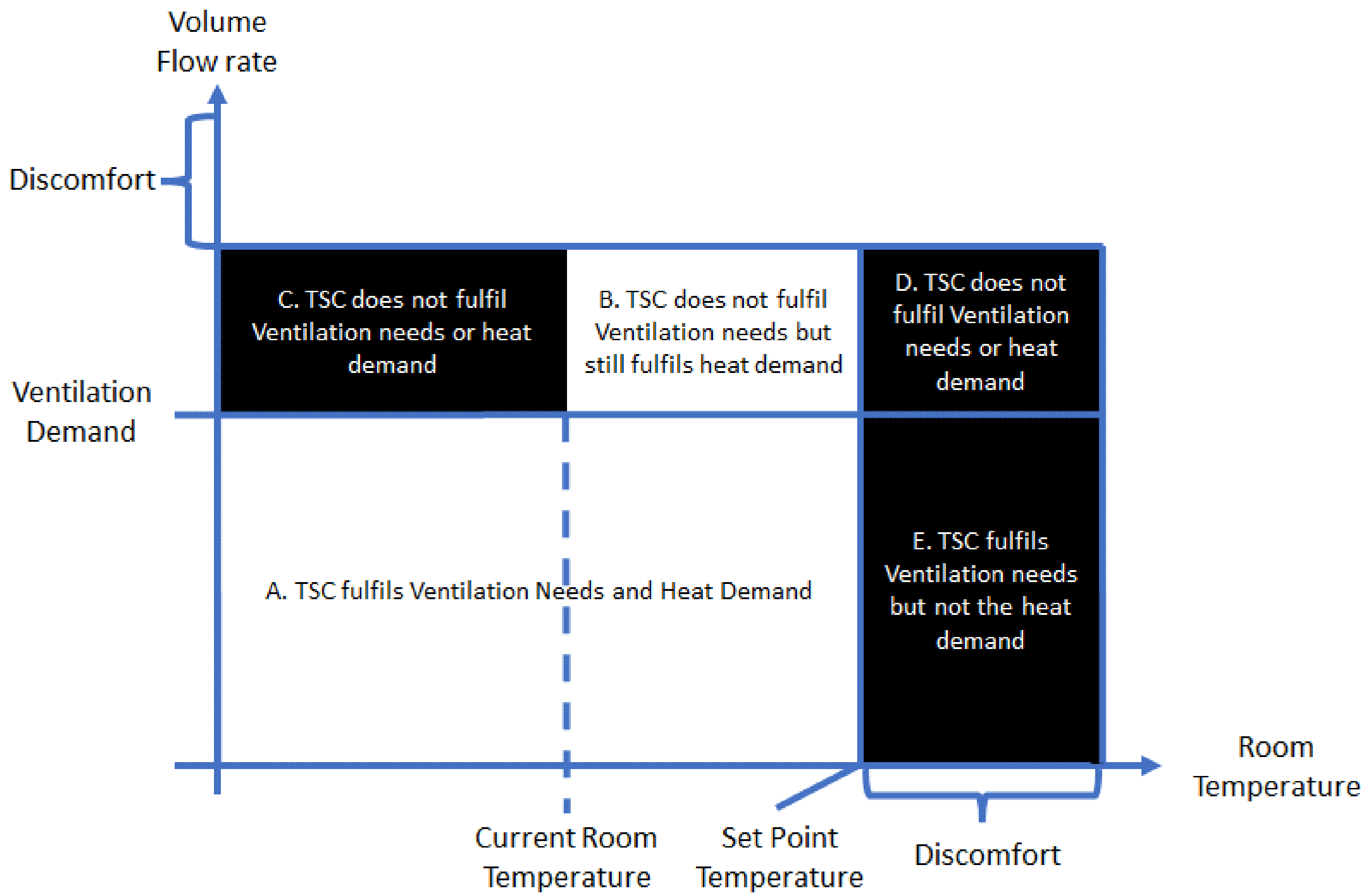


Figure 6-5 Heating and ventilation strategy; heat demand in response to ventilation flow rate and room temperature, author.

To avoid temperature discomfort, when the desired room temperature is reached or ventilative cooling is needed, a bypass damper can be activated. More information on the above strategies will be provided when selecting appropriate control strategies in the building integration section (6.1.3). When buildings are designed to optimise natural ventilation, TSC can work as a heating system that over-pressurise the fabric to minimise infiltration. This means that temperature rise is prioritised over mass flow rate to ensure draughts are not creating discomfort. On the contrary, when TSCs are incorporated to existing HVACs that use ambient fresh air, maximising mass flow rate would maximise heat delivery and displacement.

6.1.2.2 Variants, collector selection and aesthetics

There are two main TSC variants introduced in Chapter 1 and visualised in Figure 6-6 below. In more detail:

The Direct Heat and Ventilation (DHV) TSC (top diagram in Figure 6-6) uses a fan to deliver space heating and ventilation. A separate wet heating system works in parallel to the TSC. This separate heating system cannot be an air delivery system as this would compete with the TSC and disrupt ventilation. The Pre-Heat and Ventilation (PHV) TSC (bottom diagram in Figure 6-6) integrates into an air-to-air system heating and ventilation system. In this case the heating and ventilation outcome is controlled by the system. Such systems are exhaust air heat pumps, gas fired air heating systems, or mechanical ventilation systems with heating elements. Alterations of the two basic variants were studied in Chapter 4.

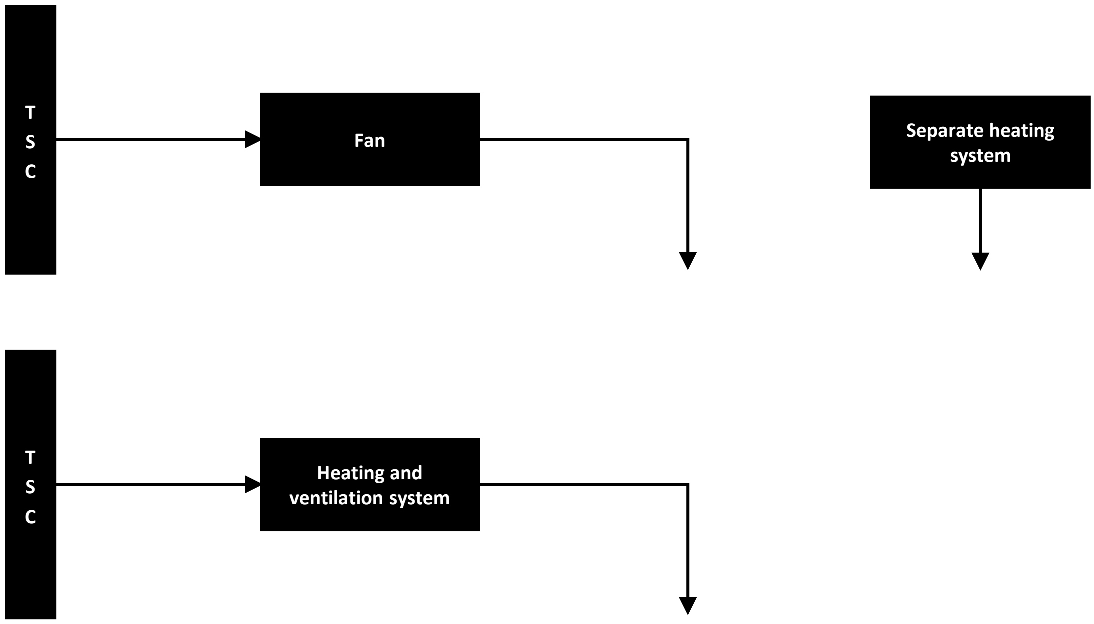


Figure 6-6 TSC fundamental variants: DHV (top) and PHV (bottom) generic schematic, author.

TSCs can have two extra mechanisms depending on design priorities: the recirculation and the bypass route. A decision-making flow chart presented in Figure 6-7 shows how to choose the most appropriate variant. If there is a need for air de-stratification or/and warm air reuse, a recirculation mechanism through a damper and filters can direct stalled air back to the fan. Bringing fresh air into the building increases the heat demand dramatically and partial air recirculation saves some of it. However, REHVA, the Federation of European Heating, Ventilation and Air Conditioning Associations, has recently (2020) called for engineers to stop recirculating air in buildings in areas with a Covid-19 outbreak. Instead of recirculating the polluted air, its valuable heat can be recycled via a heat exchanger (266). The bypass route can be selected for cooling purposes especially during the summer.

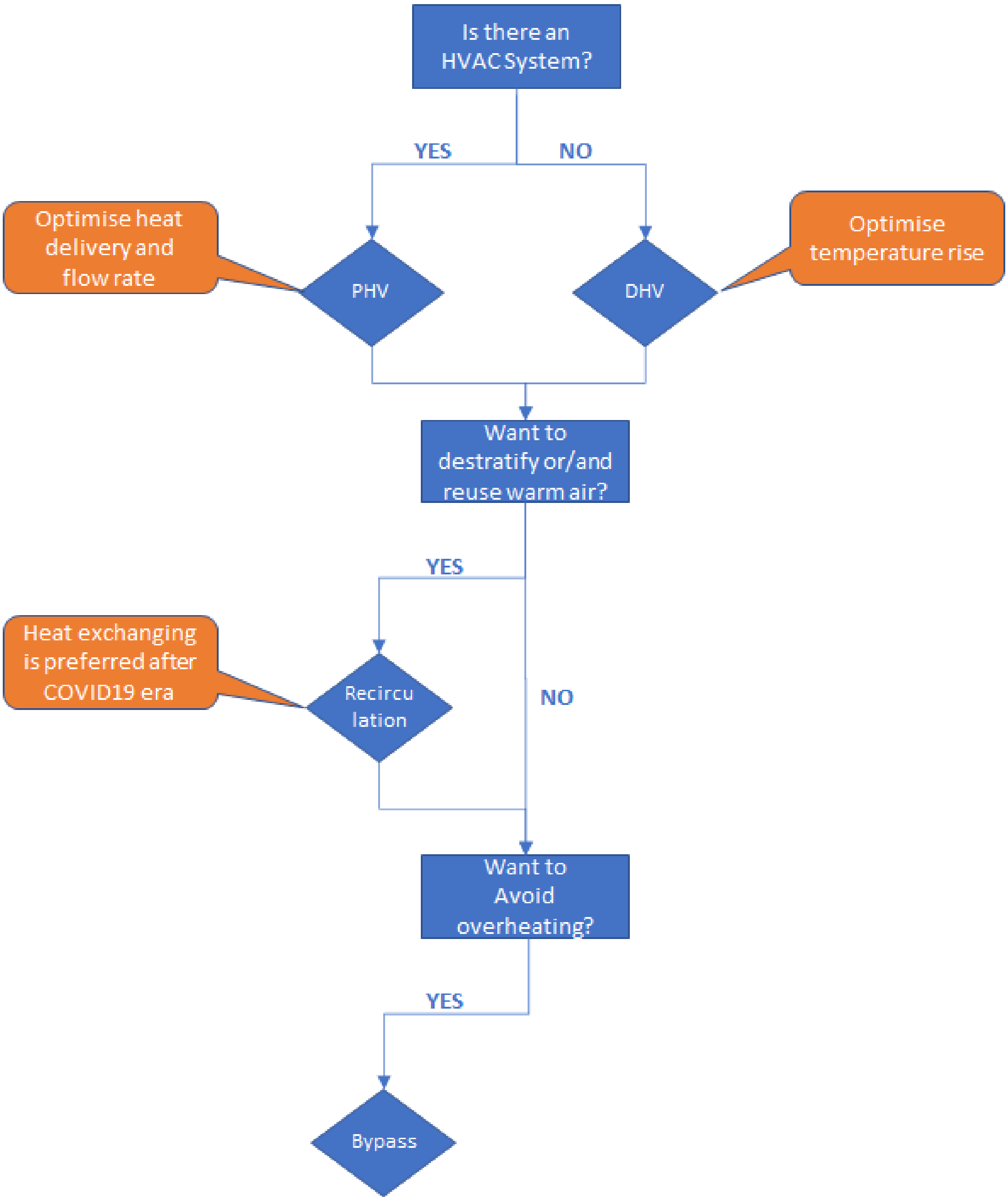


Figure 6-7 Decision-making flow chart for TSC variants selection, author.

There are some unique systems that can also be explored in conjunction with a TSC system. When an MVHR is used to provide mechanical ventilation, a TSC can assist in potential heat displacement (267). However, if the TSC delivers air temperature above room temperature (MVHR extracted air temperature), for optimal heat delivery, the heat exchanger of the MVHR should be bypassed, otherwise valuable TSC heat output will be exhausted. This mechanism is possible with modern MVHR systems as they include a heat exchanger bypass for summer mode; If TSC deliver heat that cause overheating, a separate TSC summer bypass damper and controls should take over. A decision-making flow chart that summarises the above can be seen in Figure

6-8. More details on controls will be discussed in the building integration section (8.1.3.2) and the application will be explored in section 9.1.3. Another interesting application would be for the TSC to feed an air to water/refrigerant ASHP. This is not a ventilation mechanism as the TSC would be used to create warm air which in turn contributes heat to a liquid refrigerant. The higher the air temperature that feeds the ASHP, the higher the COP (268) for most of the heat pumps. This has not been explored in the literature but is explored in this framework and the experimental case studies in SOLCER house where TSC feeds into an MVHR with an exhaust ASHP[11] and results will be presented in Chapter 9. A decision-making flow chart that summarises the the strategy when a TSC is integrated into an ASHP through an MVHR can be seen in Figure 6-8.

[11] An exhaust air source heat pump transfers heat from a ventilation system to warm air that heats a building, boosting the heat the MVHR unit extracts from the warm, stale air.

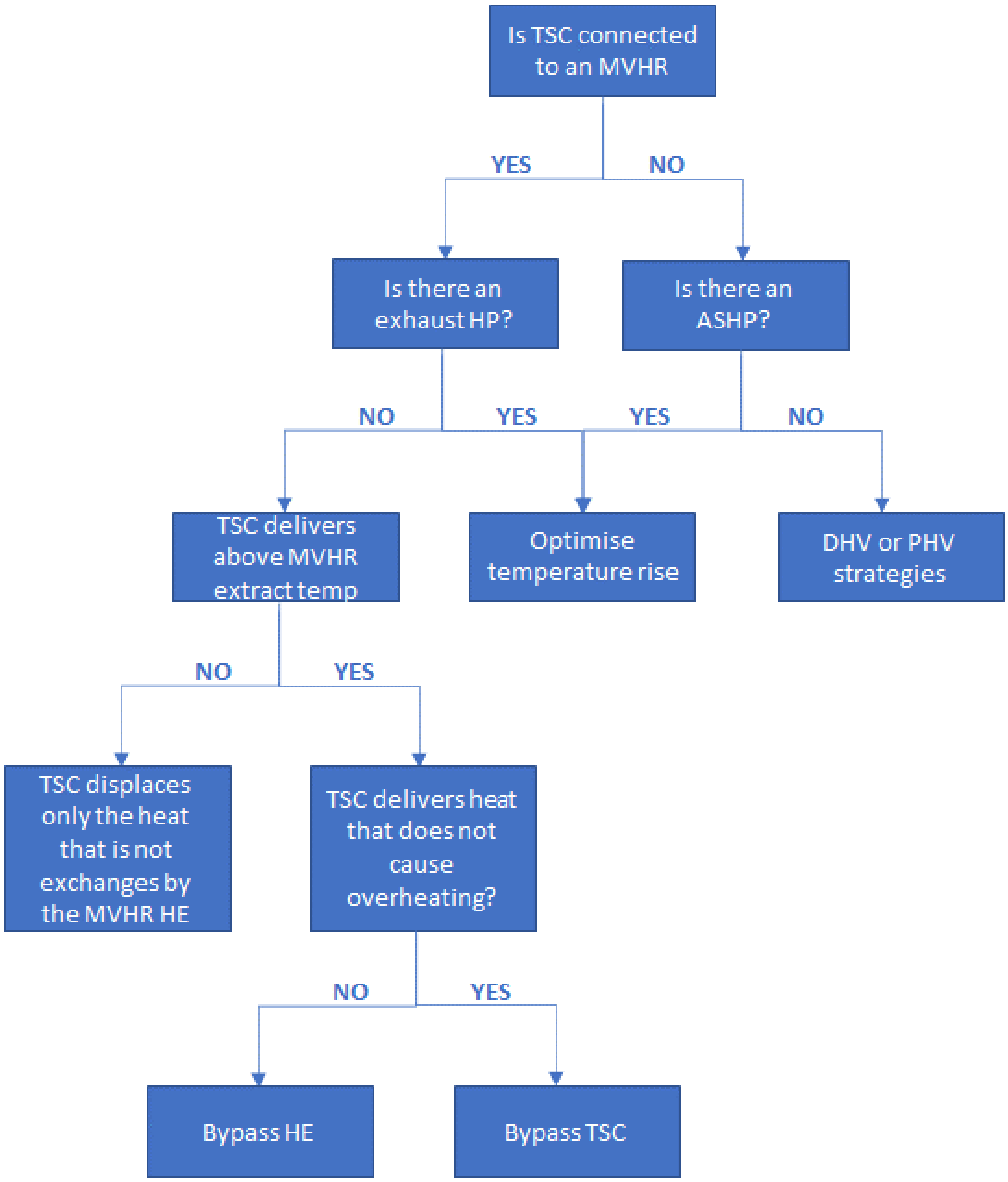


Figure 6-8 Decision-making flow chart for TSC connected to MVHR and HP, author

A summary of the collectors' parameters and associated references can be found in section 3.2.5. In terms of the geometry, the shorter the pitch and the hole diameter the better the efficiency and effectiveness. More recent installations have lower porosity (0.2%) to increase efficiency where earlier installations had higher porosity (1 to 2%) to reduce air pressure (friction). The circular hole is widely used as the best option amongst other typical shapes. Also, the triangular pitch arrangement is the most effective. This framework does not focus on collectors' parameters as manufacturers (should) have optimised the geometry but recommends that the designer knows the fundamentals summarised above and analysed in Chapter 3.

Three different profile types are available: the tongue and groove planks, the cassette panels and the profiled metal sheeting which is applied in most large installations (69). Examples of the profile types can be seen in Figure 6-9. Profiled sheeting are the least efficient; however, design and cost choices should also be considered. The predominant collector colour used in the literature case studies is black, while other dark colours such as anthracite and grey were also used as these have higher absorptivity. Lighter colours were used in demonstration projects such the TATA SBEC were special coatings would allow for relatively high absorptivity event at lighter colours. Such decisions should be discussed with the client in the early stage of design.

Figure 6-9. Examples of the three different types of metal cladding available for TSC (69).

According to an SBED study, colour, size, shape and proportion are the features that mostly affect aesthetics (238). In this study, a typical terraced British house example was used to investigate people's perception. The researchers (including the author) altered the front façade by using appropriate software and created colour, metal cladding profile shape and area alterations that can be seen in Figure 6-10,Figure 6-11Figure 6-12. Overall, 130 semi-structured interviews were conducted in Cardiff, UK. Black colour was preferred to the other two with comments relating the colour to familiar and beneficial solar renewable technologies. There was not any prevailing preference on the profiling shape as most participants were happy with all profiles presented. Most of the participants preferred the half facade integration as this gives an impression of a complete architectural element. It must be raised that the ground floor in the example does not allow for significant TSC area to be installed. The least favourable was the ¼ of the area to be integrated.

Figure 6-10 Images showing the TSC in three variations of the feature of colour. From left to right: black, brown, blue, SBED project including the author.

Figure 6-11 Images showing the TSC in three variations of the feature of cladding profiling shape. From left to right: profiled steel sheet, cassette panel, tongue and groove planks, SBED project including the author.

Figure 6-12 Images showing the TSC in three variations of elevation area. From left to right: whole façade, half façade, ¼ of façade, SBED project including the author.

6.1.2.3 Sizing, modelling and cost

The TSC area is an important parameter of the design with the reasoning behind the area selection driven by performance, aesthetics and cost. This study highlights that heating and ventilation needs and delivery flow rate of the TSC should be a priority in sizing. The proposed strategy is summarised as follows:

- When the TSC is selected as the mechanical ventilation of the building, it should serve the ventilation demand of the building according to the ventilation flow rate study; a lower flow rate would cause air quality issues in the building (e.g. increased moisture and high pollutant levels); a higher flow rate would cause increased heating demand and unwanted draughts.
- For a building designed to use natural ventilation, the TSC could deliver heat but also play a supplementary role and slightly over-pressurise to reduce infiltration (not recommended for domestic). A lower flow rate would cause the TSC impact to be overpowered by natural ventilation, whereas a higher flow rate would result to the increase of heating demand and unwanted draughts as well as damp walls.
- For DHV, the temperature rise should be optimised as a priority. Very low flows would cause turbulent phenomena within the cavity; whereas higher flows may increase efficiency; but temperature rise would decrease.
- For PDV, mass flow rate should be optimised as a priority. Low flow rates would not deliver enough preheated the air to the main heating system, whereas very high flow rates may impact performance as efficiency does not increase after a point.

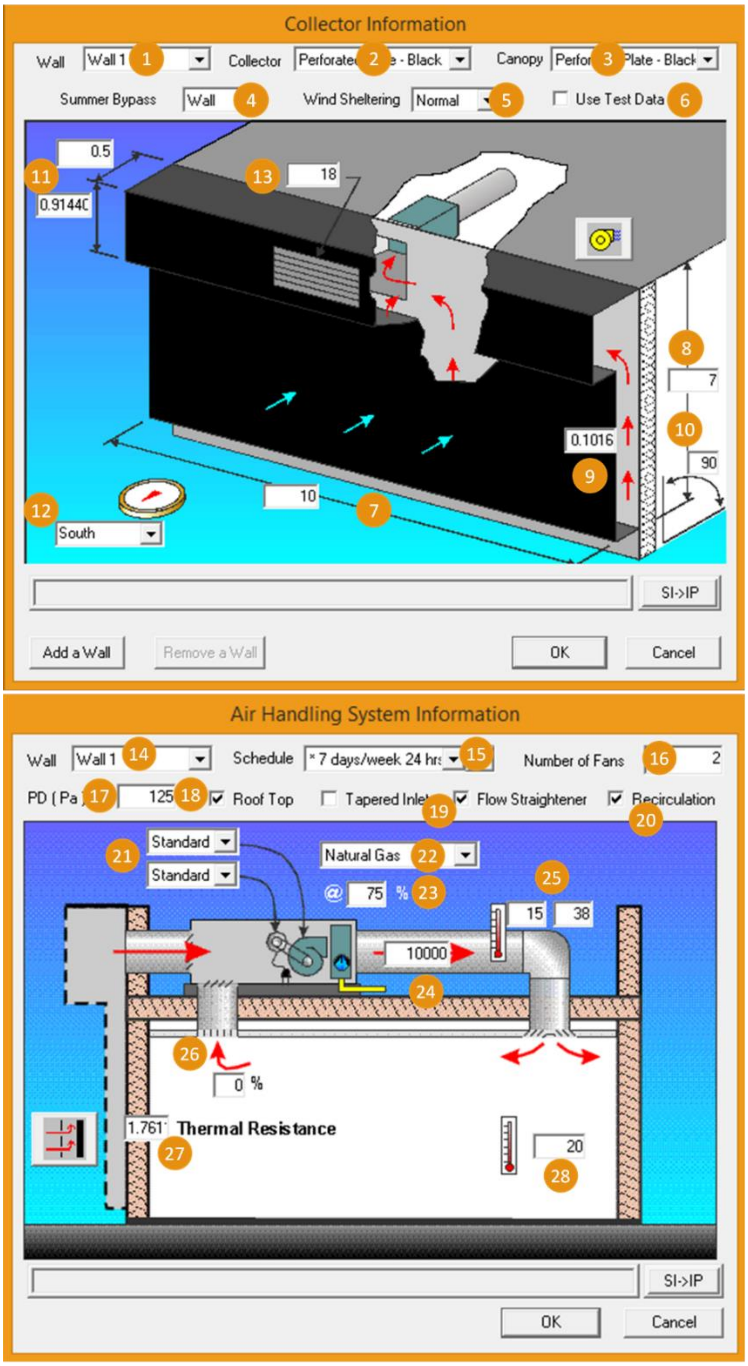
The determination of the TSC area is a compromise between temperature rise, efficiency, architectural considerations and cost. Thus, using modelling to simulate the above for different TSC areas increases the integrity of the decision. The fixed starting point is the pre-determined total ventilation flow rate and the variables would be the TSC area and the heat delivery.

SWIFT is the modelling tool selected to predict the heat delivery of the TSC for reasons analysed in 3.1.3 and 5.2.4. SWIFT requests the user to choose between (a) destratification and makeup air, (b) ventilation and air preheater and (c) process air heater applications. The first mode (a) refers to TSCs that are not connected to any heating systems and are used to de-stratify and/or re-use the air such as the DHV system. The second mode (b) is used for PHV TSCs that feed to an air heating system that also serve the ventilation needs. The third mode (c) simulates TSC systems used for drying processing which are not studied in this work. After mock testing it was found that the differences between the three modes were minor and refer to the configurability of the specific application.

The next parametrisation step is associated to the weather information input. The software allows the user to input monthly weather data for average solar radiation, temperature, relative humidity and wind speed. Both historic or monitored data can be inputted. Normalised monitoring data are suggested as a better fit; however, historic data can be used if it responds to the microclimate.

The next two parametrisation steps refer to the TSC panel and system where the user must input a variety of dimensional and operational parameters and clarify properties of materials and specifications of sub-systems. Figure 6-13 below shows the two graphical windows that assist the user to fill in the information needed. The software can accommodate up to 4 different TSCs simultaneously, with or without canopy and summer bypass damper controlled by an ambient air temperature thermostat. Swift software was designed for SolarWall, a company that used to own the TSC patent; thus, the default panel properties refer to thermal characteristics of the SolarWall panel (absorptivity, heat loss etc); however, the user can change the panel's properties according to the TSC manufacturer's specifications, which is recommended when other manufacturers are used. The last information requirements for the collector refer to the dimension, orientation and inclination where 90° is the standard value for wall installations and 0° for flat roofs; the values are adjustable.

The air handling system information pop up window includes the characteristics that refer to and affect the TSC as a system. The user sets the operation schedule, a configuration that allows great flexibility. The schedule can be set according to the ASHRAE 90.1 HVAC scheduling (269) for a variety of building types or/and according to a users' survey prior to design, allowing for ON/OFF configuration for three hourly slots, for each day of the week and fortnightly.



KEY

1. Select Wall to edit (up to 4)
2. Solarwall panel colour
3. Canopy colour
4. Summer bypass position
5. Wind exposure/protection
6. TSC panel properties
7. TSC collector length (m)
8. TSC collector height (m)
9. TSC cavity depth (m)
10. Inclination (0-90°)
11. Canopy dimensions (m)
12. Orientation (8 choices)
13. Sumer bypass temp (°C)
14. Select Wall to edit (up to 4)
15. Fan operating schedule
16. Number of fan systems
17. Ducting pressure drop (Pa)
18. AHU in/out envelope
19. Tapered inlet & straightener
20. Recirculation
21. Fan & motor efficiency
22. Fuel type
23. Fuel efficiency
24. Total mass flow rate (l/s)
25. Max/min supply temp (°C)
26. Recirculation mix (%)
27. Wall R value (m^2K/W)
28. Indoor temp (°C)

Figure 6-13 SWIFT software, screenshots collage from the inputs configuration pop-up windows for the TSC collector and air handling system information. The nomenclature is added by the author.

The software includes a cost feature where financial parameters of TSC investments can be entered in detail. Swift cost simulation feature is based on an investment for large industrial applications but can be adjusted for a variety of applications. As an alternative, literature (Chapter 4) and manufacturers' or installers' cost parameters can be used after the TSC area, design, variants and parameters are determined.

The results in Swift are shown in annual or monthly figures and include:

- Degree days with a base of 18°C (not adjustable)
- Solar incident radiation
- Solar incident radiation for system in operation
- Average day-time temperature rise
- Fresh air ventilation percentage
- TSC heat (solar collected)
- Heat recirculated through the back wall (insulation savings)
- Destratification Heat Savings
- Total savings (heat delivered/displaced)

The simulation results also include annual energy savings per m^2 of TSC and average systems' efficiency.

Also, the annual ventilation heating load for daytime and 24hr periods (i.e. including nighttime) is based on flow rate and weather data are presented in Swift modelling results accompanied by how much of this load was fulfilled by the TSC. However, heating simulations are based on HDD using the fixed baseline at 18°C which does not apply to the UK experimental case studies but may apply to other climates.

The ventilation rate is predetermined for each building according to methods discussed in section 7.2.1.3.1. This framework suggests that multiple SWIFT simulation runs are performed by increasing TSC size in order to generate air flow of approximately $120m^3/h$ per square meters as discussed in section 7.2.2.1. By keeping the ventilation rate constant, the heat delivery and temperature rise response can be observed. The sizing decision can then be based on determining the point that these two variants, heat delivery and temperature rise, reach a plateau such as in Figure 6-4 in correlation with TSC cost/m^2. Any payback projections should follow manufacturers' warranties. A sizing example using Swift runs is given in the corresponding results section (9.1.2.3).

6.1.3 Building Integration

6.1.3.1 Envelope integration

The TSC on the thermal envelope can recapture the heat losses of the fabric and recirculate the heat back into the space. TSC can be applied to both insulated and uninsulated fabric; however, a well insulated air tight whole building fabric will retain TSC supply heat for longer. If the TSC is installed together with external insulation, attaching the TSC supporting brackets before the insulation is the best practice to reduce cold bridges. TSC support system is an Ash-grid type spacer system that can be used for roofs and walls. The structural details should be included in the manufacturer's installer's method statement accompanied by necessary drawings. The type of brackets, bars screws, threads etc. is dependent on the TSC profile and the fabric material. Considering that 0.7mm thick sheet weights approximately 7kg/m^2, the attached bars and accompanied screws should be minimised to allow for uninterrupted flow through the holes and cavity. The installation of the wraparound flashing should ensure sealing and aesthetics homogeneity. Rainwater drainage should also be considered; this can be succeeded by creating little holes on the bottom of the sealing sheet as air leakage is not expected at the bottom due to fan drag and stack effect.

The plenum width was discussed in 3.2.1.3, where researchers find minor impact on TSC efficiency when changing the width. A decrease in plenum width would slightly increase the convective heat transfer, but would also require an increase of fan power to keep the suction the same (165, 182). Thus, the plenum width should be the maximum that does not affect a smooth flow. In the literature case studies (Chapter 4) the width was from 100mm to 250mm with most applications at around 200mm (4.3.1.2). The Göttingen Co-Generation Plant study suggested that a manifold on the top of a TSC can assist to gain a better uniformity especially at the upper corners of the panels (185). As suggested earlier in the envelope integration (7.1.3.1), in the UK, the system cannot protrude more than 200mm beyond the plane of the roof slope to avoid any planning permission complexity. TATA steel suggests a 200mm plenum width for the UK applications.

The ducting hole should be placed in the upper part of the cavity to minimize stack effect losses of the top part of the TSC. The width and shape should be dictated from the ducting width and shape. The diameter should allow for at least 25Pa pressure drop in the holes which is the minimum pressure drop in order to avoid flow reversals in the cavity. When a bypass damper is used, another ducting hole should be constructed away from the TSC and preferably on the north side to avoid direct sun.

6.1.3.2 Systems integration

For DHV TSCs, a ventilation system is not already in place and TSC is installed as a new ventilation system including ducting fan(s), damper(s), disc valve(s), filter(s), diffuser(s) and controls. If the building is designed for natural ventilation, then the TSC fan and insulated ducting system should ensure that over-pressurisation would equally reach all heated spaces which means that internal door cuts may be needed (136). If destratification is a priority, the ducting distribution system should be designed to homogeneously redistribute the heat and the recirculation/heat exchanger mechanism should be designed to effectively recapture the stacked ceiling heat. If the building is designed for balanced mechanical ventilation, then airtightness is a prerequisite and the ventilation system should include both supply of fresh air and extract of the polluted air. In dwellings and offices, the supply occurs in living spaces and the extracts in wet spaces as discussed in Chapter 2. When an MVHR is designed or installed, then the TSC will be connected to the system's inlet and the MVHR fan should consider the extra pressure drop of the TSC cavity and incoming duct friction. The integration of the TSC to an MVHR raises the following concern on the effectiveness of the combined system:

The MVHR by itself, would increase the incoming fresh air temperature through the extract heat exchanger. The temperature would be that of the wet room allowing for losses determined by the heat exchanger's efficiency. This means that a TSC which delivers up to the extracted temperature would only be doing work that the MVHR could do (Figure 6-8), delivering useful heat that the HE would not be able to deliver due to HE losses. The TSC delivery above MVHR extracted temperature is useful nt the heat exchanger should be bypassed otherwise will be exhausted 8.1.2.2, otherwise the TSC heat will be exhausted. This is not a problem when exhausted heat is used, for example when the heat is stored, or the exhaust is connected through an evaporator to an exhaust air-to-air heat pump (Figure 6-14).

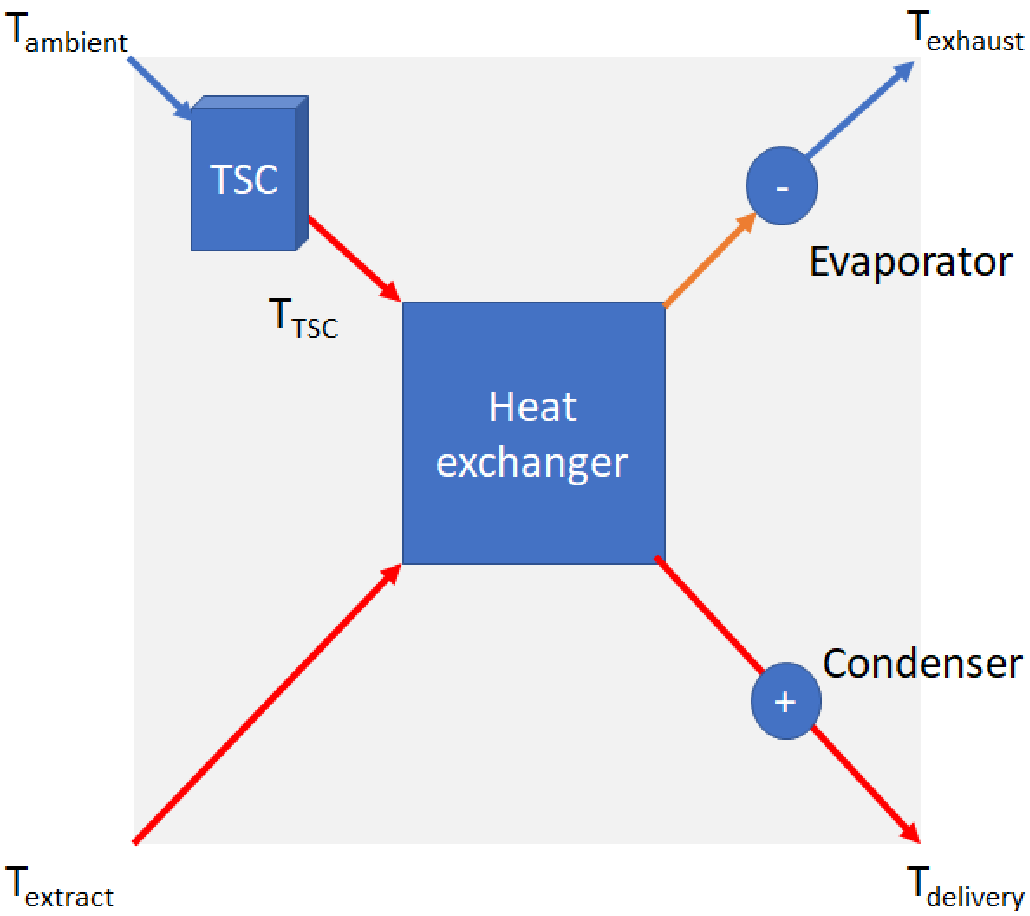


Figure 6-14 TSC with MVHR and exhaust heat pump, author.

For the PHV systems, the TSC feeds into the fresh air inlet of the HVAC, and additional fan power may be required to overcome the extra pressure drop that the TSC may cause. A spatial challenge arises when the inlet of the HVAC is not close to the TSC output. This should be considered in the feasibility stage when integration position is selected.

TSC ducting exchanges heat with the surrounding environment. This means that it can work as a heat recapturer if the surrounding air temperature is higher to the TSC delivery temperature, or it can lose heat when the TSC delivery temperature is higher to the surrounding. For this reason, the TSC ducting should be insulated especially when running externally, or in unheated spaces. Also, the bypass ducting is suggested to be insulated to minimise unwanted recapturing.

6.1.3.3 Controls

The TSCs delivered air temperature (Figure 6-15) can be directly affected by auxiliary heating items such as resistive heater, gas heater etc. Otherwise, it can be influenced by controlling the volume flow rate and air source. The volume flow rate is controlled by the fan speed (F) and the air source by the duct dampers D(i) position. The fan speed is usually expressed in fan power and the damper position is usually expressed in open-close percentage where 0% is closed and 100% is completely open. The number of dampers typically corresponds to the number of potential inputs including TSC(s), recirculation(s) and bypass(es). The control input is usually an algorithm containing a planned seasonal or daily scheduling (S) and temperature inputs (T(i)). These temperature inputs are typically the ambient, delivery, room and TSC temperature or a mathematical combination of these such as “temperature rise”. The temperatures feed the algorithm continuously or at an interval. The algorithm may contain timing delay to avoid damper(s) and fan short cycling state to protect the mechanical equipment from coming on/off too quickly. Scheduling and ambient temperature are not affected by the system whereas all the other parameters are.

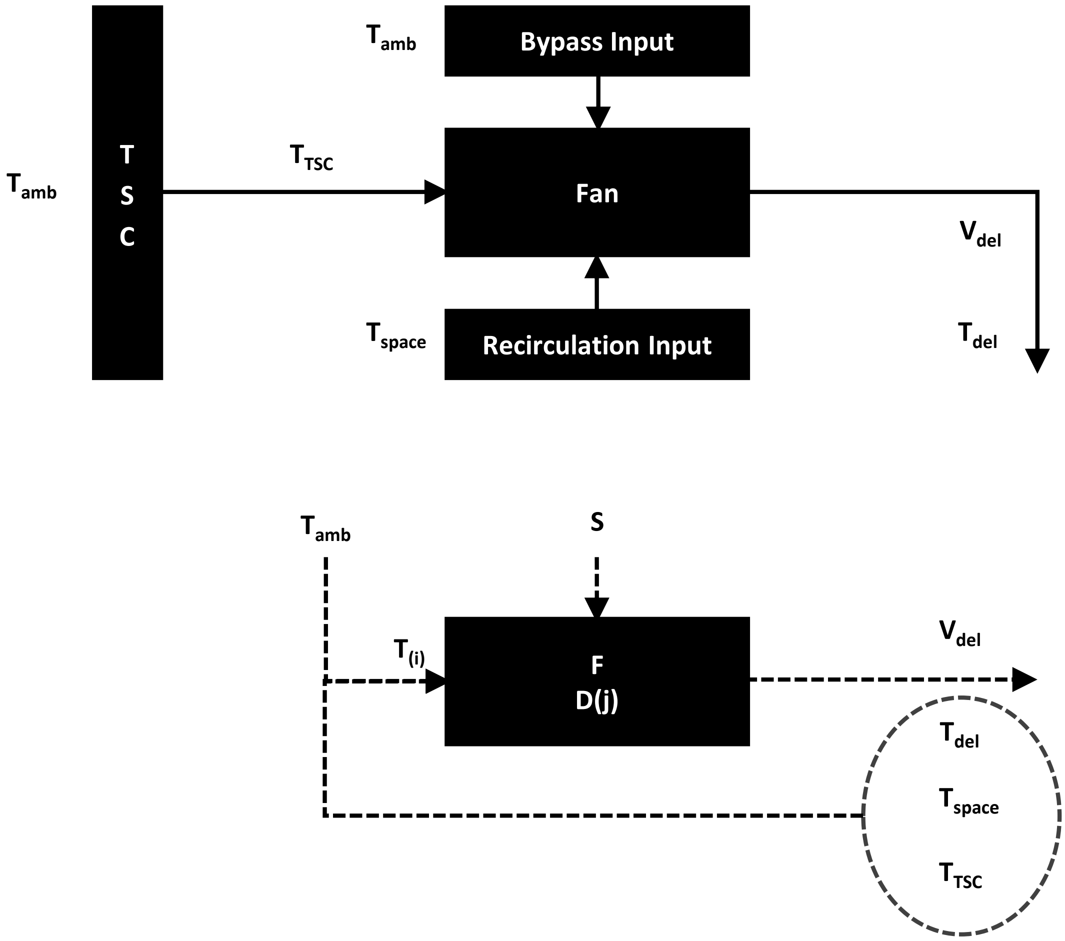


Figure 6-15 Typical TSC system (top) and control (bottom) diagram, author.

Another challenge for the control mechanism is to protect the indoor space against non-beneficial (i.e. too cold) air delivery. A triggering mechanism that guarantees starting of beneficial delivery should be considered. This can be done by using TSC surface (skin) temperature sensors which would sense the solar irradiation. Ambient, space and set point temperature conditions should be considered to assure that heating is needed. Also, ducting losses or gains as well as surface heat loss through ventilation convection should be considered when selecting the triggering surface (skin) temperature. The critical temperature can be adjusted and optimised during commissioning but experience on site has shown that $T_{coll} > T_{space} + 2^{\circ}C$ is a good starting point. When flow is settled, the algorithm can then refer to TSC delivery temperature rather than skin temperature.

The algorithm should respond to the design integration parameters discussed previously in this Chapter and especially strategy (Figure 6-5), TSC variants (Figure 6-6) and decision making (Figure 6-7). For complex systems that include mixed scheduling and demand control, multiple algorithms may be designed for different operations (drivers) such as “space temperature”, destratification mode”, “night-time purge” etc.

As the TSC is a metal cladding system, the manufacturers and installers may not be competent on M&E automations, which means that the project manager should discuss the desired outputs with the client and then communicate it with specialists to design and deliver the TSC controls. The output strategy should be presented in a “description of operation” guide including the controls requirements and system explanation.

6.1.4 Commissioning and Optimisation

The primary goal of the commissioning of any system is to ensure that it works as designed. This may include testing, optimising, verifying and documenting that the owner gets the building system they procured and that they are operating it in accordance to real life scenarios. There is no complete guidance on TSC commissioning; however, parts of building regulations, guides and codes of practice can be used to ensure satisfactory operation. After this process (including any adjustments required), a handover document should be delivered to the client including all details needed for the system to operate and be maintained safely and effectively.

6.1.4.1 Testing and commissioning adjustments

As there is no specific guidance for commissioning a TSC, a combination of documents should be used. ISO 9806:2017 specifies test methods for assessing the durability, reliability, safety and thermal performance of fluid heating solar collectors. The test methods are applicable for laboratory testing and for in situ testing (270). Similarly, BS EN12975:2022 is applicable to all types of fluid heating solar collectors. This document specifies performance requirements for fluid heating solar collectors with respect to durability, reliability, safety and thermal performance (271). The above standards suggest a series of tests and inspections but are focused on lab tests and wet systems whereas air solar heaters have some particularities.

This framework suggests that in addition to structural and mechanical durability tests, the commissioning manager should run two additional set of tests. The first refer to the fundamental performance characteristics and the other to the controls' response. Testing the controls requires the creation of thermal conditions to activate the control scenarios and verify that dampers and fan power (volume flow rates) work according to the design. In terms of performance, the TSC should deliver heat according to the heat transfer equations analysed in Chapter 3. The main variables to test are the volume flow rate and the temperature rise expected for the corresponding flow rate and radiation conditions. The volume flow rate can be tested by the use of balometer devices or velocity instruments and cross sectional area measurements according to Building Regulations F (122). The temperature rise for a given flow rate and solar radiation can be tested by using thermometers and pyranometers against manufacturers performance characteristics. The prerequisite for the above testing is to ensure steady external conditions and solar radiation measurement in plane with the TSC. More information on the instrumentation and testing can be found in 6.2.2.

6.1.4.2 Long term commissioning and optimisation

The tests on control response and heat delivery mentioned in the commissioning are processes that may require a long time to assess. It is challenging to create all the weather and indoor conditions required for testing within a few hours or days. For this reason, and if the budget allows, this framework suggests long term monitoring to ensure good performance and control response under all design scenarios. More information about this process can be found in Appendix IV.

The output of the long-term commissioning could be to adjust the controllers or algorithms or fix problems regarding installation, insulation, sealing etc. Also, modelling calibration may be needed if a systematic deviation occurs that was not predicted in the design phase. This optimisation process may be iterative as re-evaluation of changes is suggested. In fact, if possible, re-evaluation should occur after each change to enumerate impact of each optimisation action. The above procedure is minimised when design stage is effective. In any case, long term monitoring for optimisation purpose should be costed and discussed with the client in advance.

6.1.4.3 Handover

The list below contains the handover information considered important after discussions between the author, contractors and clients.

A. **Scope of works:** This may include a short description of works carried out by contractors and subcontractors accompanied by the site and building info, design intent and timeline.
B. **Inventory of components and suppliers:** This may include lists of material, products, equipment, software, etc., accompanied by manufacturers, suppliers and sub-contractors' names and contact details.
C. **Instructions**: This may include all the information needed for the client to understand and operate the system and its functions including error solving index.
D. **Maintenance guide:** This may include all the information needed to maintain and clean the system (including all its parts) to ensure that the system remains under warranty.
E. **Commissioning data:** This may include all the in-situ testing described in the previous sections as well as related lab and compliance certificates for the TSC components.
F. **Life cycle information**: This may include recycling and disposal instructions for all the components used and further information about the life cycle assessment and embodied carbon.
G. **Design and "as built" drawings**: This may include graphical representation of the site, building, system, M&E. Also, a nomenclature relating the inventory to the drawings as well as fundamental sizing parameters (volume flow rate) is suggested.
H. **Warranties:** This may include whole system warranty as well as components' warranties accompanied by contact information.
I. **Appendix:** This may include information about the process such as modelling results, photographic evidence as well as specifications and manuals of individual components.

6.2 TSC Performance Evaluation

Monitoring can assist in the design stage especially when assessing site weather data evaluating the existing building and its systems. Performance evaluation of TSC through monitoring is the most pragmatic assessment of a system in operation. The monitoring results aim to show how a specific system works when used by specific occupants and circumstances for a duration of time. Monitoring can be used as an evaluation tool to quantify performance indicators such as the real TSC space heating delivered or as a diagnostic tool to understand if the system works as designed in the long run and assist in optimisation process within the commissioning. In Figure 6-16 a Performance Evaluation section is shown in detail based on the overall Design and Evaluation framework (Figure 6-1). Four stages on performance indicators, instrumentation, data processing and data analysis with each subsection are shown in Figure 6-16 and will form the content of sections 6.2.1-6.2.4.

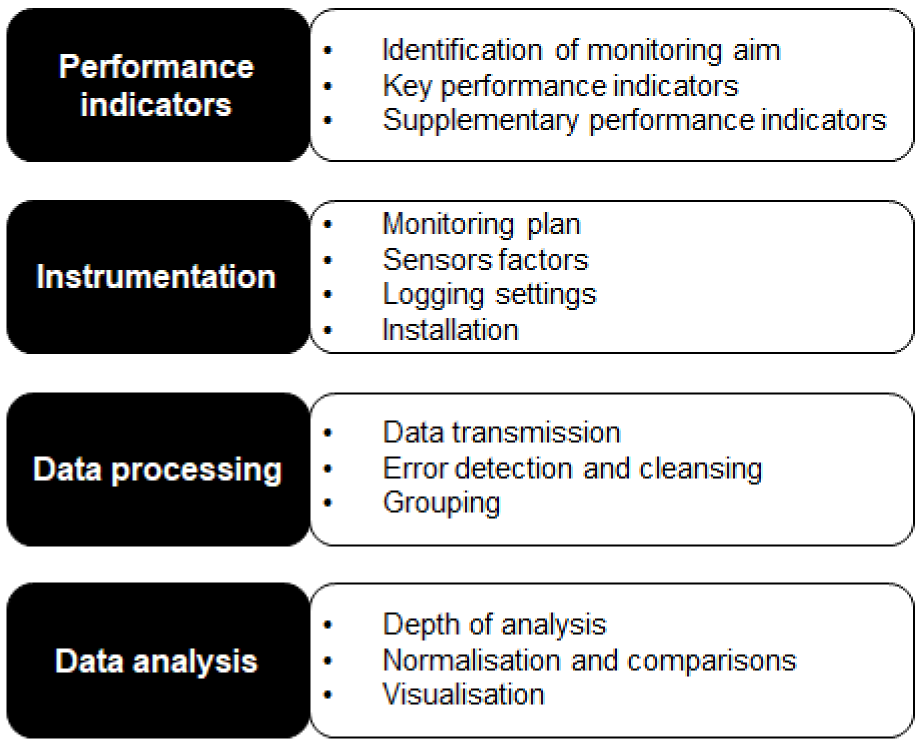


Figure 6-16 Stages for TSC Performance Evaluation, author.

6.2.1 Performance indicators

6.2.1.1 Identification of monitoring aim

Monitoring is the quantification of real time performance and can be a costly process. The following is a list of reason that TSC performance evaluation ca by purposeful.

A. Take informed decisions in the design stage: data gathering and monitoring assists the feasibility study in order to decide if TSC is an applicable and cost-effective technology take informed decisions in the integration stage. Relevant monitoring processes were discussed in 8.1.1 and 8.1.2 and instrumentation will be specified and analysed in the instrumentation section in 8.2.2.

B. Part of the controls for maintenance and diagnostics: such monitoring is a prerequisite for successful operation of the system and was described in the controls (8.1.3.3) and commissioning (8.1.4) sections. Applications of this process can be found in the corresponding results sections in 9.1.3.3 and 9.1.4.

C. Client/Public awareness: It is well understood that data visualisation of renewable generation benefits people's awareness and perception of renewables (272, 273). The aim in such process could be to present seasonal or real time data of "free" renewable energy using monitoring tools. For public authority buildings over 250m^2 the Display Energy Certificates (DEC) is mandatory and includes monitored renewable energy generation and CO_2 displacement.

D. Request from funding or assessment body: There are governmental schemes that require monitoring of heating delivery such as the RHI (does not include TSC) or environmental awards and certificates that require monitored quantification of energy and CO_2 reductions and renewables generation.

E. Post-intervention research and optimisation: Technologies such as TSC with little real life performance evaluation information require monitoring to assess and optimise the technology. The assessment may include the comparison between key and supplementary performance indicators against pre intervention performance, against modelling, against benchmarks and against similar/other technologies. An effective assessment for a significant duration (minimum one heating season) would provide information on the effectiveness of the system and potential optimisation adjustments to be considered in the long-term commissioning of future installations (indicated in 8.1.4).

It is challenging to justify the necessity and to quantify the depth of the monitoring process. In this work, monitoring relating to the feasibility is considered a prerequisite for design and should be costed. This may indicate that bespoke solo applications in domestic scale are not viable as the time and instruments to collect the data is significant. It was estimated that the cost for a feasibility study is a minimum of £500. This study focus is on the first and last purpose as monitoring is suggested as a design and evaluation tool. However, the performance indicators analysed below would cover the full range of monitoring aims reviewed above. The monitoring needs are determined by establishing the performance indicators and back-engineer the equations and variants needed to be monitored.

6.2.1.2 Key performance indicators

The fundamental performance indicator is the useful heat delivery. Usefulness is defined as the energy derived when both ventilation and comfort targets are fulfilled. The usefulness should be guaranteed by the controls analysed in 6.1.3.3; however, when evaluating the controls effectiveness, a closer look to the heat delivery against comfort, scheduling and other services providing heat or/and ventilation may need to be considered. Useful heating displaces heat that another heating device delivers or should deliver. “Should deliver” claim is based on the needs and principles on comfort and heating demand analysed in the feasibility in the design phase (6.1.1). The study also examines the impact of the TSC to other systems; for this reason, the performance of supplementary systems connected to the TSC such as MVHR units or heat pumps should also be evaluated.

Q_{TSC} represents the heat delivery (W) of the TSC system. As discussed in the literature in 3.1.2 this is calculated by the fundamental heat transfer equation (Equation 6-4):

$$Q_{TSC} = \dot{m} C_p T_{rise} \qquad \textit{Equation 6-4}$$

Where Q_{TSC} is the heat delivered by the TSC (W)

$\dot{m}$ is the delivery air mass flow rate (kg/s)

C_p is the specific heat of air in the delivery duct (kJ/Kg.K) and

T_{rise} is the air temperature rise (K)

The specific heat capacity of air is influenced by moisture content and temperature. Using standard equations from the ideal gas law, estimates for specific heat capacity were made utilising relative humidity and temperature data. Calculations suggested that the range of variation under typical TSC temperature and humidity for the UK might be between 1.007 to 1.048 kJ/kg.K, which agree with CIBSE published data (2, 202).

Temperature rise is defined by (Equation 6-5):

$$T_{rise} = T_{TSC} - T_{amb} \qquad \textit{Equation 6-5}$$

Where T_{rise} is the air temperature rise because of the TSC in K

T_{TSC} is the TSC output temperature in the delivery duct in K and

T_{amb} is the ambient air temperature in K.

The air mass flow rate in a duct could be calculated by measuring the air volume flow rate in the duct for a known density (Equation 6-6):

$$\dot{m} = \rho \, \dot{V} \quad \text{Equation 6-6}$$

Where $\dot{V}$ is the air delivery volume flow rate in m^3/s and

ρ is the density of the delivered air in kg/m^3

The air density is related to humidity, temperature and atmospheric pressure. For sea level at (1 atm or 101.325 kPa) and dry air the ρ varies from 1.292 kg/m^3 for 0°C to 1.127 kg/m^3 for 35°C. An approximation can be taken for 20°C at 1.2kg/m^3. However, if the air is very humid, the density decreases. A diagram that combines both temperature and moisture impact on density refer to the standard conditions' density at 20°C for dry air is shown in Figure 6-17. For 100% humid air at 40°C. The density drop is approximately 8% where 4% is caused by temperature rise and 4% by moist air rise.

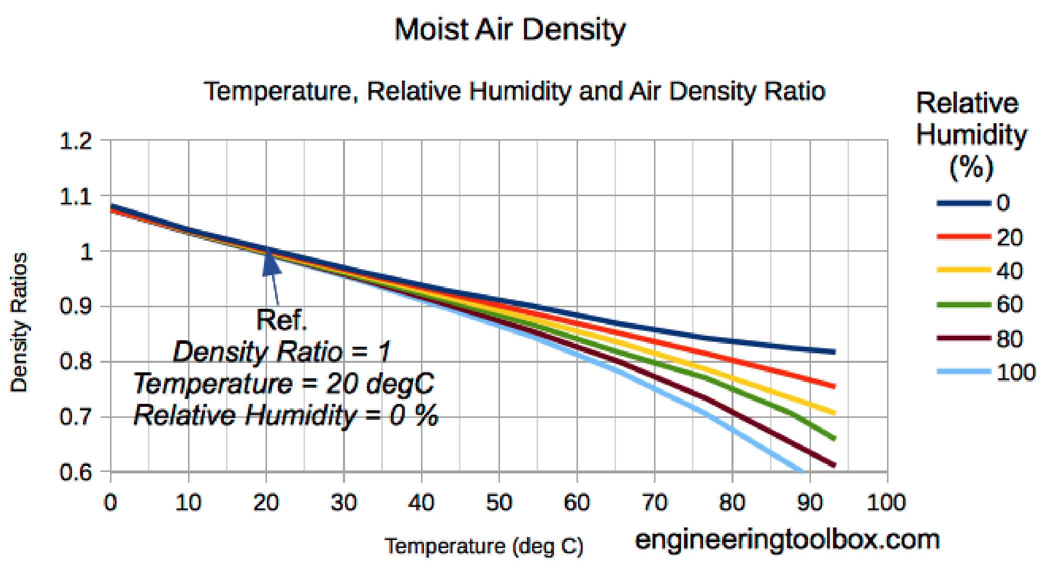


Figure 6-17 Temperature and relative humidity impact to air density (274).

If the ducts do not allow for $\dot{V}$ measurements, air velocity in the delivery duct of known diameter could be measured instead (Equation 6-7):

$$\dot{V} = \beta u_d A_d$$ **Equation 6-7**

Where β is the duct velocity coefficient (used to convert the centreline to average velocity)

u_d is the centreline averaged delivery duct air velocity in m/s

A_d is the internal cross-sectional area of the delivery ducting in m^2

Air velocity could be challenging to measure at one cross-sectional point thus an alternative is to measure dynamic velocity due to dynamic pressure at multiple cross-sectional points, more information about this will be provided in the instrumentation section (6.2.2). The air velocity is related to the dynamic pressure average by the following equation (Equation 6-8):

$$u_d = \sqrt{\frac{2q}{\rho}}$$ **Equation 6-8**

Where q is the averaged dynamic pressure which is the difference between the total pressure and static pressure that a pressure tube or grid would sense when facing the flow.

When the predetermined demand volume flow rate requires multiple flow levels (boost modes) or scheduling, the delivery flow rate averages should be assessed corresponding to the demand.

TSC do not work well with heat exchangers as they complete in rising the ambient temperature as noted in Chapter 4 and especially in Hastings. This is in principle right but as proven in author's work on TSC and MVHRs (267) and discussed warlier in this study (8.1.3.2), there are some cases that the TSC can work with a heat exchanger. In Figure 6-14, a typical MVHR is presented in version A where the ambient air will be heated through the extracted air resulting to increased delivery temperature and decreased exhaust temperature. The efficiency of the heat exchanger is related to the delivered, ambient and extracted temperature as shown in Equation 6-9 below:

$$\eta_{XE} = \frac{T_{del} - T_{amb}}{T_{ext} - T_{amb}}$$ **Equation 6-9**

Where η_{XE} is the heat exchanger efficiency

T_{del} is the heat exchanger delivered temperature (K)

T_{amb} is the ambient temperature (K)

T_{ext} is the extracted from the wet spaces temperature (K)

When a TSC is added to a heat exchanger (version B) Figure 6-18, the temperature rise of the TSC jeopardises the work of the heat exchanger. There are though, two additional benefits:

- The first is that up to the HE extract temperature the TSC would make up for the HE losses, meaning that for a 76% efficient HE, the TSC can offer the remaining 24%.
- The second is that for higher than extracted temperature, the TSC would provide useful heat providing that this heat is useful ($T_{space}<T_{thermostat}$) and the heat exchanger will be bypassed so that the extra TSC heat will not be exhausted.

Also, when the evaporator of an exhaust heat pump is added to the HE exhaust as seen in version C, Figure 6-18, the TSC addition is always beneficial as any extra heat from the TSC will be absorbed by the heat pump providing that the heat pump heat is useful through space heating, hot water or storage.

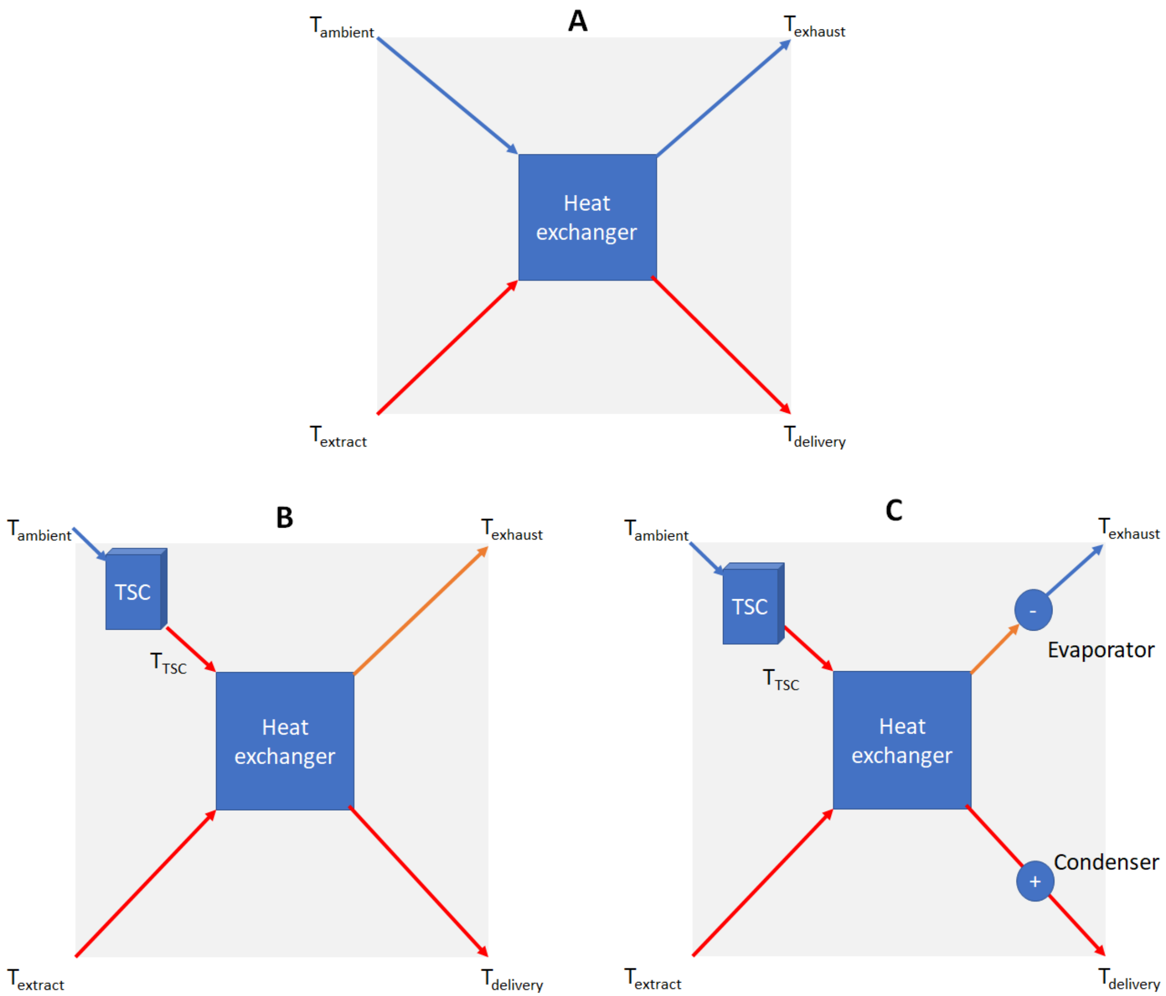


Figure 6-18 MVHR (A), MVHR with TSC (B) and MVHR with TSC and Exhaust HP (C), author

According to the above, the TSC delivery in version heat is always useful where there is a demand; however, the TSC in version B is only useful when it does not displace the heat that the HE would provide; in other words (see Equation 6-10 and Equation 6-11 below):

$$Q'_{TSC} == \begin{cases} Q_{TSC}(\eta_{XE} - 1), for\ T_{TSC} \leq T_{ext} \\ Q_{TSC<ext}(\eta_{XE} - 1) + Q_{TSC>ext}, for\ T_{TSC} > T_{ext} \end{cases} \quad \textbf{Equation 6-10}$$

$$Q'_{TSC} = \begin{cases} \dot{m}C_p(T_{TSC} - T_{amb})(\eta_{XE} - 1), for\ T_{TSC} \leq T_{ext} \\ \dot{m}C_p(T_{ext} - T_{amb})(\eta_{XE} - 1) + \dot{m}C_p(T_{TSC} - T_{ext}), for\ T_{TSC} > T_{ext} \end{cases}$$

Equation 6-11

Where Q'_{TSC} is the useful TSC heat when connected to a HE (W)

$Q_{TSC<ext}$ is the TSC heat, at for delivery temperature ≤ extract temperature (W)

$Q_{TSC>ext}$ is the TSC heat, at for delivery temperature > extract temperature (W)

With regards to the fan power contribution to savings, If the TSC is used in a building designed for natural ventilation, the TSC delivery would prevent infiltration, thus the fan power consumption should be subtracted from the heat delivery. The equation assumes that the TSC delivery is useful as defined in 6.1.2.1. When a TSC is replacing a ventilation system or is added to an existing one, the extra fan power needed to run the TSC is minimal and may be subtracted (Equation 6-12). This is because the extra pressure drop in the cavity is minimal and also, the presence of the TSC cavity minimises turbulence that would affect fan performance if no TSC was installed. To increase accuracy of the results the extra fan power can be measured or modelled based on the TSC cavity pressure drop and flow rate.

$$Q_{savings} = Q_{TSC} \begin{cases} Q_{TSC} - P_{fan}, & if\ natural\ ventilation \\ Q_{TSC} - P_{fan\ extra}, & if\ mechanical\ ventilation \end{cases} \quad \textbf{Equation 6-12}$$

Where $Q_{savings}$ is the total savings from the TSC in W

P_{fan} is the power consumption of the TSC fan in W

$P_{fan\ extra}$ is the extra power that the ventilation system to run a TSC in W

The power savings can be converted to energy savings for the duration that the corresponding equation conditions are the same. For example, Recirculation heat delivery (power) can be converted to energy for the time of the delivery provided that the power would be averaged for every hour and summed.

Cost savings have already been discussed in the design section (6.1.1.4 and 6.1.2.3). To consider TSC operational cost savings the potential money spent on energy to deliver equal amount of heat by a conventional or different system must be calculated, e.g. the gas spent to deliver space heating. Similarly, the payback time needs to be correlated to the fuel cost. The TSC payback time should include design, manufacturing, installation, commissioning and maintenance. It should also include fan energy spent depending on the TSC use.

Similarly to cost savings, CO_2 operational savings should include potential energy spent to deliver equal amount of heat by a conventional or different system. Embodied carbon should include the whole LCA stages: product, construction, use, end of life. An analysis of the Colorcoat Prisma pre-finished steel used for TSC by TATA steel can be seen in the product's environmental declaration based on EN15804 and ISO 14025 (275).

6.2.1.3 Supplementary performance indicators

The TSC savings are not only coming from the solar power absorbed by the collector. Other gains such as recirculation – destratification, summer bypass cooling, night-time cooling, and heat recapture through the duct and cavity gains could also be calculated.

The destratification benefit can be calculated based on Equation 6-13 below when only the recirculation damper is ON. The delivered temperature would equal the recirculation temperature assuming for zero fan and duct heat losses/gains.

$$Q_{rec} = \dot{m}C_p\left(T_{rec} - T_{space\ low}\right) \qquad \textit{Equation 6-13}$$

Where Q_{rec} is the TSC system recirculation or the destratification savings (W)

T_{rec} is the temperature re-entering the system from the recirculation damper (K)

T_{space_low} is the temperature in the delivered living space (K)

The cooling benefit can be calculated based on Equation 6-14 below when there is a need for summer bypass (bypass damper ON) or night-time purge. The delivered temperature would equal the ambient, but again, this is subject to fan and duct heat losses/gains. During night-time purge, the summer bypass purge is coming from the panel, meaning that the delivered temperature would equal the ambient assuming for zero fan and duct heat losses/gains and panel night convection and wall recapturing losses/gains.

$$Q_{cooling} = \dot{m}C_p\left(T_{space} - T_{amb}\right) \quad \text{Equation 6-14}$$

Where $Q_{cooling}$ is the TSC system cooling savings in summer bypass or night purge mode (W)

T_{space} is the temperature of the indoor space (K)

The ducts heat recapturing can by calculated based on Equation 6-15 below. The equation assumes zero fan losses. The duct contribution could be gains or losses for the system depending on the air temperature in the ducts and the air temperature around the ducts.

$$Q_{ducts} = \dot{m}C_p(T_{del} - T_{TSC}) \quad \text{Equation 6-15}$$

Where Q_{ductsl} is the TSC heat recaptured through the ducts (W)

The conductive heat losses of the wall behind the TSC are recirculated through the fan. This equation applies for zero TSC panel delivery, meaning that should applied for zero irradiation. This can be calculated based on Equation 6-16 below:

$$Q_{wall} = U_w\, A(T_{TSC} - T_{amb}) \quad \text{Equation 6-16}$$

Where Q_{wall} is the TSC heat recaptured from the back wall through the cavity (W)

U_w is the U value of the wall behind the TSC (W/m^2K)

A is the area of the wall in (m^2)

The above savings could be also costed and considered as a percentage of the total TSC savings.

There are two essential equations that describe the performance of the TSC which were firstly used in studies by Kutscher (154-156) and discussed in 3.1.2. The TSC effectiveness (ε_{HX}) and efficiency (η) are shown below (Equation 6-17 and Equation 6-18):

$$\varepsilon_{HX} = \frac{T_{rise}}{T_{coll} - T_{amb}} \quad \text{Equation 6-17}$$

Where ε_{HX} is the TSC heat exchange effectiveness.

T_{coll} is the skin temperature of the collector (K)

$$\eta = \frac{Q_{TSC}}{\mathrm{I}A_p} \quad \text{Equation 6-18}$$

Where η is the instantaneous efficiency of the TSC

I is the incident radiation (W)

A_p is the TSC projected area in m^2 calculated from the flat surface dimensions.

The efficiency equation is more inclusive than the effectiveness as it describes the performance of the TSC as a system to absorb, exchange and transfer heat into the building. The effectiveness equation describes the exchange and transfer only by comparing the collector's temperature to the delivered. Efficiency equation can be studied versus other dynamic parameters to show how a real-life TSC responds to these parameters. When calculating efficiency, a filtering process may be needed to exclude calculations for very small radiations that can be measured before sunrise. Cale et al. (185) suggests calculations above $75 W/m^2$.

The challenge in applying heat transfer equations is that the system has an inertia; for example, a change in irradiation will not impact temperature delivered instantaneously. There are two solutions suggested in this framework to minimise this effect. The first is by averaging the values so that the changes in time would be normalised. The second is to time the real-life inertia and include a corresponding delay in the data analysis stage. Both of those options can be used in the optimisation during commissioning.

The contribution of the TSC to comfort is another crucial area to be evaluated. The TSC may impact temperature, humidity, CO_2 and other pollutants indoors. Especially if not driven by an existing HVAC system, the TSC is expected to change the buildings comfort. With the right controls the TSC should stabilise temperature and humidity around desirable healthy targets set in the design stage and minimise polluted air. If poor controls are installed, the TSC may create unwanted cold drafts or overheating. It can also create high humidity or damp if the air is not extracted from airtight buildings. Also, it may burden the air with extra pollutants when installed in polluted areas and filters are inadequate, exhausted or not installed. The indicator related to comfort could be an average value within a timeframe accompanied with statistics such as min, max, st. dev., etc., or a percentage of time that the indicator falls into a comfort range. Another indicator could be the mathematic correlation of a parameter to a comfort indicator, e.g. space temperature vs solar irradiation through a graph and/or a regression equation.

Other, more special indicators could refer to individual performance of some parts of the TSCs such as the cavity. Again, temperature variations and their relations to other parameters such as wind could be of an interest. A study on TSC cavity temperature variation would show the thermal distribution in the cavity; this is important when investigating different TSC shapes in real life (202).

Also, another indicator to understand TSCs contribution to a retrofit scheme is to evaluate its performance in comparison to other retrofitted systems or interventions. This may include a heat delivery or reduction contribution quantification of each system and its corresponding cost or payback time. More on comparisons will follow in section 6.2.4.2.

6.2.2 Instrumentation

Monitoring demands an instrumentation mechanism appropriate for real life buildings. The solution to this requirement has evolved as an outcome in this work due to the lack of an established methodological approach at the start. The problem was approached in the following steps:

- How to break down the equations into measurable quantities and design a monitoring plan
- How to identify appropriate instrumentation including sensing
- How to choose and set appropriate logging devices.

The monitoring strategies were tested on the Bute roof rig before being refined on live projects. The instrumentation applies in both pre-installation (design) stage, commissioning and post-installation (evaluation) stage.

6.2.2.1 Monitoring Plan

Monitoring strategies and instrumentation can by summarised and visualised in a monitoring plan which shows the position of the instruments on the system. Such a plan facilitates both the organisation of the monitoring tasks as well the communication of the monitoring works and inventory with the stakeholders.

Dimensional information is important in all stages. Photography can assist in measuring distance, angles and orientation. This can happen through geographical photography such as Google maps or through digital twins' photogrammetry with tools such as Matterport. On site, orientation can be identified with compasses and dimensional measurements can be taken through meter tapes or ultrasound and laser measures.

A weather station is a fundamental part of the evaluation stage and can also assist in the design stage including commissioning. The fundamental sensor required is the **ambient air temperature** sensor as it is included in the heat transfer equation. Air temperature sensors should be protected from conductive and irradiation heat sources. **Solar irradiation** is a quantity included in the efficiency equation (see Equation 3-2) and can also assist design in the feasibility, modelling and commissioning stages. The most common device used for monitoring solar irradiation is the pyramometer. In the efficiency equation, the irradiation refers to the incident solar energy reaching the TSC meaning that the sensor should mimic the collector's plane and view. The weather station may include **wind speed and direction** to assist with the TSC installation as discussed in 6.1.1 and with correlations between performance indicators and wind variations. The **barometric pressure** sensor detects atmospheric pressure of air. The **relative humidity** sensor detects the ratio of water vapor present in the air to the greatest amount possible at the same temperature. Both barometric pressure and relative humidity sensors can be used to increase accuracy when calculating the specific heat capacity of air (C_p) or air density (ρ). Additional weather station sensors such as rainfall, hail, snowfall and cloud cover may assist in supplementary evaluation studies.

In situ one-off fabric testing was suggested in the design and evaluation testing. **Air permeability** testing is a legal requirement for UK new builds and can determine infiltration rates (123, 124). The air permeability testing equipment used and suggested in this study was a blower door and fan with a micromanometer following BS EN 13829 and ATTMA TSL1 guides. Different fans can be used for different building floor area. The test was accompanied by thermal imaging analysis of fabric air gaps by using thermal cameras and telescopic anemometers. **U value** testing was used to calculate energy recapture of losses through walls as described in equation

6-13 to facilitate heat transfer calculations. The kit includes heat flux plates and temperature sensors measuring the air temperature by both sides of the external wall as described in the relevant British standards (259).

Heat meters measure heat transferred in a fluid. The fluid heat transfer equation consists of two dynamic components, the mass flow rate and the temperature rise. The mass flow rate is measured through volume flow rate meters. Heat meters include volume flow meters installed in prefabricated pipes with specific cross-sectional area. This allows for the meter in conjunction with temperature sensors installed according to the meters specs, to internally calculate the heat transferred by producing pulses per energy unit (e,g, kWh or Wh). Usually, these meters are used for wet boilers and heat pumps output pipes and can be purchased for standard pipe diameter. For wide ducting, and air systems, volume flow rate can be measured indirectly by measuring air velocity and multiply it by the cross-sectional area. This method requires velocity or pressure meters to be installed in the duct and dimensional meters such as meter tape to be used if the cross-sectional area is unknown. The temperature rise is identified by temperature sensors positioned at the representative position of the fluid heat transfer starting and ending point. These points should be in the ducts or pipes meaning that the sensors should be integrated (pocketed).

Gas meters and electricity meters are used to measure **energy consumed** by ventilation or heating systems. For gas, volume flow meters are used to quantify the volume for a duration of time that should be multiplied by the calorific value to calculate the energy passes through the gas pipe feeding gas heating systems such as a boiler. DIN rail meters or clamp on meters are used for electricity metering. The DIN rail meters are used in consumer units and create pulses per energy unit. Clamp on meters are used on the electricity circuit and will measure the current flowing through the wire based on the magnetic induction created around a wire. This means that a known voltage value is needed to calculate power. In UK context, voltage tolerance for an electricity supply is 230 volts -6%, +10%. This gives an allowed voltage range of 216.2 volts to 253.0 volts. This framework suggests that a voltage meter should be used to measure the voltage on site regularly to reduce grid nominal uncertainty in the calculations.

In situ one-off **volume flow rate** testing of ventilation systems can be done by using a balometer. Such testing is a legal requirement when commissioning ventilation systems (136). The testing determines the flow rates of supply and extract grills to ensure actualisation of design flow rates on site. The test requires flow rate to be measured and compared against all design flow rates.

In Figure 6-19, a monitoring plan template shows a TSC installation with all the potential instrumentation location. This visualises the discussion in this section, showing all the instruments and testing that could be used in the design and evaluation process. A monitoring plan should be tailored to the individual site and systems study and could be accompanied by an instrumentation list and equipment and installation specs for the procurement and for the installers.

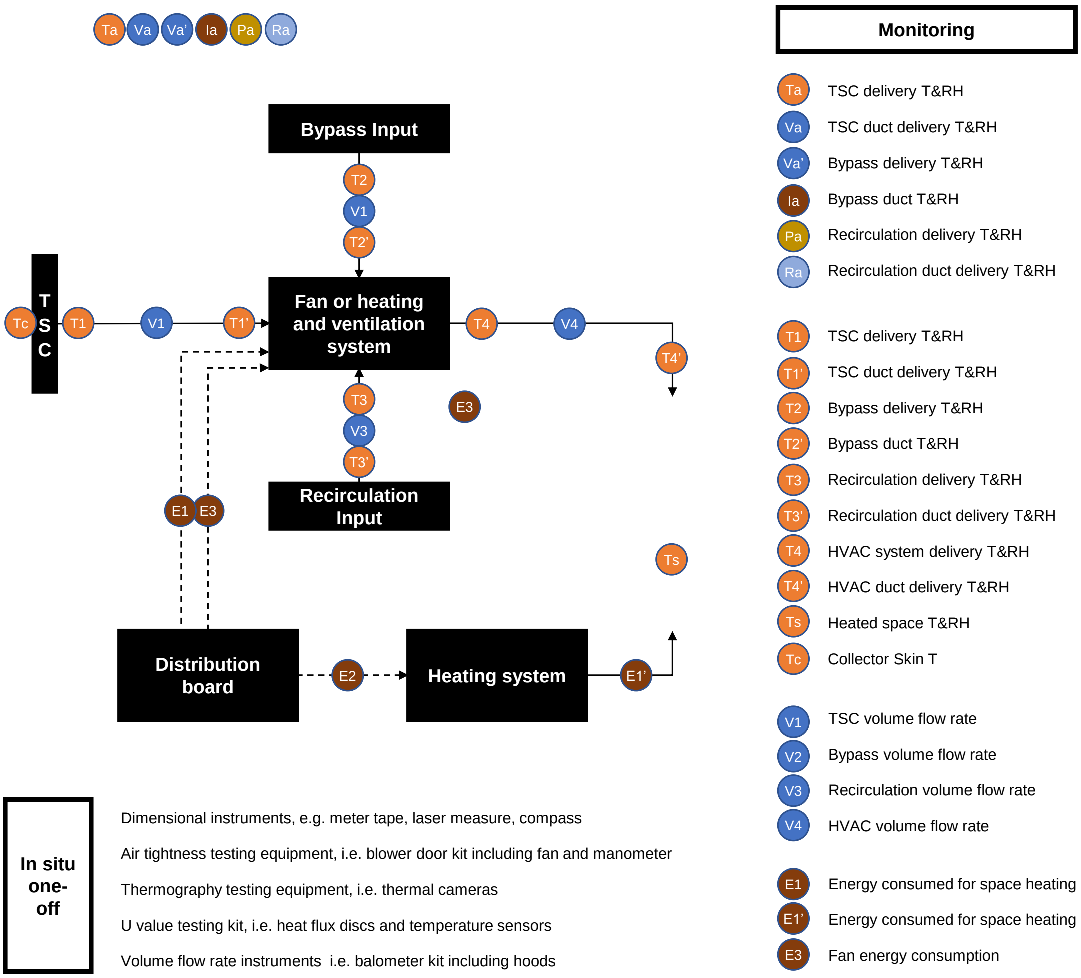


Figure 6-19 Monitoring plan template visualising all potential monitoring instrumentation and in-situ short term testing for a TSC design and evaluation, author.

6.2.2.2 Sensors factors

Long-term monitoring includes the weather station special instruments, temperature and humidity sensors, volume flow rate instruments and energy meters. Short term in-situ measurements include fabric, flow rate and dimensional instruments. This section aims to indicate what equipment are the most appropriate for the job and what are their parameters.

All instruments should be calibrated (new instruments may come with a calibration certificate). There are legal requirements to calibrate instruments related to air testing (276) and ventilation (122) when commissioning a building or a ventilation system. This framework recommends all instruments to be calibrated before and after use for long term monitoring and before use for short term measurements, even if there is no legal requirement.

Sensors should combine precision and accuracy that are fit for purpose and include an output resolution that fits the accuracy range. These are all part of the sensors specification and the calibration certificate which indicates real values within an uncertainty range. In some cases, there is a specific requirement for accuracy such as in Building Regulation F, where commissioning ventilation measurements should drop within ±5% of the design flow rates. This would mean that for a minimum flow rate, e.g. delivery in a small bedroom at 4l/s (122), the instrument should be able to measure accurately changes at minimum 0.2l/s.

Temperature sensors should have the ability to measure temperature changes, fast and accurately. In building applications, temperature sensors are within thermocouples type T class A accuracy (±1^{o}C) whereas in lab application within Pt100 Class A accuracy (±(0.15 +0.002*t)^{o}C). In this study the proposed accuracy is (±0.5^{o}C) to ensure that small temperature changes in the ducts can be captured. An important factor to be considered is the time response of the sensors. Thermocouples are very fast whereas Pt100s could be slow depending on the sensors' casing thickness, which means that if PT100s are used, thin casing is preferred. It is important to know the time inertia (time response) in slow instruments such as pyramometers especially when sampling and not averaging. It is preferred to average over a period of time that is larger than the time response to make sure that quantities have cause and effect relationship, e.g. a temperature rise is caused by an irradiation change.

Relative humidity sensors are usually embedded in thermometers. This is because the relative humidity sensor is a hygrometer sensor which is a combination of two temperature sensors, a wet bulb and a dry bulb. Relative humidity is shown in % and the typical uncertainty of the sensor is ±5% RH from 5% to 95% (277).

There is a challenge when monitoring **velocity** through pressure in the duct because of the turbulent flow. An approach is to place the sensor in the centre of the duct's cross-sectional area, which is a good solution when parameter β is known to apply to the Equation 8-7 to convert centralised maximum velocity to average velocity. However, β is a theoretical value for infinite non turbulent straight duct which is not a case for real life applications. An alternative to the above if only one sensor is available, is to place the sensor at 1/3 of the diameter as described in DIN EN 12599 (278); however the exact cross-sectional position is dependent on duct material and shape. The most accurate solution is to use flow grids and average a series of cross-sectional flows (pressures) to calculate the mass flow rate. A cost-effective solution is to use flow pipes instead of grids for measuring the centroidal axis. The method requires two pipes to be installed at two measurement planes at 90º angles to one another. The uncertainty of the measurement reduces when eliminating turbulence and increasing the number of measuring points (holes in the pipes). A way to decrease velocity irregularities in the duct is to select straight ducts for the measurements and install flow straighteners (278, 279).

In this framework **energy** meters are suggested for long term wet systems heat delivery meters and electricity consumption measurement. These meters usually produce a pulse per energy unit and they have a nominal capacity of the maximum power they can handle and measure. The frequency of the generated pulse is the output resolution of these instruments (Wh) and should be related to the performance indicator. This means that when for example an hourly fan consumption profile is the performance indicator output, for a fan average consumption at 10Wh per hour, the pulse output should be at least one order of magnitude greater at 1 pulse per 1Wh to be able to capture the variability for every hour of the day.

All the blower doors have a minimum and maximum **volume flow** rate delivery capacity. For example, the Minneapolis Model 3 and Model 4 can deliver effectively from 150 to 10,000m^3/h @50Pa. Assuming for an air leakage at 10m^3/hm^2 @50Pa, the smallest envelope area to measure with this fan would be 150/10=15m^2 and the largest 10,000/10=1000m^2 which approximates to a 400-500m^2 rectangular one storey building. If air leakage is significantly lower, the smallest area and the largest area will be bigger. For a best practice air leakage at 1m^3/hm^2 @50Pa (123, 124), the building envelope area that could be measured with the same fan would be 10 times more. As seen above a broad estimation of the expected leakage is needed to select the right fan capacity.

For **U value** measurements, both the synchronisation and the accuracy of the sensors involved are important. The temperature sensors should be able to measure as fast as the heat flux plates so that the heat transfer equation can be used for the same moment in time. U value measurement should be taken during heating season, when the building is heated and away from internal gains (259). The aim is to measure an uninterrupted flow of the heat from the internal fabric to the external, meaning that any human activity, convection losses, solar gains etc will add error to the test. For this reason the BRE suggests a minimum of five days experiment duration with 30 minutes maximum data intervals (280).

A factor to consider when measuring is to avoid disturbance of the quantity due to the instrument. For example, when measuring ducts and a flow grid or a balometer is introduced, extra friction is introduced to the system that needs to be accounted for. Some meters consider the extra friction by adjusting the settings whereas for some others cannot do this automatically which means that the fiction impact should be calculated. Another factor to consider is the possibility of measuring a quantity on the sensor and not around the sensor. For example, when measuring air temperature, the sensor should sense the temperature of air and not any radiative heat. This is a common issue with external temperature sensors and the way to deal with this is by covering the sensor with a reflective cover such as a Stevenson screen that also allows the ambient air to travel inside the reflective shelter.

6.2.2.3 Logging settings

Monitoring is the observation of change over a period of time. This means that the minimum number of observations are two, at the start and the end of monitoring. Depending on the performance indicator, more frequent time intervals are needed to quantify or correlate changes over seasons, months, days, hours etc. This means that a sensor needs to have an output that can be logged in predetermined intervals manually or automatically. Manual reading would demand physical presence of the observer at times, which may be feasible for occasional readings but impossible when variations are to be observed. For this reason, logging systems are used in this type of exercises to be able to log values from a lot of sensors. Logging systems have a processing capabilities to:

- get a signal from each sensor in predetermined moments in time
- convert the signal to a value
- add a timestamp
- save the information in a memory
- run the sequence again in a predetermined time interval

A sensor or a team of sensors (e.g. a weather station) may have an embedded logger. This makes the monitoring unit compact and independent but individual programming and synchronisation may be an issue when there are a lot of units in one site (281). One unified data logger can be used for all compatible sensors on site and is suggested in this framework especially in long term monitoring exercises as the evaluator would need to program and collect data from one unit only.

There are two ways to transfer data between the sensor and the logger, through a wired or through a wireless connection. The wired is usually more robust but technically demanding on large sites with a lot of sensors. The wireless is less technically challenging but is vulnerable to interference. The sensor and the logger need to speak the same language in order to communicate. These communication protocols can be digital or analogue and serve wired or wireless or mixed connections.

The logger has a specific capacity, if the memory is filled, logging will stop or overwrite existing data. It is important for the evaluator to know the capacity and plan a visit to collect the data if needed. Another way to approach data collection is for the logger to be connected to the internet so that real time data are available remotely. This gives the evaluator flexibility to analyse data on demand, create backups and manipulate data sets depending on performance indicators. The following diagram (Figure 6-20) visualises a wired or wireless system that can log and transmit data to a server. The server could be a commercial platform or a data centre. Computational skills are needed in programming the logger and servers. Also, appropriate skills are needed to wire the sensors to the loggers. Some commercial bundles can facilitate this process; however, there is a gap in the market for holistic building monitoring systems that combine sensors and parameters discussed in this section.

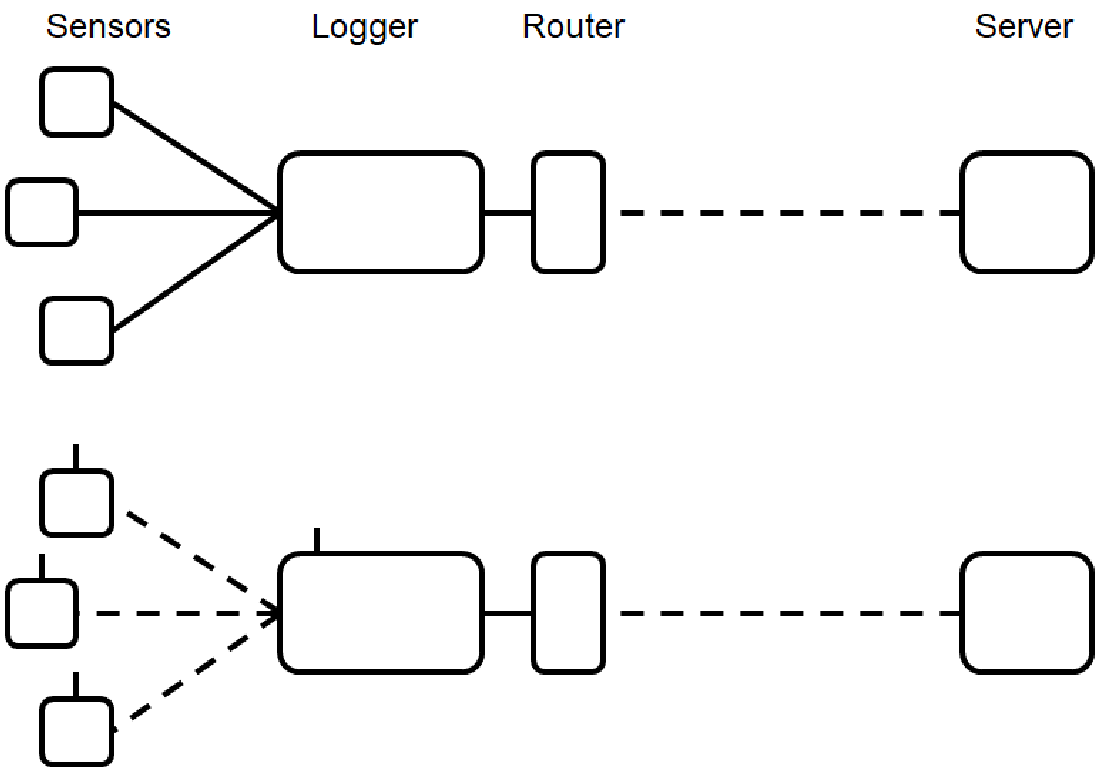


Figure 6-20 Logging system for remote monitoring; wired (up) and wireless (bottom) system, author.

6.2.2.4 Installation

Wired monitoring systems should be installed during new build or retrofit construction in TSC applications to minimise occupants' disruption and reduce installation costs. Wireless systems are easier to install at any time. Maximum wireless communication range should be considered together with potential physical obstacles that reduce range. Power to operate meters and loggers should also be considered. There are sensors that do not need power such as thermocouples that generate a signal caused by the thermoelectric phenomenon. Battery powered instruments are easier to be installed but there is a risk for data loss if the battery fails. Mains powered instruments are more robust but require easy access to a socket. The logging station can provide power to wired sensors which means that the connection cable will include data and power wiring. The loggers can be connected to a router via an ethernet connection or wirelessly and proximity should also be considered. The router can be connected to the internet through a SIM card dongle or via a land line.

When installing sensors, the fundamental principle is to capture the most representative sense of the measured quantity. A space temperature sensor should be installed where the occupants are whereas, a duct temperature sensor should be installed at the point of interest capturing the temperature at the flow. This means that the TSC temperature sensor should be installed just after the cavity but in the beginning of the duct to get the averaged TSC temperature but not affected by air heat exchange between the duct and surroundings. A space temperature sensor follows the location selection of a thermostat: in the centre of the space, where most of the activity is, away from drafts and at chest height (282-285). The ambient temperature sensor should be installed close to the TSC panel but preferably on a shaded place. The pyranometer should mimic the TSC plane which means that the best location is on the TSC, without obstructing any holes. The skin temperature sensor is installed on the back of the TSC skin to avoid direct sunlight and sensor self-heat.

The velocity or pressure sensors were already discussed in terms of the cross-sectional location parameters. In terms of the duct length, the best position is away from turbulence, thus away from fans, dampers, filters, diffusers and curves. DIN EN 12599 states that flow needs a duct length equal to seven times of the duct diameter to be normalised after a disruption; however if a flow grid is used, two duct diameters would be sufficient to get good results (278, 279).

Similar principles are followed for heat meters for fluids. A certified plumber should install heat meters in wet systems and preferably during the system installation. Retrofitting pipes is challenging, and major works and flow adjustments may be needed when trying to create a straight pipe to minimise turbulent flow. Heat meters have their one prefabricated pipe that should match the system's piping diameter to avoid further flow disturbance. The meter should be installed on the cold side of the wet system (return) and has an embedded temperature sensor prefixed in the prefabricated pipe. The other sensor is wired to the meter and should be manually inserted to the hot side (supply). The tip of the sensor should not touch the inner pipe as this would affect the fluid temperature measurement.

6.2.3 Data processing

Data processing is the conversion of electrical signals to groups of data that carry useful information. This section will follow the data trip from the sensor output to a machine-readable form, with a focus on transmission, error detection and cleansing and data grouping.

6.2.3.1 Data transmission

The sensors have an electrical output that is transferred to the logger's input. Loggers can have variable inputs such as digital, used for example for pulse counters, or analogue used for a variety of voltage or current signals. Every sensor has a measuring range and a resolution as discussed in the instrumentation section. For example, some relative humidity sensors have a 0-10V range corresponding to 0-100% relative humidity. This conversion can happen on the logger, on server or on the end user machine. No matter where the conversion happens, the important factor is to know the conversion mechanism. This can be found in most of the cases within the instruments' specs. There are some cases that this mechanism is known from literature, for example thermocouples are manufactured in a unified standard method that relates voltage to temperature with a global conversion mechanism (286). When converting, data should be followed by the corresponding unit before any further manipulation. The same applies when using equations to calculate quantities from various data. Raw data should be stored and saved before conversions or calculations. This framework recommends that any data processing after transmission should happen in a copy of the raw data. This is suggested to facilitate traceability of the data, as information can be re-generated when the raw data are accessible.

There are two types of data transmission, real-time transmission, and asynchronous transmission. In real time, the logger will be programmed to store and transfer a timestamped set of data from all the sensors that are connected to it. The transfer is happening through internet to a server that will also store the timestamped data.

Asynchronous transmission is also timestamped and refers to the process when the logger sends sets of data to the server upon servers' request. This usually happens periodically, e.g., every 1st day of the month. Raw data may include errors or missing information; thus, transmission should be optimised. Data loss can be reduced by using back up methods on the logger, server or end machine. This can be done by using a daily saving routine programmed on the logger or the server.

6.2.3.2 Error detection and cleansing

There is a variety of issues that can cause data error. Sensor errors, power cuts, transmission faults, wiring cuts, programming faults etc. There are ways to reduce error before creating datasets, for example, by making sure that the sensors measure the right quantity, or by testing wiring, programming etc. However, there are errors that occur because of unexpected reasons such as weak transmission signal. These errors can cause data analysis discrepancies and need to be addressed before grouping data.

Data error detection method should be selected according to the error type; this can be an outlier, a duplication, or a missing. To detect and address this error types, statistical tools and machine learning techniques can be applied (287, 288). This framework suggests the following simple mechanisms to address the three error types.

Outliers can be detected when an expected range is determined. For example, ambient temperature is expected to fluctuate in Wales within the extreme values (-8.0ºC to 37.1ºC) (289). This means that a logic testing formula that would test all data for an expected temperature range (-10 ºC to 40ºC) could detect any unreasonable data. However, this will not necessarily detect a systematic error, such as an offset or a bad installation. For this reason, an average for a defined duration (one month) can be compared against meteorological data and, if necessary, corrections to the sensor can be made. For non-systematic errors, the outlier is usually a data transmission error and can be corrected using interpolation by replacing the outlier by the average of the preceding and following value. The interpolation technique can be applied for missing values which can cause problems in the analysis especially if they are interpreted as "zero values". This method does not work for a high percentage of outliers as it will introduce high uncertainty. In this case a review of the data transmission system and method are suggested.

Data duplicates usually refer to a repeated time stamped row (series) of data. This can cause problems when applying statistical analysis. A way to detect missing or duplicate rows is to count the rows and compare against expected data. For example, for an hourly interval, the expected rows for January are 744. If more or less rows are detected, the data set contains errors. A way to clean this is by running programming routines to erase duplicates and generate missing rows through interpolation. Another way to approach this is by creating hourly bins through pivot tables or by normalising the aggregation for the expected row count.

All the above techniques should be carefully applied as if there is a significant data miss, then any interpolation or averaging techniques increase uncertainty. In such instances, error should be added in the uncertainty analysis or missing data should not be included in the results. Interpolation techniques apply better in non-stochastic data sets where the variation is predictable. For example, fan power for a continuous 24/7 flow is a predictable value especially when time interval is very frequent, whereas solar irradiation in a cloudy day at 2pm is hardly related to the 1pm and 3pm value.

6.2.3.3 Grouping

Grouping data plays a significant role when dealing with large data. The grouping should respond to the performance indicator; for example, if the variable is weather dependent, then, a monthly grouping could be used to facilitate further analysis. Space heating could be grouped in heating and non-heating seasons whereas the TSC delivery can also be grouped for day and night-time delivery. Frequency bins can also be used to understand variability, for example TSC efficiency can be presented in ranges by using frequency distribution of the grouped data.

A starting point when dealing with power data is to convert the data to aggregated hourly values for easy conversion to energy. An internal averaging can increase data resolution. For example, minute sampling of power or temperature data can be averaged for one hour accompanied by min, max and standard deviation. This will reduce big data but still carry sufficient information for further analysis. Another layer of grouping that facilitates data analysis is to group according to a filter, for example, CIBSE comfort temperature ranges (87), or a TSC output when delivery temperature is above space temperature.

6.2.4 Data analysis

This section refers to the last part of evaluation, the data analysis, which aims to respond to the performance indicators according to the evaluation workflow (Figure ***5***-***5***) presented in Chapter 5. The section discusses how the depth of analysis is related to the performance indicators, how normalisation allow for comparisons and how good results' visuals facilitating information communication.

6.2.4.1 Depth of analysis

The depth of the analysis is related to the depth of the question. The question drives the instrumentation and analysis. For example, ıf the aim is to find out how TSC heat delivery is related to solar radiation variations, then annual figures would not work; a combination of monthly figures, daily profiles and R values in a heat delivery versus solar irradiation graph would respond to the question. The resolution of analysis is also related to the variability of the measured value. For example, a fixed velocity fan is expected to create a steady velocity supply, meaning that daily observations may not be needed especially if the stability of the value is observed statistically through tools such as standard deviation, min and max. Another parameter that determines monitoring depth is facilitating diagnostics. This is common when unexpected performance is observed during commissioning as discussed in 6.1.4. In this case, zooming in to hourly or even higher interval data and correlating variables can assist in understanding the cause of any performance gap.

6.2.4.2 Normalisation and comparisons

When comparing two sets of data or values, there is always the risk that they cannot be directly compared (apples to oranges rather than apples to apples). To make a fair comparison, the two sets or values should refer to the same or similar context in terms of time, conditions and parameters. This is important when TSC performance indicators include comparisons against other data sets or values such as:

- TSC heat delivery against space heating

This is a comparison between the main TSC space heating delivery (monitored or modelled) against a conventional system space heating delivery (monitored) or demand (modelled) that is in series (PHV) or in parallel to the TSC (DHV). When comparing modelling data (TSC vs space heating), it is essential to ensure that both calculations include the same or similar weather data. If this is not possible, the result should be normalised for monitored or historic weather data sets. When comparing monitored against modelling data, on the top of weather data normalisation, the analysis should include performance gap corrections due to the difference between real (space temperature) and target (set point) temperature. Also, in all cases, the analyses should consider that the TSC heat delivery should be the useful delivery that displaces space heating delivered by the conventional sources.

- TSC performance indicator A against TSC performance indicator B

This can be a comparison between (e.g.) TSC space heating delivery against efficiency or mass flow rate against temperature rise. In these cases, instantaneous measurements comparisons are risky due to instrumentation and heat transfer inertia analysed in 6.2.2. The comparison should refer to a specific duration of data such as heating season, monthly, etc. Also, a daytime and nigh time split is beneficial as the TSC heat transfer mechanism is different in the night (night purge and back wall and ducting heat recovery).

- TSC performance indicator A against weather, building or systems variables

This can be a comparison between (e.g.) TSC space heating delivery and external wind velocity. This type of comparison includes a lot of risks and direct correlations are challenging thus they should be done in controlled environments. In order to draw such correlations, all the other parameters that would affect the relation should be kept constant or normalised.

- TSC performance indicator A against TSC performance indicator A'

This comparison refers to the same performance indicator assessed in a different context. This may include, different time, different location, building, etc., for example, when comparing TSC heat delivery in one of the experimental studies versus the TSC heat delivery in one of the literature case studies (Chapter 4). This comparison is highly risky as there are a series of variables involved that would compromise any similarities or differences outcome. If, this comparison is still important as perhaps a statistical indicator, then the first normalisation should ensure that output is calculated per TSC area. Also, volume flow rate could be normalised through data or specs graphs. Weather normalisation would also allow for a fairer comparison. Lastly, such comparisons are easier when referring to similar TSC orientation and size and similar buildings with similar heating and ventilation systems. When comparing TSC monitoring data for the same TSC but for two different time periods, it is important to normalise for weather and also include similar seasons, e.g. heating season A versus heating season A'.

A simple ratio-based normalisation can be applied when the cause-and-effect relation is linear. For example, when normalising monitored annual space heating delivery with calculated HDD for historic HDD (97, 101). When the cause-and-effect relation is non-linear then appropriate cause-and-effect data sets are needed to produce the regression equation to normalise (290, 291).

6.2.4.3 Visualisation

Another challenge when dealing with innovative technologies is the lack of common language in the decision-making process between designers, contractors and clients. Thus, simple visuals such as tables, graphs and sketches facilitate the communications. The aim when visualising data is to communicate a change that the visual should bring about to the viewer. The type of change (message) and the type of audience should be considered and drive the content, form and complexity of the approach. Different types of data should be visualised differently as human visual perception prioritises visual attribute properties differently for different data types. For example colour or texture is not very important in qualitative data visuals in comparison to ordinal or nominal data visuals (292, 293). This idea is based on Gestalt Principles that describe how the human eye perceives visual elements (294). Bar graphs are best for comparing categories; line graphs are used to show trends over time and pie charts show the relationship of categories in regard to the whole (295). When visualisation energy values such as monthly TSC heat delivery or annual modelled versus monitored TSC delivery, bars are more effective to focus on the different categories. When visualising temperature variation, line charts with data points are better as they demonstrate changes and trends. When indicating percentages such as TSC heat displacement to the total heat demand, a pie chart is a better visual to illustrate the proportion regarding the whole. When visualising multiple data sets with different units or ranges, secondary axis allows for data representation in one graph.

Tables, sketches and graphs are used in all the stages of TSC design and evaluation as they are tools that can help is communication and summarisation of information. This framework suggests that the viewer of the information should feedback on the visualisation method to ensure effective information transmission.

7 Results – Framework application

This Chapter includes the application of the framework (Chapter 6) to the experimental case studies (introduced in Chapter 5). For the reader to be able to navigate between the different case studies discussed, alternative, shorter names were given summarised in Table 5-1. The presentation narrative was built around the Rhondda end-terraced house case study introduced in Section 5.4. This residential vertical application is the last one designed and evaluated by the author and includes knowledge and experience from all the nine previous case studies and test rig (Section 5.3). The format of the presentation follows the design and evaluation methodology shaped in Chapter 6. The Rhondda end-terraced will be accompanied by the other experimental case studies applications to indicate differences when needed. Results will be summarised, explained, and discussed as needed in this Section; however, a separate discussion Chapter follows (Chapter 8) that deliberates the design and evaluation process built through this research.

7.1 TSC Design

7.1.1 Feasibility Study

This includes the framework application on climate and site analysis, building envelope exploration and building demand survey. The B&Q store and Solcer house were new builds meaning that feasibility could be incorporated in the design stage, whereas for the other eight case studies only the existing status and potential could be explored.

7.1.1.1 Climate and site analysis

In terms of context, metal cladding is broadly used in industrial, institutional and commercial sites as well as new residential buildings; however, it is not common in residential retrofits and Victorian neighbourhoods. The author amongst other researchers carried out online questionnaires and semi structured interviews to identify public perception on TSC aesthetics (238). The online questionnaire suggests that there is a support for metal cladding solar devices capable of generating sustainable sources of energy amongst the respondents.

The experimental case studies are in Wales which has a “CfB” classification under the Köppen-Geiger Climate Classification system, meaning weather is characterised as a temperate, oceanic climate (239). This classification (CfB) means that the coldest month averages above 0°C, all twelve months temperatures average below 22°C, and at least four months average above 10°C. Also, the classification is described by no significant precipitation difference between seasons. All experimental case studies will require external heating for at least four months assuming no internal gains as the 10°C is significantly lower to the desired temperatures.

Further analysis was performed through the collection of weather data and identification of heating degree days. Carbon Trust suggests a base temperature of 15.5°C for UK HDD calculations as explained in Section 6.2.1.1 where heating will be needed. Five different sources were used to calculate HDD in Rhondda end-terraced site to understand the differences between nearby weather stations and differences between historic and annual data. Equation 6.1 was used to calculate monthly HDD in Table 7-1. The first column is calculated applying equation 6.1 to external temperature from 25-years CIBSE historic data for the area (243); this data was also used later in the modelling process. The second and third column is from 5-years historic data and 2017 data respectively from Cardiff airport weather station (28km away). The fourth column indicates 2017 data from Caerphilly weather station (20km away) (101, 241). The next column shows the HDD calculated based on temperatures from the weather station installed by the author on site during the 2017 pre-retrofit monitoring period.

Table 7-1 Heating degree days for the Rhondda site calculated from historic data and local weather stations, author.

Month	CIBSE near airport historic (25-year)	Cardiff airport WS historic (5-year)	Cardiff airport WS 2017	Caerphilly WS 2017	Rhondda House 2017	CIBSE vs Rhondda %
January	288	285	311	318	331	13.0
February	296	281	252	253	273	-8.6
March	276	267	213	211	225	-22.7
April	211	185	186	182	201	-4.8
May	106	104	86	86	91	-16.8
June	53	36	34	38	39	-34.8
July	18	18	16	20	15	-21.5
August	11	24	24	34	31	63.0
September	53	48	54	70	81	34.3
October	134	109	78	91	104	-29.0
November	208	196	218	232	242	13.9
December	271	235	285	295	305	11.0
Annual total	**1926**	**1788**	**1757**	**1830**	**1937**	**-0.2**

By using CIBSE historic data HDD as a reference, a difference of 7% to the Cardiff airport weather station 5-year historic data and a difference of 9% to the Cardiff airport weather station 2017 data can be noticed. The 25-year data indicate a colder averaged year in total comparing to the last 5-year data where the sample is shorter but seems to better represent the global warming trend. Compared to the local experimental weather station capturing 2017 weather data, the CIBSE historic data are in good agreement with only 0.2% difference for the entire year. From this it could be argued that weather-wise, 2017 was a representative year; however, it has to be noted that 2017 deep winter (January and December) was colder whereas some shoulder months (March and October) were warmer comparing to historic data. Also, comparing the 2017 site weather to weather stations nearby for the same year, it could be argued that the Rhondda site is colder than the airport and the Caerphilly site which have 9% and 5% less HDD annually. This can be explained as both airport (60m) and Caerphilly (85m) have lower elevation compared to Rhondda site (148m), and Rhondda is located in south Wales Valleys surrounded by hills. The HDD analysis shows that a building within this location will need heating all year and especially from October to May. Further analysis for specific building heating demand will be explored in Section 7.2.1.3.

The microclimate is affected by a river running to the south and west as seen in Figure 7-1 below. The south plane is open to the sun-path with insignificant vegetation affecting the west as seen in the panoramic photo (Figure 7-2) taken from the street towards south plane. In the same photo some two-storey terrace houses in the east could slightly affect the site early in the morning if solar systems would be installed on the lower part of the elevations.

Figure 7-1 Satellite Google Earth photo of the site area, author

Figure 7-2 Rhondda end-terraced house; panoramic 180° view of the site facing the solar path, author.

Based on the location, there will be some solar availability even in deep winter, this can be shown in Figure 7-3 where the horizon and sun path is shown for winter and summer solstices (21st of December and 21st of June). The horizon is informed by natural landscape shadows using JRC PVGIS (244) built-in horizon information with 90m accuracy. The sun will face the site from -35° to +30° during the 21st of December, at 14° maximum elevation at noon. In the same figure, the horizon for the Solcer house site is shown. This site is much more open to the sun path as is exposed from the sunrise (-52.5°) to sun set (-51°) for identical elevation.

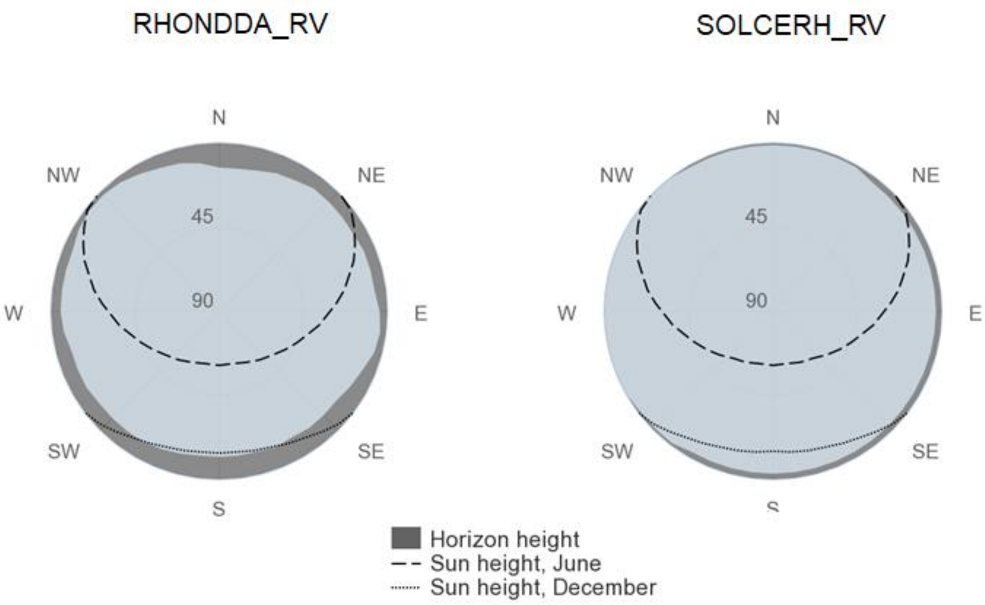


Figure 7-3 Outline of horizon for the Rhondda end-terraced site on the left and the Solcer house site on the right indicating the difference between winter sun path exposure, using PVGIS, author.

All the horizon graphs can be found in Appendix V. All the sites except the two sites in Rhondda valleys are open to the horizon utilising the available sun even in deep winter.

7.1.1.2 Building envelope exploration

None of the case studies introduced in Chapter 6 were Listed Buildings; however, most of them have interesting architectural particularities and challenges that were discussed with the clients before exploring how envelope geometry responds to solar availability. The B&Q store was already designed when the SBED team approached the clients and the elevations were aesthetically finalised whereas the roof was a huge corrugated unexploited and aesthetically neutral area structurally suitable as it was designed to carry vegetation (Figure 7-4). TSC was considered in very early stages of the Solcer house. As the house was a demonstration, and replicability was of a high priority, the envelope should suit both end and mid-terrace, and the front and rear should be interchangeable. This meant that only the south elevation was available for TSC. Exposed brick elevations such as the ones at Saxon court or the schools were also discussed with the partners; some of the clients were not in favour to install TSCs in such facades whereas some others did not have this reservation. Most of the clients were happy with using the roofs however, structural audits caused rejection of some potential case studies in early stages due to technical and cost implications related to need for extensive structural roof enhancement.

Figure 7-4 B&Q store case study. B&Q Green roof in Merthyr, Wales, author.

The Rhondda end-terraced house has an interesting envelope. The roof is a double pitch with West and East exposure. The south end-terrace elevation includes the triangular gable end, the west external wall is available but with uneven door and windows geometry and the east external wall was an aesthetically pleasant stone cladding one integrated to the entire neighbouring terrace (Figure 7-5). This last façade includes five windows and a door, and any solar integration would look fragmented. After discussions with the housing authorities and considering findings from Drozynski et al.'s study (238), it was decided that the roofs and the end terrace elevation would be more appropriate and that design integration would be prioritised.

Figure 7-5 Rhondda end-terraced house; From left to right, west, south and east elevation, author.

The house is located in the Rhondda valley, south Wales, with a sea level elevation of 149 m. There is a 120m^2 southwest open space adjacent to Rhondda riverbank, allowing for a relatively free horizon as discussed earlier. The presence of the river is expected to have some impact in external temperature peaks and external humidity. As seen in Figure 7-6 the two-storey house footprint area is 50.4m^2 (5.6m x 9m); however, very thick external walls would take approximately 28% of this space. The living room and kitchen are on the ground floor and the two bedrooms and bathroom are on the first floor The double pitched roof is inclined at 34° ±1° and the south end terrace wall is 90° (vertical). The exact orientation of the wall is SSW at +13° from south (Figure 7-7) meaning that the east roof is at -77° and the west at +103° from south (azimuth). All dwelling dimensions, slopes and orientations were calculated combining physical measurements and Google Maps measurements.

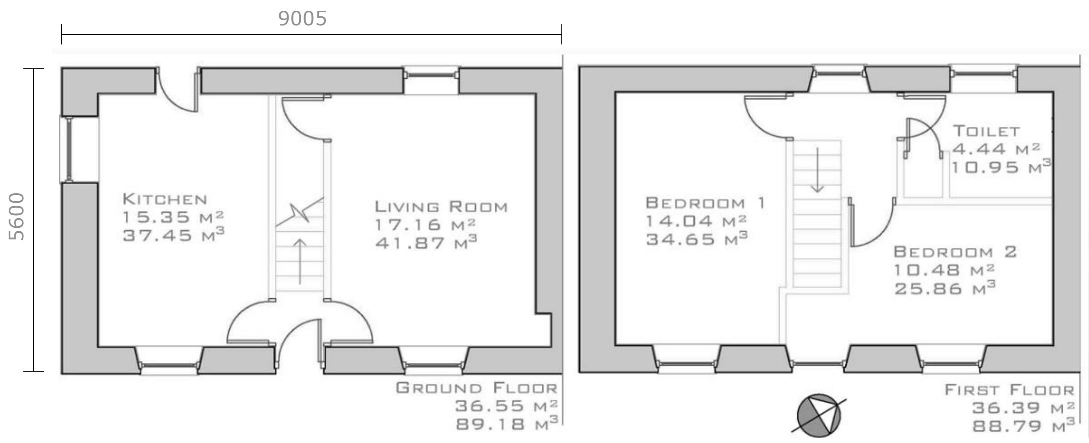


Figure 7-6 Rhondda end-terraced house plan, LCBE team including author

Figure 7-7 Rhondda end-terraced house orientation and natural context.

The above dimensional inputs were then used and combined with historic weather data and metrics from PVGIS 5 and from HTB2/Virvil Sketchup. Virvil was used as an early-stage annual solar radiation visualisation indicator whereas PVGIS was used to study the monthly solar availability of different the slopes. The annual global solar radiation is shown in different colour coding indicating the annual potential for the two roofs and the south elevations wall taking into account artificial surroundings (Figure 7-8). The weather data used for the Virvil model is from 25-years historic data set from CIBSE, whereas PVGIS-SARAH2 16-years historic data set was used for the PVGIS model. The annual analysis for both models shows that the east roof has the most potential whereas the west roof and south elevation have approximately 10% and 20% less potential respectively. When using TSC, the solar potential should be harvested during the heating season thus a monthly study is needed to re-evaluate the optimal slopes. Also, both TSCs and PVs were considered in the early stage thus a seasonal/monthly analysis would prioritise which of the three available envelope surfaces is the best for each technology.

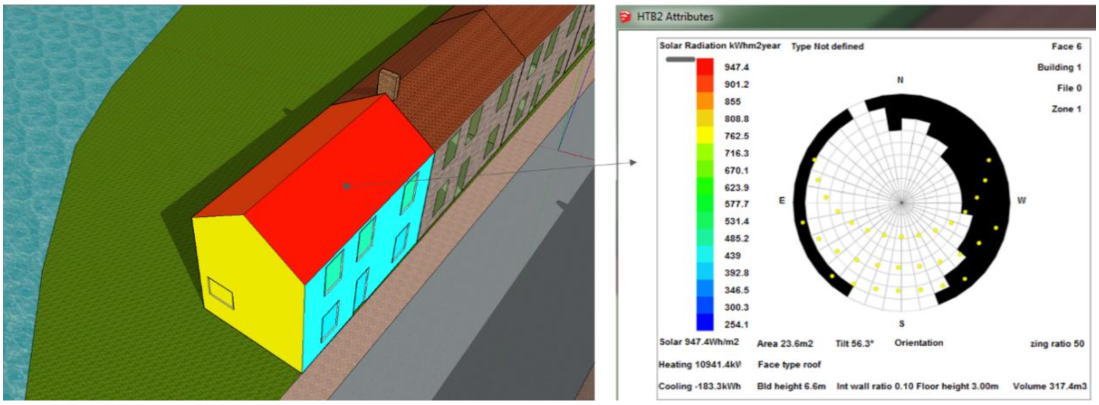


Figure 7-8 Rhondda end-terraced house; HTB2/Virvil Sketchup total global irradiation including artificial surroundings with shading mask. LCBE team including author.

A monthly summary of the solar radiation is presented in Table 7-2. The first column indicates the monthly optimal plane inclination to install a solar system on the building assuming that there are no fixed slopes. This test is to understand what the best inclination per month and per season is. The optimal annual inclination was found to be 35^o – this is not a straight average over the 12 months (42^o), as PVGIS normalises the angle considering higher potential production during the summer. The average inclination for the heating season (Oct-Apr as defined in Chapter 2 (80, 87)) was found to be 55^o with maximum of 64^o for December indicating that a solar thermal system utilised for heating season would ideally be placed at 55^o facing south. This scenario explores the ideal inclination and could work for new buildings early-stage design; it verifies that for this site a vertical TSC installation is preferable to a horizontal one. The real retrofit scenario is investigated in the last three columns of Table 7-2 where the existing 34^o pitched roofs and the vertical elevation are explored. The east roof has annual potential (1001 kWh/m^2 compared to the west (904 kWh/m^2) and to the south wall (801kwh/m^2). However, during the heating season, the south wall has a greater potential (390kWh/m^2) which is 6% better than the east roof and 20% better than the west roof. There was no evidence of any future development in the area affecting the open access to the sun path, meaning that the south elevation has the best potential.

Table 7-2 Rhondda end-terraced house; solar potential analysis for different slopes using PVGIS-SARAH2 historic data envelope geometry. Heating season is indicated in italics, author.

Month	Inclination (°)	Average Amb. Temp (°C)		Total Global irradiation (kWh/m^2)		
	optimal	daytime	24 hour	East roof (34°)	West roof (34°)	South Wall (90°)
Jan	*62*	*5.2*	*4.4*	*21*	*17*	*31*
Feb	*56*	*5.6*	*4.7*	*37*	*31*	*46*
Mar	*49*	*7.5*	*6.1*	*90*	*75*	*91*
Apr	*35*	*10.1*	*8.8*	*121*	*108*	*94*
May	21	12.2	11.2	145	136	89
Jun	14	14.9	14.0	146	140	81
Jul	17	16.9	16.0	141	134	82
Aug	27	16.3	15.4	116	107	81
Sep	42	15.1	13.9	88	77	79
Oct	*53*	*12.0*	*10.9*	*53*	*44*	*60*
Nov	*62*	*8.9*	*8.0*	*28*	*22*	*41*
Dec	*64*	*6.9*	*6.1*	*17*	*14*	*27*
Annual average	**42 35 (opt)**	**11.0**	**10.0**	**1001**	**904**	**801**
Heating season average	***55***	***7.7***	***6.7***	***366***	***311***	***390***

Table 8-3 includes daytime and 24hour monthly temperature averages. The average monthly temperatures during sun-hours (daytime) are approximately 1°C higher temperature for each month without significant variations. Although the heating season is generally assumed to be October to April, data on Table 7-2 shows that May is only marginally warmer than October. For this reason, it may be worth including May in the heating demand and therefore the inclination considerations. When May is included, the east roof has a marginally better potential than the west and south. When adding the possibility of installing PVs, the East and West slopes are more effective annually as indicated in Table 7-2, When weighing all option and considering the above solar availability analysis, the best combination for this site is to host PVs on the East-West facades and TSCs on the South elevation.

The annual average wind fulfils the less than 5m/s criteria set in Chapter 3; however, it is significantly higher than the optimal 2m/s as the average is approximately at 4m/s with a peak in December at 4.8m/s. It is expected that this will have an impact on the

TSC effectiveness. The recorded peak is at 12.1m/s and it is expected that such wind speed will create significant turbulence in the TSC cavity (Figure 7-9). The prevailing winds are coming from west and sometimes from northeast meaning that cross winds to the south elevation are not that common as seen in the wind wheel graph in Figure 7-10. This is another reason to select the south facing elevation for TSC installation.

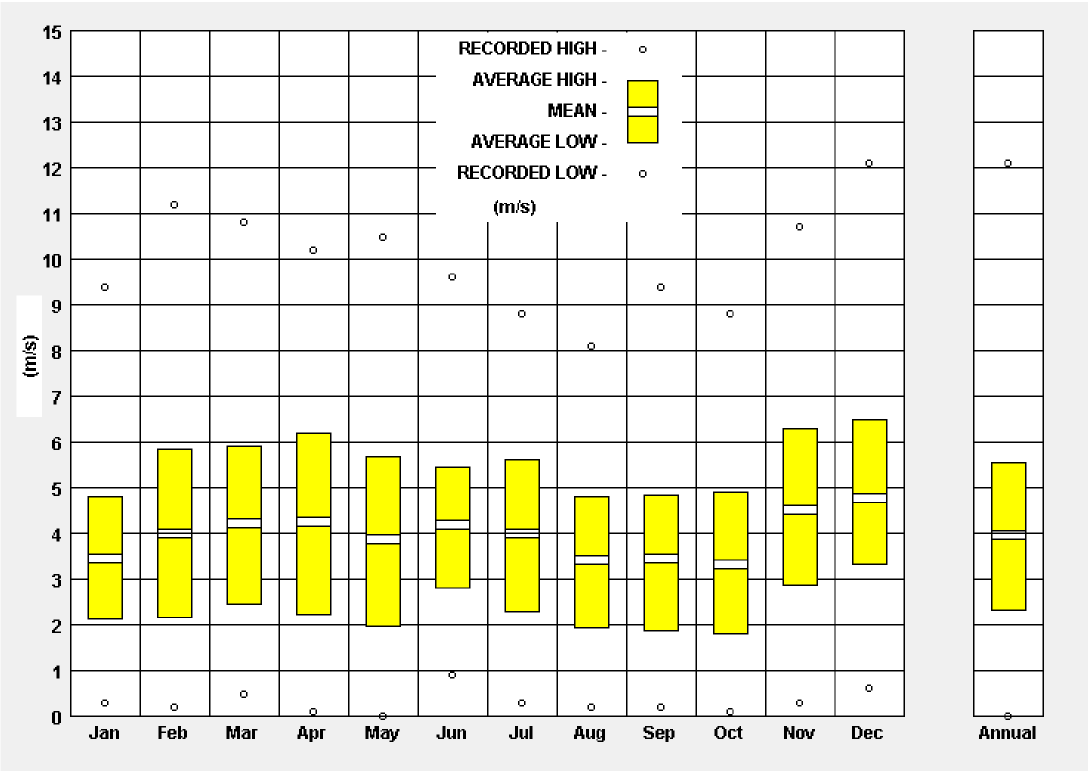


Figure 7-9 Rhondda site; wind speed analysis using PVGIS SARAH2 historic weather file visualised in Climate Consultant software, author.

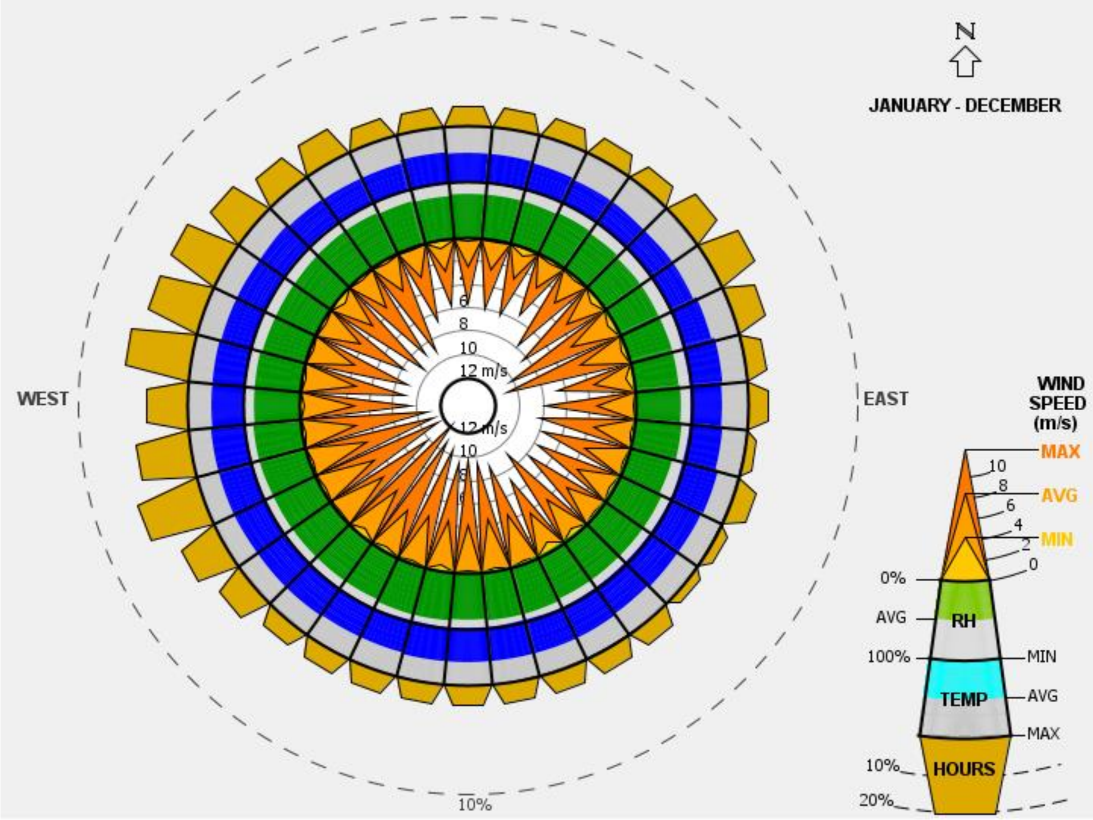


Figure 7-10 Rhondda site; wind direction and speed using PVGIS SARAH2 historic weather file visualised in Climate Consultant software, author.

None of the experimental case studies were installed by the sea meaning that potential corrosion was not an issue. However external relative humidity was a challenge as can be seen in the green band in Figure 7-10 and in more detail in Figure 7-11. From historic data, the average daily high is 83% with an average daily low at 63%. At 4am the daily average relative humidity was 94% whereas 63% was the average for 1pm.

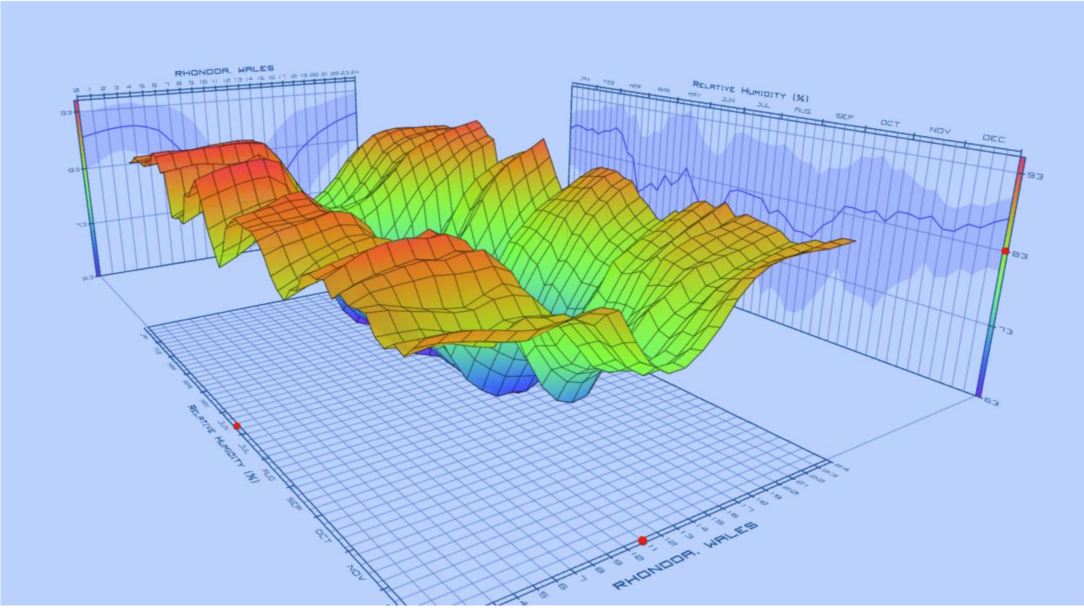


Figure 7-11 Rhondda site; external relative humidity analysis using PVGIS SARAH2 historic weather file visualised in Andrew Marsh web app, author.

Air permeability estimations or testing was carried out in some of the case studies. In SEDA factory, B&Q store and the schools, testing and calculations were not applicable as open doors and windows were a default setting even during heating season. When Solcer house was initially delivered, the permeability was tested at 3.1 $m^3/(h.m^2)$@50Pa. In order to increase the airtightness, better sealing was installed around the doors and the attic hatch. The author re-tested the house using the same blower door and the permeability dropped to 2.6 $m^3/(h.m^2)$@50Pa. In Rhondda end-terraced, the pre-retrofit permeability was at 6.8 $m^3/(h.m^2)$@50Pa. After the new insulation and some windows' sealing the permeability dropped to 5.1 $m^3/(h.m^2)$@50Pa which is an acceptable rate for mechanical ventilation use as seen in Chapter 2 and discussed in the framework.

7.1.1.3 Building Demand Survey

7.1.1.3.1 Ventilation demand survey

Following the framework, in order to establish the ventilation demand, appropriate targets were determined using Building Regulations Part F (122) and CIBSE Guide A (87) and related methods discussed in the literature (Section 2.2.2) and framework (Section 8.1.1.3) Sections. In Table 7-3, the ventilation demand is specified for all the experimental case studies in l/s including the calculation method.

Table 7-3 Ventilation Demand targets for the experimental case studies, author

No.	Experimental case study name	Floor area (m^2)	Ventilation Demand Target (l/s)	Calculation
1	**SEDA Ltd. Blackwood, production hall**	22,500	1350	10l/s*135 occupants
2	**B&Q store Cyfarthfa, retail store**	5,000	2400	10l/s*240 occupants
3	**Lampeter School, main hall**	300	1500	10l/s*150 occupants
4	**Lampeter School, cloakrooms**	200	400	10l/s*40 occupants
5	**Glan Clwyd School, theatre**	400	2000	10l/s*200 occupants
6	**Glan Clwyd School, corridors**	450	500	10l/s*50 occupants
7	**Saxon Court residence, corridors**	450	135	0.3l/s*m^2
8	**Rhondda House (terraced)**	80	17	2 bedrooms dwelling
9	**Solcer house (detached)**	105	45	0.3l/s*m^2+ 4l/s
10	**Rhondda House (end-terraced)**	100	17	2 bedrooms dwelling

SEDA factory, introduced in Chapter 5, is a gigantic open plan warehouse and from conversations with the client, half of the 270 employees could work together in a shift. The space includes large doors that are frequently open to outside; it also includes an interlinked storage space with very low occupancy. Introducing fresh air for ventilation, the space would be slightly over-pressurised eliminating infiltration through the openings. Similarly, B&Q store's ventilation rate was calculated for a maximum of 250 people. By using Cho et al. (256) method for a retail with porch, 2043l/s of ventilation rate would equal the maximum infiltration rate through the doors. The school occupancy was discussed and estimated with the head teacher. Again, the benefit of positive pressure was a driver as all the spaces included doors and windows that would be regularly opened. Saxon court residence is a unique case study as the ventilation rates refer to the buildings corridors leading to 31 flats and ancillary spaces. As the 450m^2 of corridors is a transitional space, extra occupants were not considered in the calculation. Again, the idea is that positive pressure will create a barrier to the staircase and lobby infiltration.

Another way to calculate the minimum domestic ventilation demands targets is shown in Table 7-4 using the CIBSE Guide A flow rate calculation based on the number of kitchens and bathrooms.

Table 7-4 Domestic ventilation demand targets for the experimental case studies; comparison between Building Regulations part F (122) and CIBSE Guide A (87) calculated values, author.

No.	**Experimental case study name**	**Target (l/s) Build Regs F** (122)	**Target (l/s) CIBSE Guide A** (87)	**Comment**
8	**Rhondda House (terraced)**	17	21	1 kitchen (13l/s) 1 bathroom (8l/s)
9	**Solcer house (detached)**	25	29	1 kitchen (13l/s) 2 bathroom (16l/s)
10	**Rhondda House (end-terraced)**	17	21	1 kitchen (13l/s) 1 bathroom (8l/s)

After discussions with the owner and given that high ventilation could cause some draft issues in low ceiling houses, the Building Regulations F values were used.

7.1.1.3.2 Heating demand survey

Both heating degree days, desired temperature targets and average heating demand for buildings similar to the experimental case studies (table 2.4) have set a useful context. However, none of these items consider building specific fabric performance. To analyse the actual heat demand both modelling and monitoring tools were used to explore variations.

The monitoring strategy is visualised in the monitoring plan below (Figure 7-12). The gas mains and the gas consumed by the boiler are monitored by two gas meters, W1 and W2 respectively. The gas consumed in the kitchen can be calculated by subtraction. The space heating delivery and hot water output are monitored by two heat meters, W3 and W4 respectively. All four meters log number of pulses per hour converted to kWh. Temperature and relative humidity sensors are installed in the living room (TRH L) at the ground floor and the main bedroom (TRH B) at the first floor. An external temperature and humidity sensor (TRH ext) is installed nearby. All temperature/relative humidity sensors log every 5min. More information on monitoring techniques and instrumentation applied in the case studies can be found in the evaluation-instrumentation Section (7.2.2.2). Both the ground and the first floors are heated using radiators in all spaces; the loft space is unheated and uninsulated. The house has access to the gas grid and the tenants (during the experiment) used “pay as you go” tariffs to fuel the gas combi boiler, a Vaillant eco TEC pro 28. The boiler (used for both space heating and hot water) has a space heating maximum nominal output at 16.5kWh and a SAP annual nominal efficiency of 89.5%.

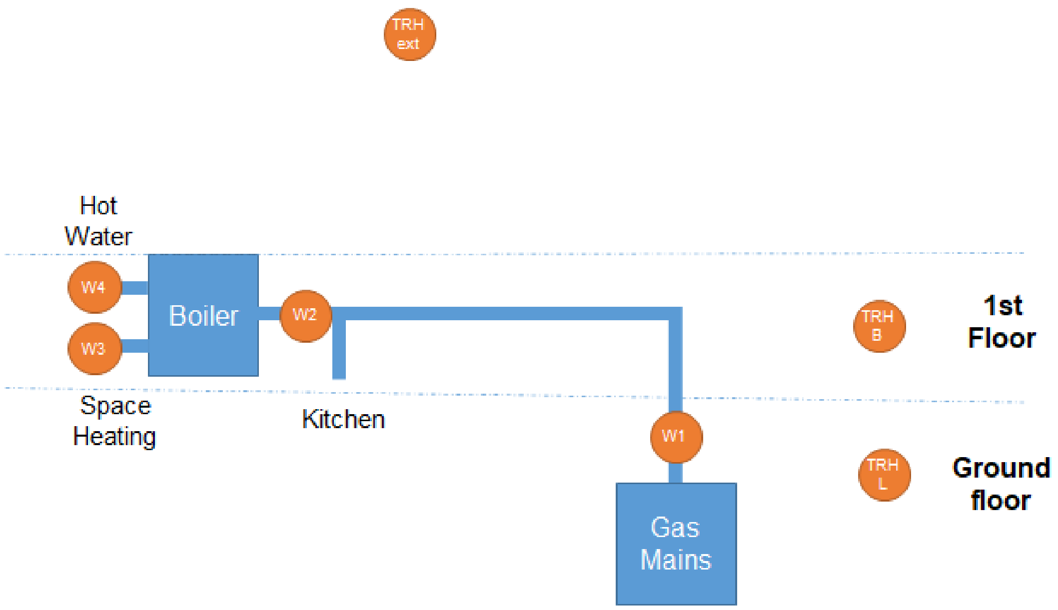


Figure 7-12 Rhondda end-terraced house; pre-retrofit monitoring plan for space heating delivery, boiler, Gas an essential comfort, author.

The heat balance equation was applied to SAP modelling and HTB2 modelling to calculate annual heating demand. This was referenced against the Welsh average as the experimental case study represents an average Welsh domestic example. The Welsh average space heating data were calculated in Table 2-4 by using data from NEED (109) and Odyssee-Mure report (108). Monitoring data for a full pre-retrofit year are also included as measured and normalised based on heating degree days normalisation method discussed in the corresponding framework Section (6.1.1.3.2). All annual totals described above, are compared in Figure 7-13 resulting to the findings below:

- The normalised monitored annual figure (10,953 kWh) is only 0.6% lower than the monitored 2017 figure following the 0.6% different between the CIBSE 25-year historic and 2017 calculated HDD as shown in Table 7-1.
- The Welsh average space heating annual data normalised for a 100m^2 house such as Rhondda end-terraced (94.8m^2 is the Welsh average) is 7.7% higher than the normalised monitored which indicates that Rhondda end-terraced is a house that represents average house stock.

- The SAP modelling space heating annual data is lower than the normalised monitored (15%); however, the HTB2 is significantly lower (19%) than the monitored.

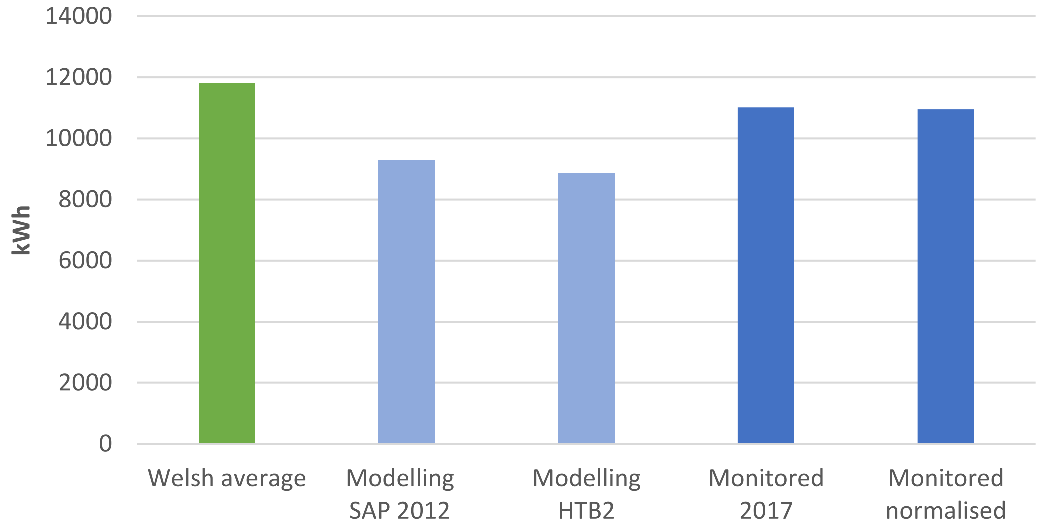


Figure 7-13 Rhondda end-terraced house; pre-retrofit modelled, monitored and reference space heating annual data, author.

When investigating space heating for new builds, only modelling figures can be calculated; however, modelling can be calibrated for specific use. For example, in Solcer house, the initial purpose of this WSA project was to build a demo house for a typical UK household; however, the building was used as an office. In Figure 7-14, the space heating demand is shown adjusted for house and office use. Welsh average and PassivHaus benchmarks were adjusted for 105m^2 space. The house-use space heating demand is 38% lower than the office-use; still significantly lower than the Rhondda end-terraced pre-retrofit figures. This is due to different fabric materials and airtightness.

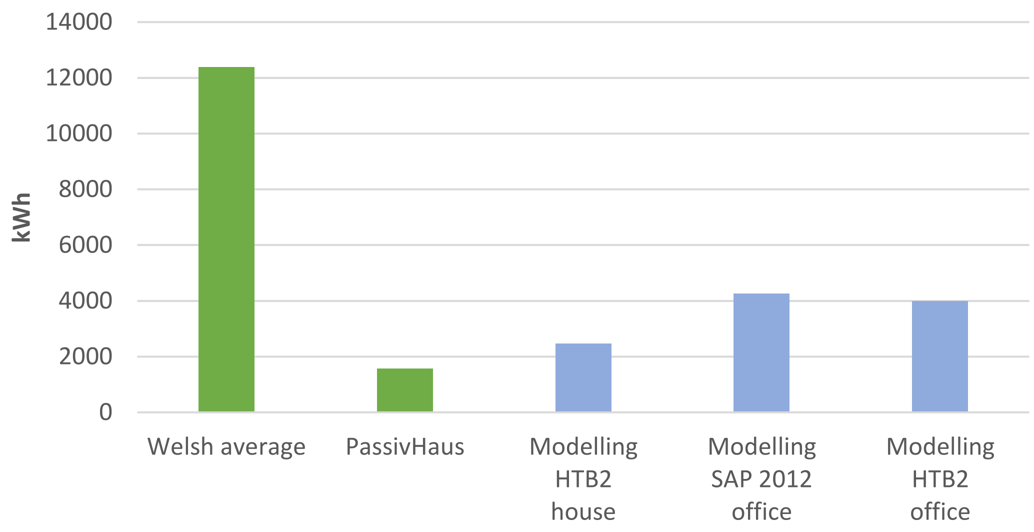


Figure 7-14 Solcer house new demonstration house/office; modelled and reference space heating annual data, author.

In order to understand performance gap reasons and take informed retrofitting decisions, more comfort variations and occupancy patterns should be explored. The first parameter to consider is the temperature variations that refer to the monitored space heating deliver data. In Table 7-5, some low temperatures are observed in comparison to CIBSE Guide A benchmarks (87) presented in table 2-2 in Chapter 2. Yellow highlights indicate temperatures which are borderline to the recommended values. Orange highlights indicate significantly lower temperatures to the recommended values. The lowest value was 17.6°C for December when the suggested range is at 22-23°C. It has to be mentioned that the thermostat is installed on the wall at the bottom part of the staircase by the living room and the living room is constantly opened, the monitored annual average for the living room is at 20.3°C, however, the winter average is at 18.7°C and the heating season average at 18.7°C. These values need to be compared to the SAP and HTB2 set point value at 21°C and 20°C respectively. The modelling set point difference explain the annual heating demand difference between SAP and HTB2, as more energy is needed to reach higher temperature; however, it does not explain the difference to the monitoring data as monitored average temperature for the heating season is lower than the modelled thus lower space heating than modelled would be expected. By taking semi-structured interviews from the occupants, extra information was revealed:

- The occupants spend more time in the house than average as they are unemployed or part-timers.
- They open the window backyard external door and lounge windows more often than average due to smoking emissions.

- They would use the rotary thermostat at peak ON-OFF mode; instead of setting a desired temperature, the thermostat was turned clockwise at maximum (30°C) which is a theoretical target as it is unlikely that the corridor would ever reach that set point during heating season due to heat losses. This does not allow for the house to reach a temperature plateau and leads to uncontrolled heating patterns that are not shown when averaging temperature over a month or season.

Table 7-5 Rhondda end-terraced house; pre-retrofit monthly temperature averages for the living room and main bedroom, author.

	Temperature (°C)	
	Living room	**Main Bedroom**
Jan-17	19.1	16.9
Feb-17	19.3	17.3
Mar-17	20.2	18.2
Apr-17	19.9	19.4
May-17	21.0	21.4
Jun-17	21.9	21.9
Jul-17	22.7	22.8
Aug-17	21.3	21.2
Sep-17	20.9	20.2
Oct-17	20.6	19.3
Nov-17	18.9	17.0
Dec-17	17.9	17.0
Average 2017	**20.3**	**19.4**

The issue with manual control of the set thermostat is demonstrated in Figure 7-15 for March 2017 when bedroom air temperature was monitored. The temperature variation is from 14 to 22°C but never reaching a plateau indicating a manual ON-OFF operation. The occupants had indicated that they use the heating 2 hours in the morning and 2 to 4 hours in the evening during heating season; however, this is not backed up with data. Figure 7-16 shows that the thermostat is used, on average, 8 hours per day switching manually to ON and OFF various times per day. The need for opening the kitchen external door multiple times per day explains the heating system scheduling and operation and the increased consumption. The hourly peak is at 9.8kWh for this representative week and the annual peak is at 12.1kWh for monitored space heating delivery.

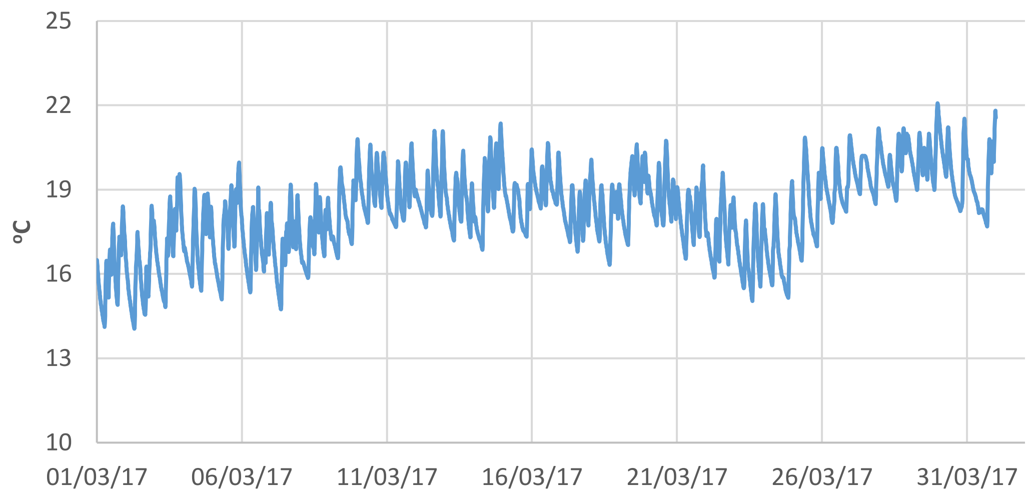


Figure 7-15 Rhondda end-terraced house; pre-retrofit monitored temperature variation in the main bedroom for March 2017, author.

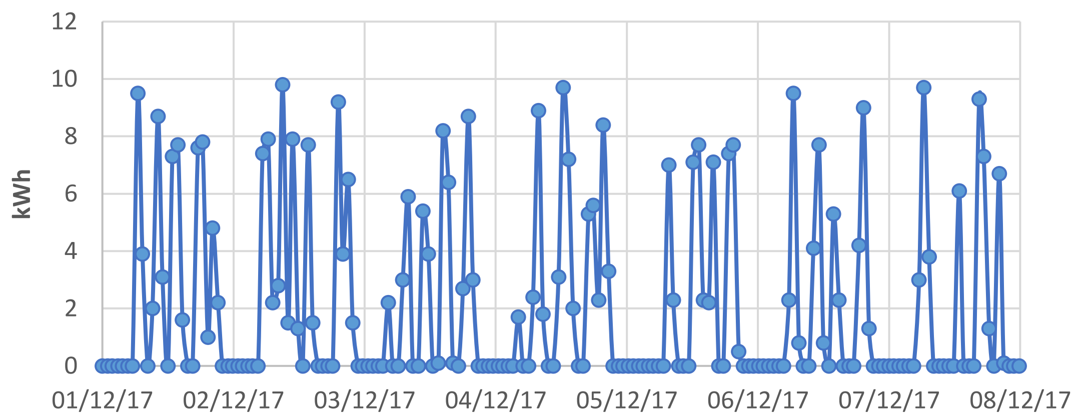


Figure 7-16 Rhondda end-terraced house; pre-retrofit monitored space heating delivery for the first week of December 2017, author.

Figure 7-17 demonstrates the heating season profile for the existing occupants. The house is occupied by two adults and two kids that are part-time home-schooled. The graph indicates hourly average space heating delivered for 2017 heating season showing a 2.1kWh average power heat delivery or approximately 50kWh per day for the seven heating season months. There are two peaks that are expected in the morning and evening but the in between heat delivery is significantly high revealing that the house is highly occupied and heated during the day. This pattern does not match the typical UK profiles where the energy used around noon is significantly lower than morning and dinner time as shown in Figure 6-3 in Section 6.1.1.3.2. This profile (Figure 7-17) is representative for social housing where heating demand during sun-hours is a better match for solar thermal applications. During the heating season, 21.7kWh (45%) of heating requirement occurs between 9am and 6pm. In other words, almost half of the space heating could be covered by solar thermal during ideal solar availability.

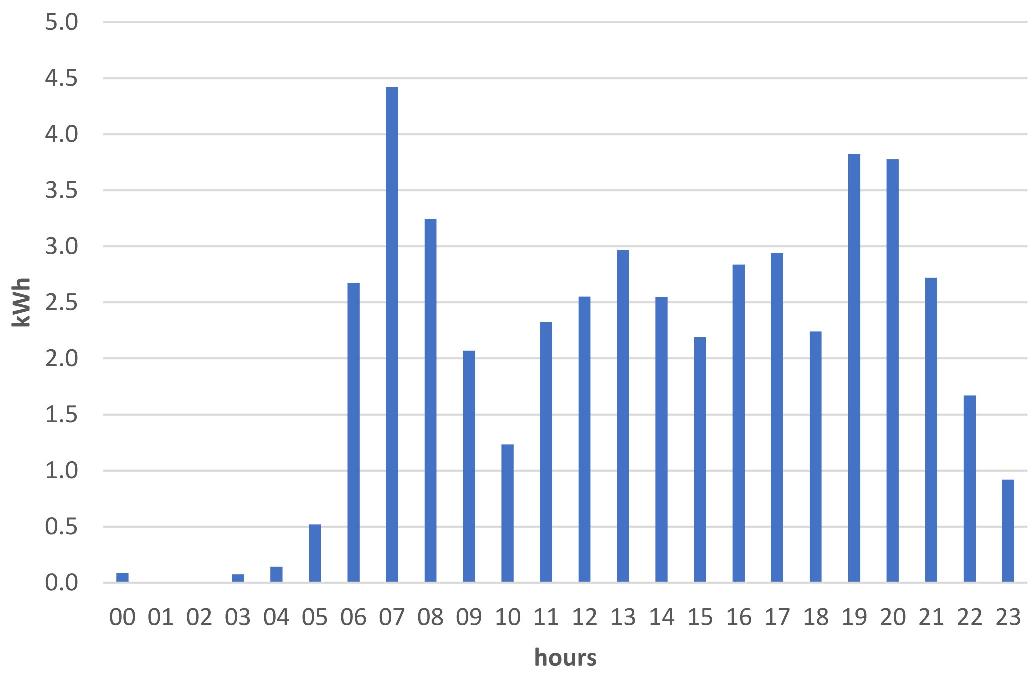


Figure 7-17 Rhondda end-terraced house; pre-retrofit monitored space heating delivery daily profile in hourly bins for the heating season of 2017, author.

Another source of potential mismatch between monitoring and modelling is the U value assumptions made as the SAP and HTB2 use fabric thermal transmittance data that is hard to be verified through measurements. An example of this deviation is that the U value for external walls used in the Rhondda end-terraced modelling was 1.3 W/m^2K whereas the averaged monitored value measured was $1.5W/m^2K$; a change that would impact 6.5% the annual modelled figure. Also, SAP default calculations will not consider any space heating for summer months and September which account for another 8.3% as seen in Figure 7-18. This mean that if SAP is calibrated for U values and summer heat demand, the annual total space heating demand will be close to the normalised monitored one.

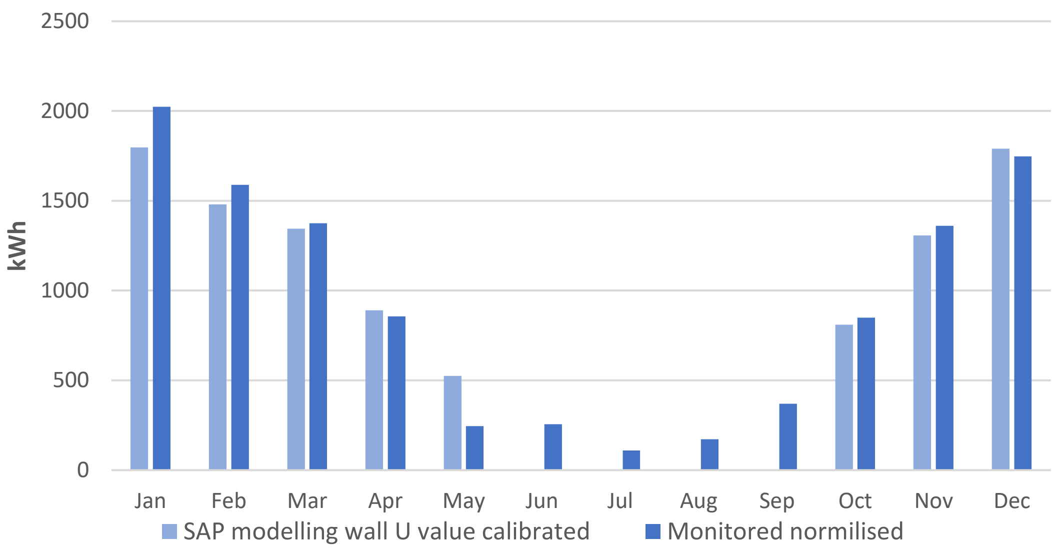


Figure 7-18 Rhondda end-terraced house; pre-retrofit monthly space heating demand modelled and calibrated for real wall U values and monitored normalised for historic weather data, author.

A fundamental use of TSCs is to displace/reduce the conventional fuel used for space heating delivery. To find out how much fuel was used to deliver heating for space, any system losses such as the boiler's losses should be added to the space heating delivery. There are two ways to approach this; the first is by using the nominal efficiency factor and the second is by monitoring the real monitoring efficiency factor. The nominal efficiency for Rhondda end-terraced boiler is at 89.5% meaning that in theory 12,308kWh of gas would deliver 11,016kWh of space heating in a year. The monitored-calculated efficiency for the boiler is at 78.6%, increasing to 82.8% during heating season. This was measured and calculated following the monitoring plan in figure 12. The gas volume used for the boiler was measured with a flow meter (m^3) and converted to kWh, while the heat products of the boiler (space heating and hot water) were individually measured with heat meters (kWh). More information can be found in the instrumentation Section (7.2.2). The house has hot water taps in the kitchen and in the bathroom where an electric shower is also used. Any difference between the energy equivalent of gas and the total of hot water and space heating would be consumed by the boiler and considered as losses. Figure 7-19 shows the breakdown of gas use in the house including losses for monthly daily averages and annual total. The boiler losses when delivering hot water are slightly different to when delivering space heating. Nevertheless, hot water accounts for less than 8% (956kWh), which means that the total boiler losses percentage could be used when referring to losses when producing space heating. At 21.4% losses, 11,016kWh space heating was delivered by 14,015kWh of gas.

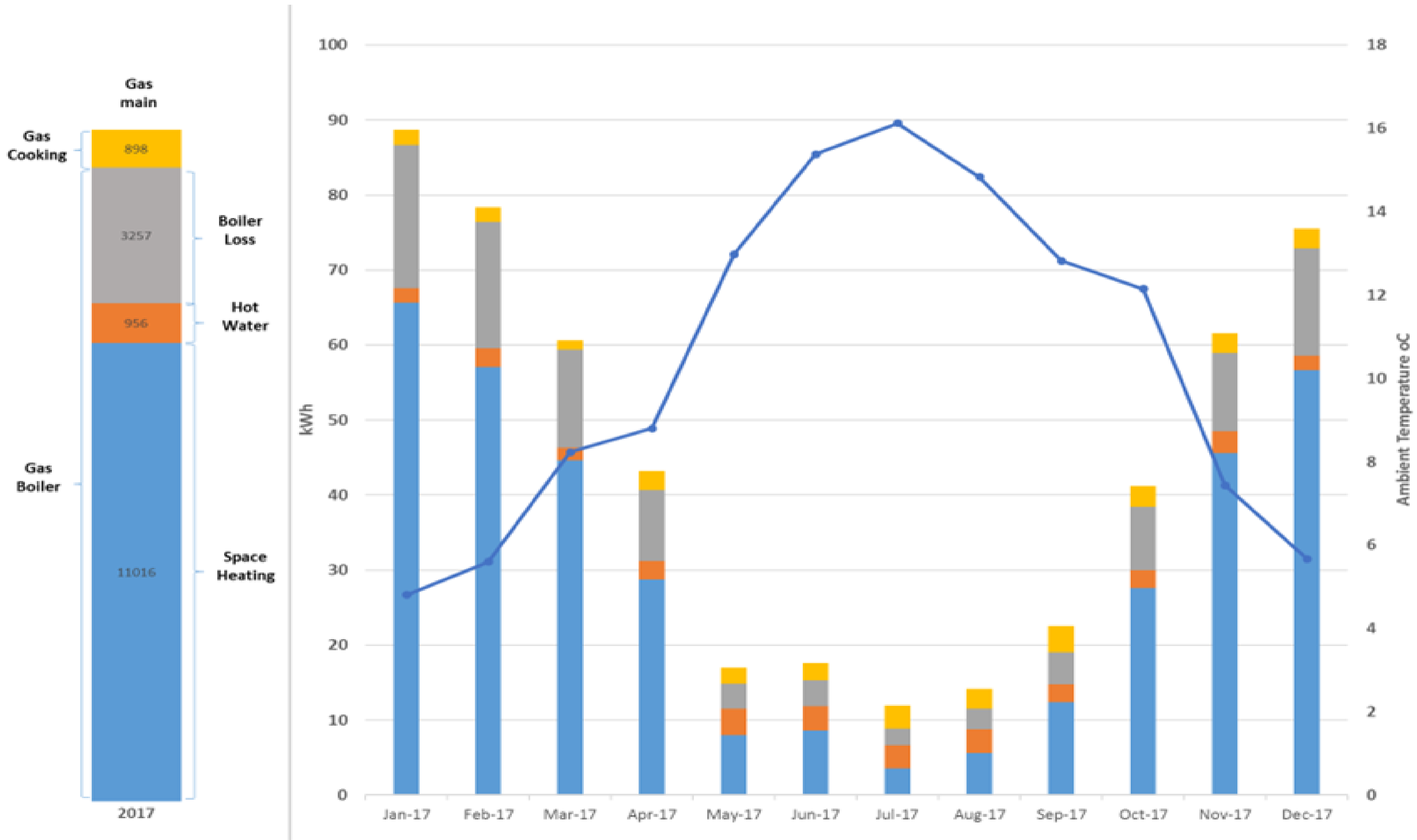


Figure 7-19 Rhondda end-terraced house; pre-retrofit 2017 daily averages per month and annual total gas consumption break down including losses and average monthly external temperature, author.

Summarising for this house, the total space heating delivery for 2017 was 11016kWh. The total gas consumed in the house was 16127kWh and the electricity consumed was 3175kWh, meaning that space heating accounted for 68% of the gas and 57% of the total energy consumed in 2017.

When the heating system is a heat pump, seasonal COP should be considered to estimate/calculate electricity consumed to deliver space heating. Again, nominal values or monitored values can be used. In SOLCERH_RV, the seasonal COP of the heat pump used was 3.2 (manufacturer) meaning that it was expected that annually the 4267kWh of space heating (Figure 7-14) would be delivered by 1333kWh of electricity.

7.1.1.4 Cost and further feasibility considerations

Access was considered in all experimental sites in terms of TSC installation and ducting of heated air to the desired supply space. In Rhondda, the end-terraced south-east garden is accessed from the rear façade (kitchen) and a side gate from the street. The attic is accessed by ladders with a maximum height at 1800mm. In comparison, in Saxon Court, the complexity and low height of the attic, as well as the roof dormers (Figure 7-20) made a roof installation not preferable. Also supply to the ground floor would need very long ducting meaning potential high losses. This is the case with all the multi-storey buildings where the heat needs to reach the ground floor. This was also an issue with the Glan Clwyd corridors where the TSC could not be installed away from the corridors, however the adjacent vertical wall was in an area where students had access. This raised two concerns; the first was structural as children might damage the surface and the second was about risk of burn as students might touch the warm TSC surface during a sunny day. The concerns will be discussed in the integration phase (Section 7.1.3).

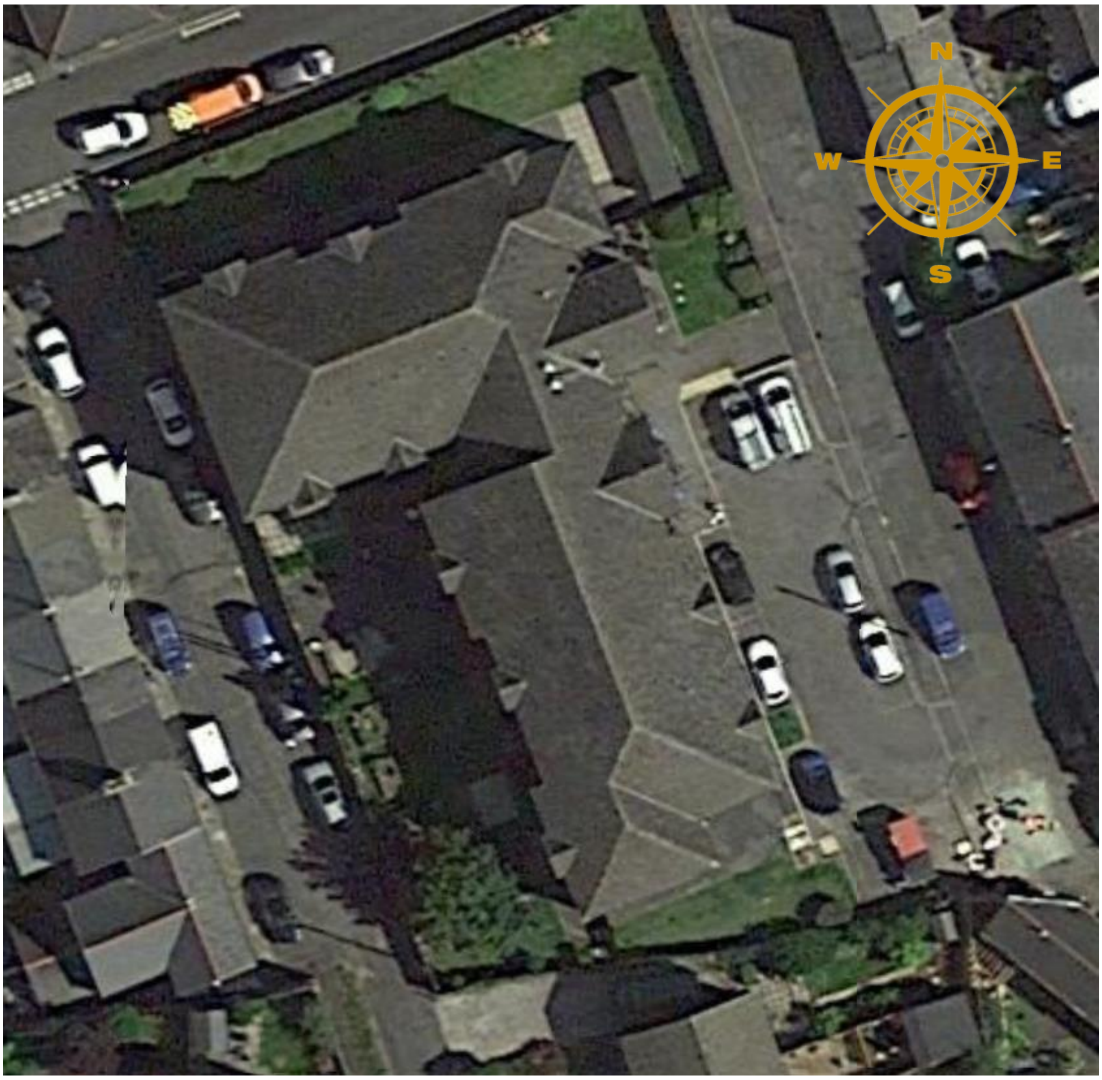


Figure 7-20 Saxon Court residence – roof profile including dormers, Satellite Google Earth photo, author.

Extra information was gathered on existing or future services for all the buildings. The EPC of the Rhondda end-terraced house published in 2015, indicated an Energy Efficiency Rating of 47 which is middle range band E. This is lower than the average energy efficiency rating for a dwelling in England and Wales which is band D (rating 60). Although double-glazed windows had been installed, the property lacked insulation. In addition, condensation and damp were observed in the west wall during the initial survey (Figure 7-21). The occupants reported deterioration of asthma conditions and stated that “the kids were constantly ill”. They also reported that the thermal comfort of the main bedroom and the living room was poor (west façade) whereas the kids bedroom condition was fine in the winter however there was some overheating in the summer. Adding to the cold west rooms, the occupants described that the damp smell was more intense in the morning. The relative humidity was monitored during the pre-retrofit year (2017). At first, sensors were placed in the living room and main bedroom (bedroom 1 in Figure 7-6); and later (May 2017), another sensor was placed in the living room by the west wall where damp was highly evident. In Table 7-6, average monthly relative humidity figures in % are shown; yellow colour was used to indicate borderline (65-70%) and orange to show unacceptable values >70%. The internal moisture problem is evident all year with average values significantly higher than the recommended 40-70% CIBSE range (87). The problem with moisture is even more visible when data are analysed against a timeline. As an example, a 30-minutes interval master bedroom relative humidity data set for March 2017 indicates that relative humidity was continuously above 70% all day long for the whole month. Similar results were obtained for a series of months during the pre-intervention stage.

Figure 7-21 Rhondda end-terraced house; pre-retrofit condensation and mould across the west wall.

Table 7-6 Rhondda end-terraced house; pre-retrofit monthly and relative humidity averages for the living room and main bedroom, author.

	Relative Humidity (%)		
	Living room centre	Living room west wall	Main Bedroom
Jan-17	54.5		71.9
Feb-17	58.8		77.8
Mar-17	58.3		82.0
Apr-17	50.7		65.7
May-17	57.0	65.6	58.5
Jun-17	61.8	70.7	63.2
Jul-17	62.8	71.0	63.3
Aug-17	66.8	78.8	70.8
Sep-17	67.0	79.7	78.2
Oct-17	67.2	80.6	85.6
Nov-17	62.0	74.5	81.7
Dec-17	54.9	70.3	76.8
Average 2017	**60.2**	**73.9**	**73.0**

In order to ventilate the house, the occupants would use natural ventilation by controlling the opening of windows/doors and their trickle vents. However, both the kitchen and bathroom had manually controlled extracting fans. The occupants were conservative gas users due to financial reasons. As is common for this type of occupant, they tended to under-ventilate spaces; this has health implications, particularly in spaces occupied by smokers. CO_2 measurements tests indicated an average of 1200pmm in the living room, dropping to 550 during the night and rising to over 2000ppm during high occupancy. CIBSE guidance characterizes CO_2 level of 1200pmm as “very bad” indoor air quality, recommending values of 1000ppm and below (23, 87).

As a response to the observations above external wall insulation and MVHR were prioritised together with a PV panel on the east and west façade and electric storage battery. The above decisions impact the TSC decision-making process in the following ways:

- The PV would occupy the roof meaning that the TSC could be installed on the south wall only and an aesthetically pleasant integration of the two systems should be considered.

- The south wall will carry external wall insulation meaning that the TSC would have to be attached in a way that ensured structural robustness and minimisation of thermal bridges via the wall brackets.
- The MVHR was preferred to ensure moisture control and heat recovery all the time. Therefore, the TSC would have to integrate with a system that also warms up the air through the heat exchanger – this raised doubts on effectiveness.
- The attic would have to accommodate a lot of technologies and ducting including a connection from the back of the TSC to the MVHR unit.

The above feasibility considerations for Rhondda end-terraced were discussed with the team and contractor and considered resolvable, and solutions are provided in the building integration Section (7.1.3) later in this Chapter. A cost analysis will be presented in the sizing and modelling (Section 7.1.2.3); however, as suggested by the framework a basic cost estimation could be considered in the feasibility stage to make sure that it is reasonable to proceed to the design and building integration phases (presented in 7.1.2 and 7.1.3).

- **Solar availability for available fabric**:
  The total south wall area is 35m^2 however, only 20m^2 could be utilised due to the window (Figure 7-6) and fence shading. The solar availability per square meter of the vertical façade for each month is shown in Table 7-2.
- **Desired volume flow rate:**
  The ventilation needs as determined in 6.1.1.3.1 is 17-21l/s or 61 to 75.6m^3/h. Allowing for a 30% boost, the maximum requirement would be 100m^3/h. The TSC flow rate range is from 15m^3/h per m^2 of TSC (167, 218) to 73.4m^3/h per m^2 of TSC (219, 264), meaning that the in the worst case scenario approximately 7m^2 of TSC would be installed to serve the maximum house flow rate with the minimum TSC flow rate.
- **TSC average efficiency and Heating output**
  For 15m^3/h per m^2 of TSC the efficiency could approximately go down to 15% (193). According to Table 7-2, approximately 390kWh/m^2 fall onto the vertical wall during the heating season (Table 7-2) meaning that if 15% of solar is converted to heat, 7m^2 of TSC would produce 410kWh of heat per year. The remining non heating season solar availability would produce approximately 432kWh of heat per year through the TSC and could be used for storage.
- **Heating output cost**
  This may cost:

£172.2 per year for £0.42/kWh (2022 Oct electricity cap Ofgem (265)) if produced by a 100% efficient electric heater.

£57.4 per year for £0.42/kWh (265) if produced by a HP with an average COP of 3.

£40.2 per year for £0.12/kWh (265) if produced by a 80% efficient gas boiler.

- **Cost and payback**

  The price including all costs according to NREL and adjusted for inflation is £230 per m^2 of TSC as discussed in Chapter 4. This means that a worst-case scenario of installing $7m^2$ of TSC would cost £1610. This means that with the October 2022 energy prices, the worst-case scenario is for the TSC to have approximately 40years payback when replacing space heating delivered from a boiler, 28years from a HP and 9years from an electric heater.

7.1.2 Design Integration

The application of design integration of the ten experimental studies is presented in this Section. TSC was discussed in early design stage in Solcer house, whereas in B&Q store there was minimum flexibility as TSC was a late design addition. Of the remaining eight retrofits, only two (Rhondda end-terraced and Rhondda-terraced) had the heating system decided in parallel with the TSC potential. For the other six, TSC had to incorporate the existing heating system. All ten case studies went through feasibility testing to enable informed decisions on design intention and strategy, variants and collector selection and sizing and modelling. All the above design integration parameters will be discussed through the application of the framework to the experimental case studies.

7.1.2.1 Design intention and strategy

The whole building services intervention approach is presented below for the Rhondda end-terraced house as an example of defining the context before discussing TSC design priorities and parameters. The analysis of the pre-intervention monitoring informed the decision-making process to select appropriate improvements to the house. Key issues to be addressed were identified as:

- Damp walls with high RH and CO_2 levels causing respiratory health issues.
- Heat loss through fabric and infiltration.
- High gas and electricity grid use.

The key decisions to address the above were:

- introduced solar PVs to reduce grid needs.

- Improve heat retention of building fabric (improve insulation and air tightness).
- Introduce MVHR to improve ventilation.
- Introduce air solar thermal (TSC) to preheat fresh ventilated air.

The MVHR unit was considered to be an appropriate response because it would:

- Provide continuous year-round extract ventilation aiming to reduce issues such as mould or condensation by controlling RH and CO_2.
- Provide filtered fresh air (supply) which will increase the air quality and thereby address health issues and wellbeing.
- Decrease the need to open doors and windows and trickle vents during deep winter and suffer from resulting significant heat losses, exposure to noises, smells, or reduced security.
- Recover and reuse the waste heat within the property.
- Provide, during summer, fresh cooling air in living areas through summer bypass.

The above example set the scenery to better integrate a TSC system. Before the design intention is presented, design priorities are detected through summarizing the feasibility, aesthetics and systems integration opportunities and obstacles.

Table 7-7 highlights the opportunities and challenges that emerged from the feasibility study of all the experimental case studies. In all the cases there was a requirement for ventilation and heating although in B&Q store natural ventilation strategies had been designed before TSC discussions. The schools had an optimal demand scheduling that matches the solar availability. The domestic retrofits had moisture problems that could be resolved with mechanical ventilation. Area and ducting limitations were observed in the schools. Only the domestic buildings were airtight which makes over pressurisation an option for the non-domestic to reduce infiltration. Some of the walls include openings that required bespoke finishing and potential to cause TSC cavity flow turbulence. Retrofitting ducting, especially in domestic buildings is both a special and aesthetics challenge. More application details will be discussed in the building integration Section (9.1.3).

Table 7-7. Opportunities and obstacles extracted from the feasibility analysis of the experimental case studies, author.

No.	Experimental case study name	Feasibility opportunities	Feasibility challenges
1	**SEDA Ltd. Blackwood, production hall**	• Good roof and south wall potential • Robust roof • High heating and ventilation demand	• Low airtightness • 24/7 heating demand • Skylights in the roof
2	**B&Q store Cyfarthfa, retail store**	• New building • Good roof potential • Robust roof • High heating and ventilation demand • Scheduling match solar	• Low airtightness • Tight deadlines • Designed to optimise natural ventilation
3	**Lampeter School, main hall**	• High heating and ventilation demand • Robust roof • Scheduling match solar	• Limited south roof areas potential • Low airtightness • Insulate external ducting
4	**Lampeter School, cloakrooms**		
5	**Glan Clwyd School, theatre**	• High heating and ventilation demand • Robust roof • Scheduling match solar	• Limited south roof and wall areas potential • Low airtightness • Roof away from HVAC • Insulate external ducting
6	**Glan Clwyd School, corridors**		
7	**Saxon Court residence, corridors**	• Good south wall potential • High heating and ventilation demand	• Stairwell with low airtightness • Many doors and windows on the south elevation
8	**Rhondda House (terraced)**	• Good roof potential • Comfortable attic • Internal moisture issues	• Retrofitting ducting • Works during occupancy
9	**Solcer house (detached)**	• New build - early design integration • Good roof and south wall potential • High airtightness	• Should consider both domestic and office use • Windows and door on south elevation
10	**Rhondda House (end-terraced)**	• Good roof and south wall potential • Comfortable attic • Internal moisture issues	• Retrofitting ducting • Works during occupancy

Table 7-8 underlines opportunities and challenges concluded from the discussion with clients and contractors on aesthetics for the experimental case studies. The expectations on the industrial, retails and schools were not high, as in most of the cases the TSC installations would not be visible. Where case studies had existing HVAC and ventilation systems ducting was already in place meaning that TSC would have no or minimum impact to the indoor aesthetics. For the domestic buildings where the ventilation system was a new addition, risers, suspended ceiling or boxed-in solutions should be designed to enclose ducting with a view to use minimum living space. For the non-domestic, visible exposed ducting was decided. Skylights and openings should stay unaffected including provision for aesthetically pleasant window seals. Dummy panels should be installed to homogenize the façade which would mean provision for not transpired identical panels to integrate into the TSC installation. This was decided for the east-north-east façade in Saxon court as seen in Figure 7-20. Also, PVs were designed for both Solcer and Rhondda end-terraced house. This increased the integration complexity as the TSCs should blend with both the surrounding fabric and photovoltaic panels. Metal cladding finishing, colour and dimensions matching were explored for this purpose. More details on building beatification will be discussed in the building integration Section (7.2.3).

Table 7-8 Opportunities and challenges extracted from the aesthetics evaluation of the experimental case studies, author.

No.	Experimental case study name	Aesthetics opportunities	Aesthetics challenges
1	**SEDA Ltd. Blackwood, production hall**	• No high expectations • Existing ducting	• Skylights should remain
2	**B&Q store Cyfarthfa, retail store**	• No high expectations	• Part of roof was green (flora) - unavailable • Need for exposed ducting
3	**Lampeter School, main hall**	• No high expectations	• Retrofitting ducting • Part of ducting should be external
4	**Lampeter School, cloakrooms**	• No high expectations	• Retrofitting ducting
5	**Glan Clwyd School, theatre**	• No high expectations • Existing internal ducting	• Part of ducting should be external
6	**Glan Clwyd School, corridors**	• Available adjacent vertical option	• Retrofitting ducting
7	**Saxon Court residence, corridors**	• No high expectations	• Retrofitting ducting • Potential dummy panels to homogenise south elevation
8	**Rhondda House (terraced)**	• Roof is not visible from street	• High expectations • Retrofitting ducting
9	**Solcer house (detached)**	• Suspended ceiling with integrated ducting	• High expectations • Integrate with PV • Potential dummy panels to homogenise south elevation
10	**Rhondda House (end-terraced)**	• Good potential to use south wall gable-end	• High expectations • Retrofitting ducting • Integrate with PV

Table 7-9 summarises the opportunities and challenges identified in the integration of TSCs to existing or designed heating and ventilation services for the experimental case studies. In SEDA factory and Glan Clwyd theatre, the TSC should fit into an existing HVAC system which addresses sizing calculations and duct concerns; however, a bespoke connection has to be designed. For most of the other case studies ventilation needs were met or supposed to be met by natural ventilation and heating was provided by wet systems. This gives the opportunity to design a TSC system based on over-pressurisation and reduce infiltration. The was not the case in

Solcer house and Rhondda end-terraced where air tightness was high meaning supply and extract should be considered; for this reason, MVHR systems were considered and the TSC should integrate to the supply side. A challenge across the board was that all buildings included a heating system controlled by thermostats which means that TSC should incorporate these controls and relate them to automations including flow adjustments and bypass or recirculation controls. Another challenge is that the MVHR system may control boost mode via a humidistat or other controls forcing the TSC to increase the flow. More on the systems integration and controls will follow in the building integration Section (7.2.3).

Table 7-9 Opportunities and challenges extracted from the assessment of the designed/existing heating and ventilation services of the experimental case studies, author.

No.	Experimental case study name	Existing services opportunities	Existing services challenges
1	**SEDA Ltd. Blackwood, production hall**	• Existing HVAC system	• Integration into two big AHUs with controls
2	**B&Q store Cyfarthfa, retail store**	• Wet heating system, no physical integration	• Incorporation with natural ventilation • Ensure destratification despite high elevation
3	**Lampeter School, main hall**	• Wet heating system, no physical integration	• Integration with existing thermostat
4	**Lampeter School, cloakrooms**		
5	**Glan Clwyd School, theatre**	• Existing HVAC system	• Integration into big AHUs with controls • Integration with a system including Heat Exchanger
6	**Glan Clwyd School, corridors**	• Wet heating system, no physical integration	• Integration with existing thermostat • Supply to two different floors
7	**Saxon Court residence, corridors**	• Wet heating system, no physical integration	• Integration with existing thermostat • Supply to three different floors
8	**Rhondda House (terraced)**	• Wet heating system, no physical integration	• Integration with existing thermostat
9	**Solcer house (detached)**	• MVHR/HP inlet could be used as TSC outlet	• Integration with a system including Heat Exchanger
10	**Rhondda House (end-terraced)**	• MVHR inlet could be used as TSC outlet	• Integration with a system including Heat Exchanger

In Table 7-10, the design intentions and strategies are presented for each of the experimental case studies. Reduced space heating demand is a fundamental intention across the board. When natural ventilation is already embedded in the design, The TSC could over pressurise, thus prioritising temperature rise to avoid cold drafts. When the TSC feeds into an HVAC, then the priority is to increase the mass flow rate per TSC area up to 120m^3/h per m^2 of TSC in response to cost parameters. For NREL the cost-effective applications should have a flow rate at maximum 73.4m^3/h per m^2. The maximum flow is the flow that maximises heat delivery, meaning the TSC efficiency peaks just before reaching a plateau as shown is 3.2.3 and also tested in figure 4 Chapter 8. The TSC performance graph depends on the panel characteristics and the 120m^3/h refers to TATA steel dark anthracite panels used in most of the case studies. In Solcer house and Rhondda end-terraced house maximising temperature rise was a priority to deliver temperatures close or above the heat exchanger (recovery) temperature. In these two houses, aesthetics was a priority and integration detailing was a strategic decision that would impact costs. Bypass and recirculating dampers were also decided based on the design intentions for some of the case studies and details will be discussed in the variants selection and building integration Sections (6.2.3).

Table 7-10 Design intentions and strategies based on feasibility, aesthetics and services priorities for the experimental case studies, author (continued overleaf).

No.	Experimental case study name	Design Intention	Strategies
1	**SEDA Ltd. Blackwood, production hall**	• Integrate to existing HVAC • Reduce heat demand • Avoid overheating • Integrate on roof without affecting skylights	• Maximise TSC efficiency by maximising flow rate /m^2 • Use of summer bypass • Use transparent panels where skylights are
2	**B&Q store Cyfarthfa, retail store**	• Work together with natural ventilation • Reduce heat demand • De-stratify heat • Aesthetically pleasant design	• Over-pressurise building • Prioritise temperature rise over mass flow rate • Recirculate heat using multiply supply vents • Use proportion architecture for TSC panel and ducting
3	**Lampeter School, main hall**	• Work with natural ventilation • Reduce heat demand • De-stratify heat • Minimise external ducting heat loss	• Over-pressurise building • Prioritise temperature rise over mass flow rate • Recirculate heat using multiply supply vents • Highly insulate external ducts
4	**Lampeter School, cloakrooms**	• Work with natural ventilation • Reduce heat demand • Minimise external ducting heat loss	• Over-pressurise building • Prioritise temperature rise over mass flow rate • Highly insulate external ducts
5	**Glan Clwyd School, theatre**	• Integrate to existing HVAC	• Maximise TSC efficiency by maximising flow rate /m^2

No.	Experimental case study name	Design Intention	Strategies
6	**Glan Clwyd School, corridors**	• Reduce heating demand • Avoid overheating • Minimise external ducting heat loss • Work with natural ventilation • Reduce heat demand • Feed to two floors • Hide ducting that are reachable	• Use of bypass • Highly insulate external ducts • Over-pressurise building • Prioritise temperature rise over mass flow rate • Use of two TSC outputs, fans and controls • Box-in internal ducts
7	**Saxon Court residence, corridors**	• Work with natural ventilation • Reduce heat demand • Feed to three floors • Avoid overheating • Hide ducting that are reachable • Homogenise south elevation	• Over-pressurise building • Prioritise temperature rise over mass flow rate • Use of three TSC outputs, fans and controls • Use of summer bypass • Box-in internal ducts • Use of dummy panels
8	**Rhondda House (terraced)**	• Work with natural ventilation • Reduce heat demand • Recapture attic heat • Avoid overheating • Hide ducting	• Over-pressurise building • Prioritise temperature rise over mass flow rate • Use of attic recirculation damper and filters • Use of summer bypass • Box-in internal ducts
9	**Solcer house (detached)**	• Integrate to MVHR/HP • Reduce heat demand • Avoid overheating • Integrate with PV and fabric	• Prioritise temperature rise over mass flow rate • Use of summer bypass • Metal cladding finishing, colour and dimensions matching • No need for dummy panel on a south elevation
10	**Rhondda House (end-terraced)**	• Integrate to MVHR • Reduce heat demand • Avoid overheating • Integrate with PV and fabric	• Prioritise temperature rise over mass flow rate • Use of summer bypass • Metal cladding finishing, colour and dimensions matching

7.1.2.2 Variants, collector selection and aesthetics

From the 10 case studies (Figure 7-22), only the three, namely SEDA factory, Glan Clwyd theatre and the Solcer house, included an air heating system that could utilise the TSC as a preheater. SEDA factory and Glan Clwyd theatre had an HVAC system, however they were very different in terms of ventilation priorities. SEDA HVAC would provide fresh air but with significant infiltration through the loading doors, so the ventilation was not the priority. Heat recovery in SEDA was the case through de-stratification recirculation; this was a viable option when filtering the polluted recycled air as the places was predominantly naturally ventilated. The theatre on the other hand, would get the benefit of the mechanical ventilation but heat recovery could only happen through a heat exchanger to ensure that only fresh air would ventilate the space. Similarly, in Solcer house, heat recovery could only happen through a heat exchanger thus an MVHR was selected to feed an exhaust heat pump. The TSC could feed the MVHR unit with preheated air and increase the and delivery air temperature. In all three cases, a bypass damper is needed to ensure summer cooling. Also, the heat recovery should be able to shut down when TSC would deliver at temperatures higher to the extracted air to avoid reverse unwanted heat exchange. This could be done by a recirculation damper in SEDA and by a heat exchanger internal bypass in the other two buildings to force the extracted air to be exhausted around the heat recovery cell. In all three PHV TSC, the mass flow rate was predetermined by the existing heating systems. The gas boiler sizing in Glan Clwyd theatre and the HP sizing in Solcer house were calculated to reach constant flows that simultaneously serve ventilation and heat demand.

For five of the remaining case studies (B&Q store, Lampeter corridors and hall, Glan Clwyd corridors and Saxon court) the TSC would not replace the natural ventilation. In these cases, the TSC is an air heater with the additional benefit of mechanical ventilation preventing infiltration through over-pressurisation. This means that summer bypass is not needed as in an overheating event, the TSC could just stop operating and the natural ventilation would ventilate the spaces. An exception was Saxon Court as during the building survey, it was observed that the corridors were very stuffy; thus, it was decided for the TSC to be able to provide 24/7 all year and include a summer bypass. Heat recovery through recirculation was decided only for the B&Q store and the Lampeter hall as these two were the only DHV with high elevation that would benefit de-stratification.

Finally, for the two houses in Rhondda, the TSC would be the mechanical ventilation system, providing 24/7 mechanical ventilation. These both include a summer bypass and a heat recovery mechanism. The heat recovery in Rhonnda end-terraced happens through an MVHR heat exchanger and in Rhondda terraced through recirculating warm air from the attic filtered into the main supply duct.

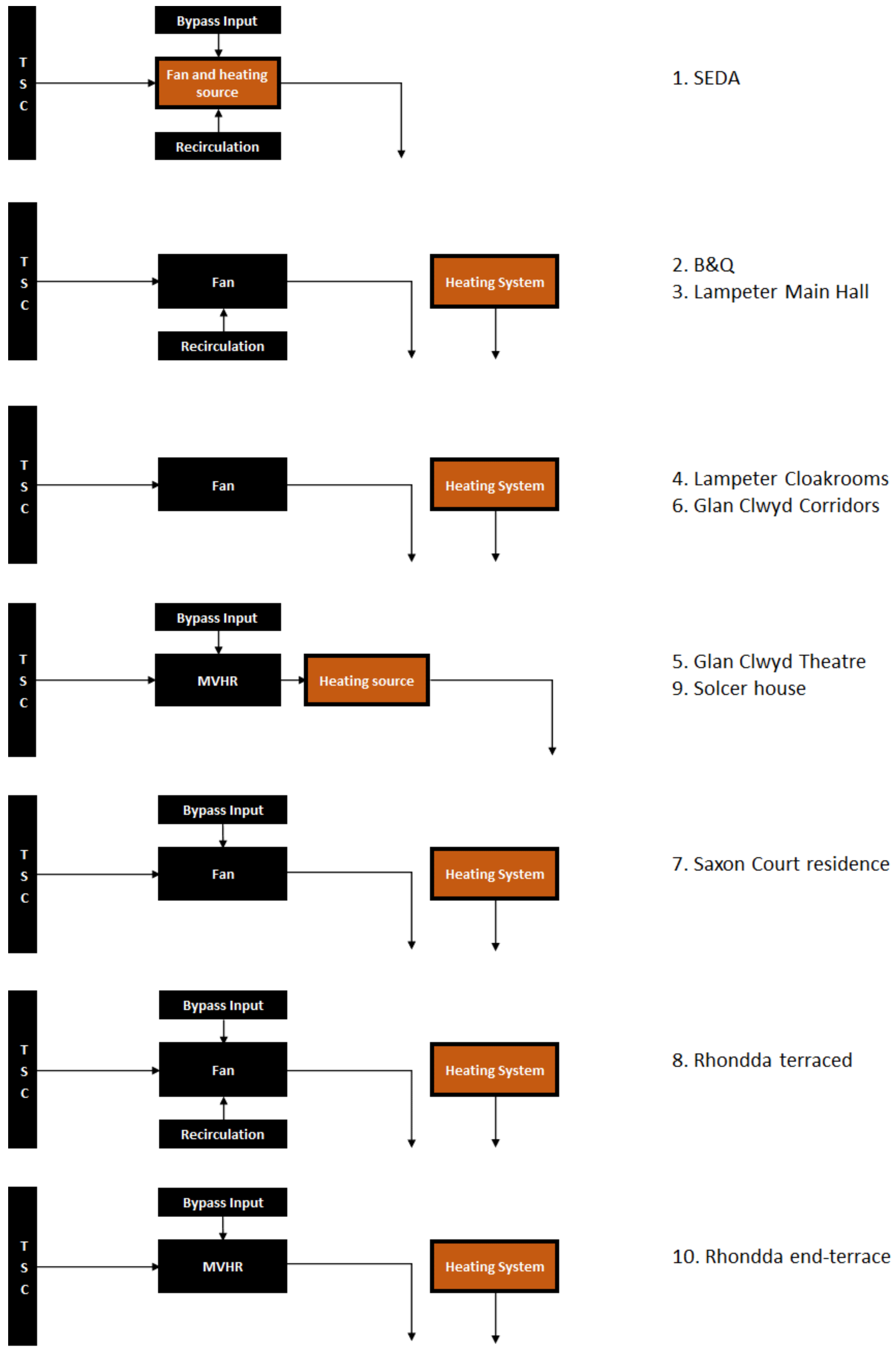


Figure 7-22 TSC Variants and alterations for the experimental case studies, author

Two types of profiles were used in the eight SBED sites (No1-8 Figure 7-22); R32 and the WP40 Colorcoat Trisma profile from TATA steel; both 0.7mm thick (Figure 7-23). The R32 is a roofing sturdy wind-proof industrial profile from TATA steel and was used in B&Q and SEDA. The WP40 is a more refined profile mostly used to mimic flat surfaces and was used in the schools, Saxon Court and Rhondda terraced. A profile called Opus from Euroclad (similar to the WP40) was used for Rhondda end-terrace and a similar bespoke plank profile was used for Solcer house. WP40 and Opus are both aesthetically more pleasant when the adjacent planes are also flat which is the case in schools and houses.

In terms of colours, anthracite and black were used in all the sites except SEDA factory where grey slate was used to better match the light grey roof. As anthracite and black have very similar absorptivity values (81% and 82% respectively (275)), the choice was based on context. For example, anthracite was a better match to the Glan Clwyd roof covered by the typical Welsh graphite slate.

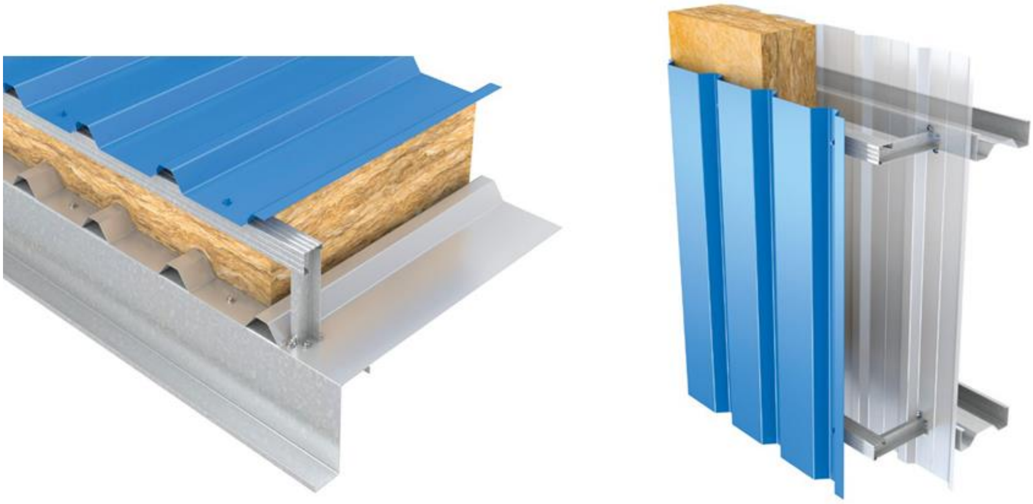


Figure 7-23 Example of R32 (left) and WP40 (right) Colorcoat Trisobuild profiles used for TSC applications from TATA steel, photos from Tata steel Europe website (296).

The perforation was optimised according to Section 3.5.2. In all cases the panel included circular holes with a diameter at 1mm, with a triangular pitch arrangement, pitch of 20mm; this results to a 0.2% porosity.

Following the suggestions for aesthetics “completeness”, The intention was to use the first-floor elevation in Solcer house and the upper part of the south wall in Rhondda end-terraced. This intention will be backed up with sizing optimisation in the following Section (9.1.2.3).

7.1.2.3 Sizing, modelling and cost

Sizing should echo design intent and consider desired ventilation rate as discussed in the framework. The Rhondda house minimum supply ventilation rate based on a two-bedroom dwelling is 17l/s (297, 298). Balanced ventilation strategy is considered to be common practice for dwelling as discussed in Section 2.2.1; for this reason, a balanced MVHR system with a 17l/s (61.2m^3/h) supply and extract was designed with a boost option at 30% more volume flow rate. Two extract ducts would take polluted air from the bathroom and kitchen and three supply ducts would deliver fresh air to the two bedrooms and living room. The MVHR fresh air intake will be connected to the back of a TSC panel to preheat the incoming air dragged from the MVHR supply fan. The system would run continuously as suggested for air-tight buildings (297).

The SWIFT model was used by the author to calculate heat delivery as this would vary for different TSC areas assuming a stable flow rate at 17l/s. Monthly averages for CIBSE 25-year data were input to the modelling including average daily global horizontal radiation, ambient temperature, relative humidity and wind speed. Latitude, longitude and elevation was also included. Inputs according to the framework were filled in the parametrisation of the software. Collector specifications were included such as absorptivity, heat loss coefficient and colour. Orientation and inclination were taken from the site and envelope analysis for the Rhondda south elevation and cavity depth was optimised at 200mm as discussed in Section 3.2.1.3.

As discussed in the framework and in Chapter 3, 120m^3/h per m^2 TSC is the maximum flow rate to test; this would mean that with 0.5m^2 of TSC the 61.2 m^3/h design flow rate target could be reached. This area is expected to deliver the greater heating output per m^2 of TSC but with the minimum temperature rise as discussed in the framework Section (6.1.2.1). Indeed, as seen in Figure 7-24, 0.5m^2 of TSC would deliver 250kWh of heat annually (approximately 500kWh per m^2 of TSC) but with an average temperature rise of only 2.6°C. The simulation was repeated 16 times with 0.5m^2 TSC area increments to 8m^2 while keeping the total flow stable at the design value of 61.2m^3/h. The total heat delivery, heat delivery per m^2 of TSC and temperature rise for the increments are presented in Figure 7-24 while the efficiency variation is presented in Figure 7-25. This figure also includes the annual vertical solar incident energy plotted against the collector's annual average efficiency again for the same area range. There is no reason to go above 8m^2 for this study as the flow per m^2 would drop at 7.65 m^3/h/m^2TSC resulting in flow reversals in the cavity due to low pressure drop (Chapter 3). Also as seen in the graph, both heat delivery and temperature rise reach a plateau for high TSC area. From both graphs, we can extract that for TSC area greater to 2m^2, the heat delivery and the temperature rise will not increase drastically. For increasing the area from 1m^2 to 2m^2, there is 167kWh space heating delivery rise whereas for increasing from 2m^2 to 3m^2 the increase is only 28kWh.

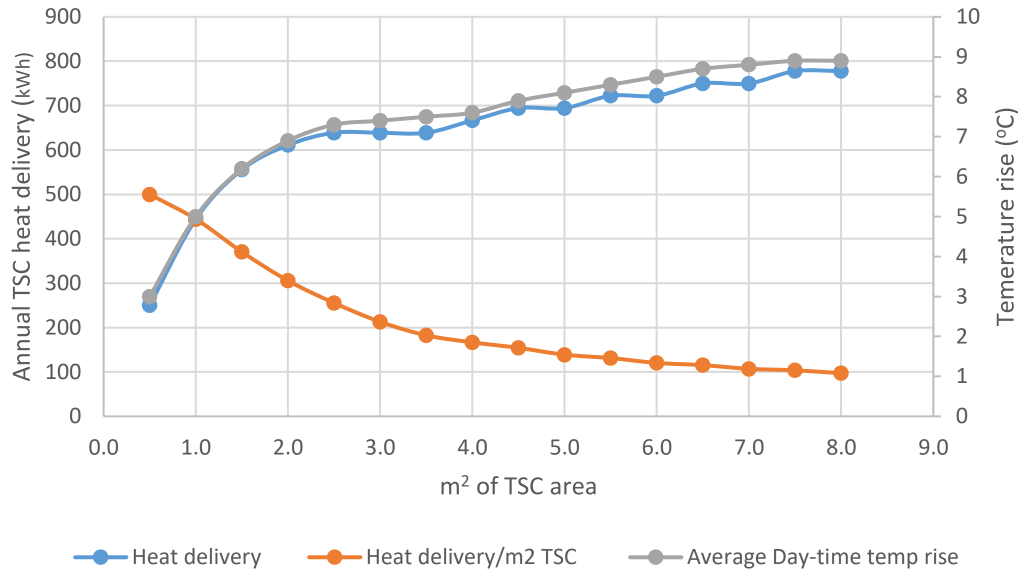


Figure 7-24 Rhondda end-terraced; TSC modelling using SWIFT for sizing. Annual heat delivery and temperature rise against different TSC sizes for 17l/s flow, author.

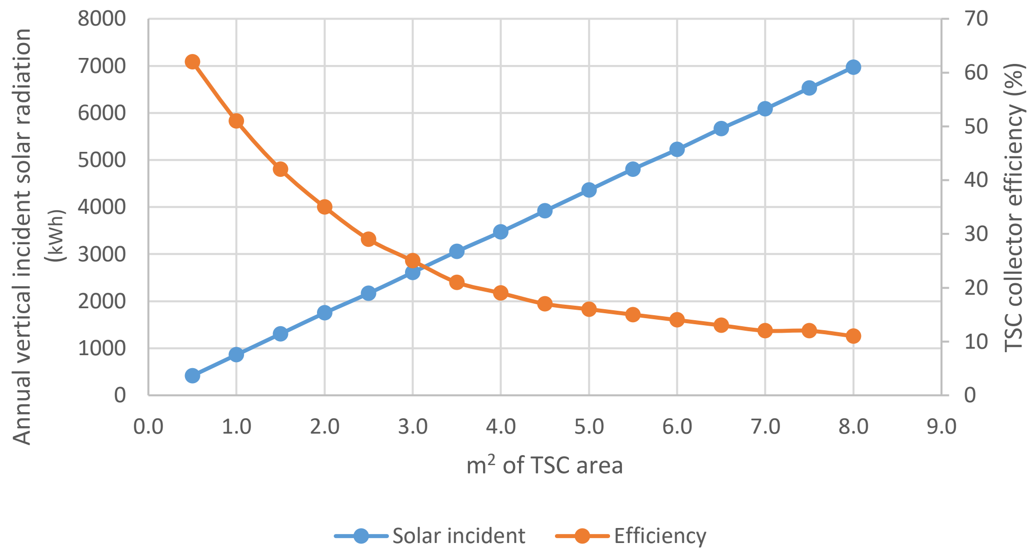


Figure 7-25 Rhondda end-terraced; TSC modelling using SWIFT for sizing. Annual vertical incident irradiation and collector's efficiency against different TSC sizes for 17l/s flow, author.

In Figure 7-26 three different designs are shown for 2m^2, 4m^2 and 6m^2 of TSC. The 2m^2 was considered as the ideal Swift modelling choice, combining heating delivery and temperature rise just before both parameters reach a plateau. The 4m^2 was considered as the ideal aesthetics choice; the TSC covers all the triangular part of the wall and would integrate easily with the east-west PVs. The 6m^2 was considered as when exceeding this area, none of the heat delivery, temperature rise and

efficiency increase significantly. The LCBE team and the clients (WWHA) preferred the 4m^2 option because of the aesthetics; this is also backed up by the Drozynki (238) survey analysed in the framework indicating the importance of proportion design.
An investigation similar to the cost investigation in the feasibility stage (6.2.1.4). The suggested TSC price discussed in the framework is £230/m^2 but in reality, the cost is not proportional to the area, especially for small applications. A way to make informed decisions is to request quotes for different TSC areas. The TSC in Rhondda end-terrace will displace heating coming from a boiler at 0.12£/kWh. For 2m^2 of TSC application, in 10 years the savings for the heat displacement would be £630 whereas for 4m^2 the additional benefit would be £70 and for 6m^2, another £70 as seen in Table 7-11. The manufacturers, suggested a £50/m^2 cost for the panel only, meaning that in a mature market the extra 2m^2 area of the 4m^2 choice would need 14 years to payback. In any case, the aesthetics priority drove the design area to be agreed at 4m^2.

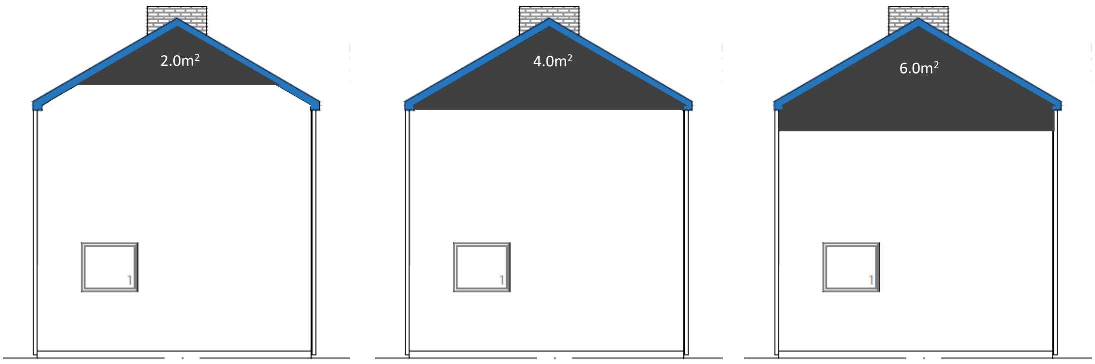


Figure 7-26 Rhondda end-terraced; south elevation design testing for three different TSC areas, author.

Table 7-11 Rhondda end-terraced; space heat displacement and gas cost savings for different TSC areas, author.

TSC area m^2	Annual heat displacement kWh	Annual Gas boiler savings Ofgem Oct 2022 £	10-year projected Gas boiler savings Ofgem Oct 2022 £
2	**639**	73	730
4	**667**	80	800
6	**722**	87	870

The annual heat delivery for a 4m^2 TSC was modelled using both HTB2 and SWIFT. Results summarised for heating and non-heating seasons are shown in Figure 7-27 for both modelling processes, using the same 25-year CIBSE weather dataset for the location as discussed in the site analysis. Very similar results were obtained for the two modelling processes (within 4% deviance). The summer bypass damper was set at 18^{o}C external temperature and no temperature limits were introduced for delivery temperature.

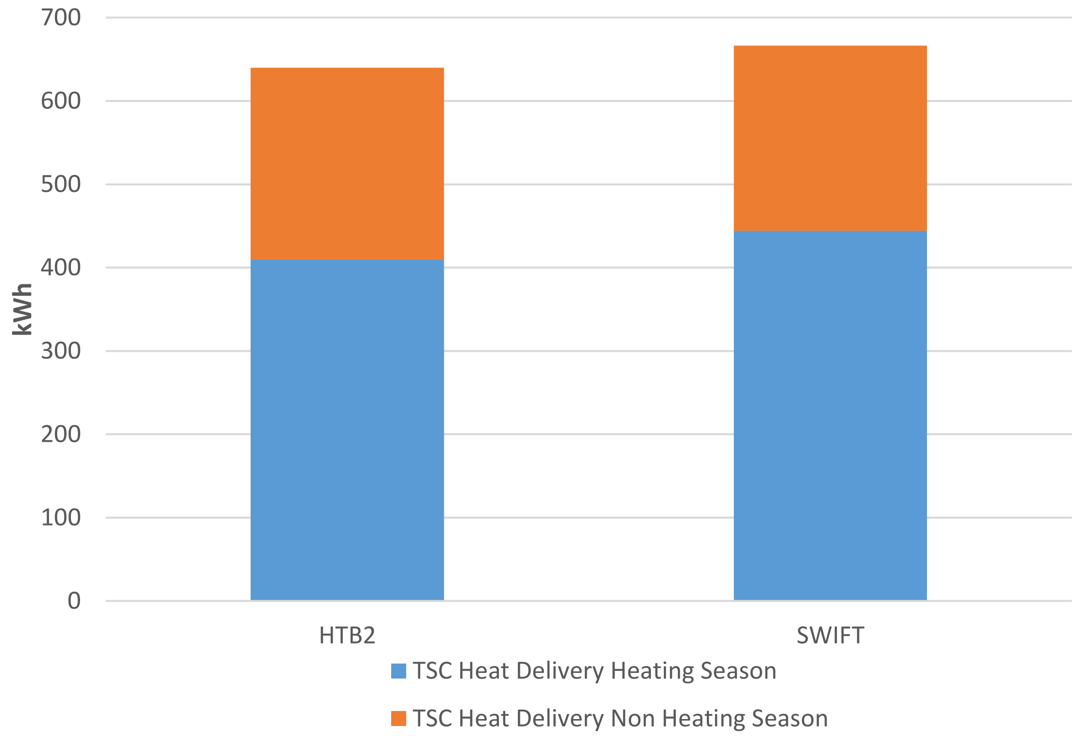


Figure 7-27 Rhondda end-terraced; modelled heating season TSC Heat Delivery by using HTB2 and SWIFT, author.

In Table 7-12, an analysis of the effect of the TSC to the incoming daytime ambient air temperature is presented. The first two columns include monthly averaged ambient day-time historic temperature for from CIBSE and PVGIS. The Swift modelled monthly temperature rise is presented to the next column indicating a 7.9°C annual average temperature rise to the ambient daytime air temperature. The delivered temperature (ambient plus TSC temperature rise) is shown in the last two columns based on CIBSE and PVGIS ambient temperature. The yellow highlighted value shows potential overheating in August, especially if midday temperature variations and irradiation strength is considered. This can be adjusted by introducing further damper' controls that would run the system (MVHR and TSC) according to indoor comfort.

Table 7-12 Rhondda end-terraced; TSC damper control strategy reasoning. Monthly TSC supply temperature by combining historic ambient daytime temperature data and SWIFT temperature rise modelling, author.

Months	CIBSE average Ext Air Temp daytime (°C)	PVGIS average Ext Air Temp daytime (°C)	SWIFT average TSC temp rise daytime (°C)	CIBSE+SWIFT TSC average supply temp daytime (°C)	PVGIS+SWIFT TSC average supply temp daytime (°C)
Jan	6.6	5.2	8.1	14.7	13.3
Feb	5.6	5.6	10.6	16.2	16.2
Mar	7.6	7.5	8.5	16.1	16.0
Apr	9.4	10.1	7.9	17.3	18.0
May	12.8	12.1	7.0	19.8	19.1
Jun	14.7	14.9	5.7	20.4	20.6
Jul	16.8	16.9	6.0	22.8	22.9
Aug	17.0	16.3	7.1	24.1	23.4
Sep	15.1	15.1	8.2	23.3	23.3
Oct	11.8	12.8	7.7	19.5	20.5
Nov	9.3	9.1	8.7	18.0	17.8
Dec	7.4	6.9	9.5	16.9	16.4
average	**11.2**	**11.0**	**7.9**	**19.1**	**19.0**

The MVHR Heat delivery was also modelled in HTB2 using the same flow rate, CIBSE weather data and TSC temperature rise impact. The predicted annual space MVHR heating saving is 1303kWh. Figure 7-28 shows the annual space heating delivery prediction from the TSC and MVHR compared to the pre-retrofit monitored space heating delivered and gas used to deliver it. The 1970kWh combined delivery for the two systems accounts for 17.9% of potential savings. With the TSC contributing 6.1% and the MVHR 11.8%

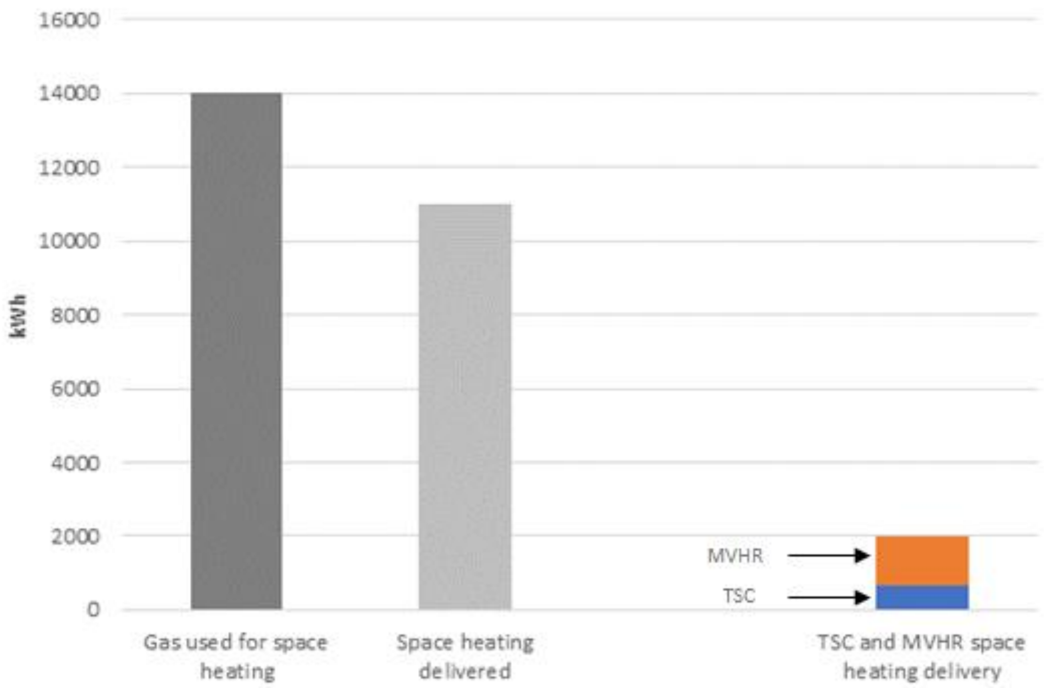


Figure 7-28 Rhondda end-terraced; Modelled MVHR and TSC space heating delivery compared against the pre-retrofit space heating delivered and gas used to deliver it, author.

7.1.3 Building Integration

7.1.3.1 Envelope integration

In Rhondda end-terraced the TSC was decided to be installed on the triangular side wall gable end for performance and aesthetics reasons and also to be integrated to the PV roof by using aluminium flashing. In Figure 7-29 the supporting structure and fixing details as well as the end-product are presented. The aluminium sill extension is covering the external insulation to protect from rainwater. The plenum depth is 150mm at the insulated and 250mm at the uninsulated part. The insulation overlaps part of the cold gable end to minimise cold bridges to the second floor. The attic is cold but due to stack effect, the gable end wall is expected to circulate some of the heat losses back through the TSC cavity. In Solcer house, Figure 7-30, the fixing sits on a plastic foundation to minimise water ingress and cold bridges. More details about fixing and finishing of the other experimental sites can be found in Appendix VI.

Figure 7-29 Rhondda end terraced; TSC supporting structure (left) and end-product (right), author.

Figure 7-30 Solcer house; TSC supporting structure (left) and end-product (right), LCBE project.

The Opus 200 profiled cladding from Euroclad Ltd in anthracite colour was selected for the Rhondda end-terraced (Figure 7-31). The 200mm panel has a very narrow 3mm leap which makes the surface look homogeneous and flat and reduces solar absorption losses due to corrugation as discussed in 3.2.1.2. In the schools' roof the 300mm WP40 with a 25mm leap was used which is easier to install as the wider leap creates a base that comfortably sits on the backet. A 1250mm diameter inlet hole was drilled through the wall into the attic following the ducting sizing recommended for the design flow rate. Ideally the hole would be positioned at the upper part of the triangle and to the centre to drag air as equally as possible and use any stack effect; however, this coincided with a large wall stone. To reduce any structural risk, the hole was drilled slightly to the east of the triangle centre. The impact of the hole position will be studied in 7.2.4.

In Rhondda terraced, the slate roof was challenging as typical PV trays could not be used because the warm air could not be ducted out without compromising the water drainage system. Instead, roof window flashing for slate roof was used and the TSC sat where the window would sit. In Figure 7-32 the two panels and one of the inlet ducts are shown during the installation phase. As the TSC is perforated, a back sheet was installed to avoid water penetration as the slates were removed. Also, careful sealing applied between the sheet and the duct and also the felt and the duct.

The vertical application in Glan Clwyd corridors presented an interesting challenge as that TSC was the only one reachable by students. The NUT suggests that pupils should not access surfaces hotter than 43°C (90). This would not be a problem during TSC operation but could be a problem when the fan stops as the absorbing panel would retain the heat. A measure to eliminate risks would be for the TSC to be installed no lower than 2.5m above the ground.

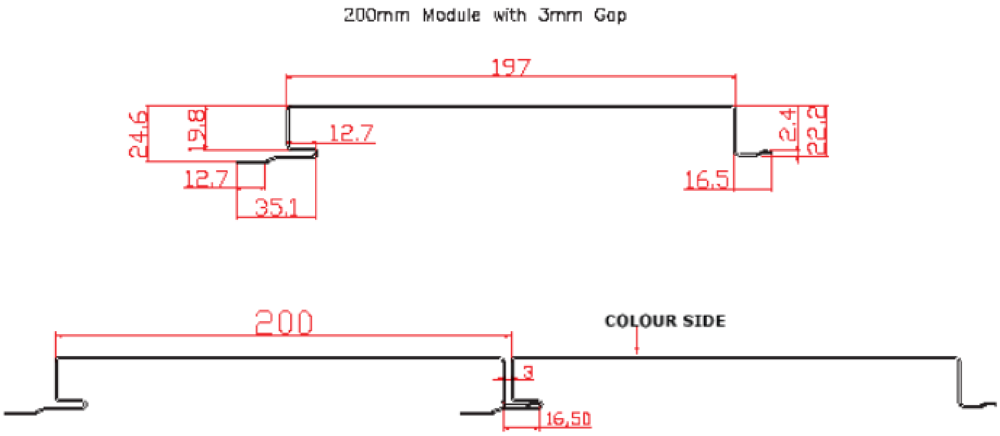


Figure 7-31 Profile used in Rhondda end-terraced; Opus 200mm with 3mm gap, Euroclad Ltd.

Figure 7-32 Rhonnda terraced; roof integration (left) and duct inlet (right) during installation, author.

7.1.3.2 Systems integration

The different systems that the TSC had to integrate with and the most significant challenges that this integration process created are shown in Table 7-13. The TSCs that work with natural ventilation do not include any physical connection or integration to a system, but they still need to integrate to the building.

Starting from the simplest natural ventilation integration, the Lampeter cloakrooms TSC had to feed two spaces with two ducts running externally. The ducts were highly insulated with 100mm waterproof premium Kingspan insulation and the ducting system was elevated on racks to avoid water ingress through standing rainwater (Figure 7-33). A window Section was removed to fit a grill, dictating the dimensions of the last part of the duct and slightly compromising natural lighting (Figure 7-33). Aesthetics was not a priority for this installation as all external ducting was in a non-visible service roof corridor. Aesthetics together with practicality was an issue in the Glan Clwyd corridors where there were no external ducts but the two outputs of the TSC was at the staircase area; thus, two internal ducts were installed to direct the flow towards the school's corridors. The internal ducts were not insulated as any heat loss would be beneficial for the staircase but were later boxed in to better integrate with the visual context. Residents of Saxon Court also requested for the delivery staircase ducts to be boxed in (shown in Figure 7-14). A combination of the strategies above was used in Lampeter where the external ducts were insulated. One of the window panels was used as a duct entry point and the internal ducting was not insulated. The distribution system included eight supply grills coming from a 15m supply ducting installed by the ceiling (Figure 7-7). The recirculation grill was installed by the mixing box and the fan was outside minimising potential noise. A similar system was installed in B&Q store where the fan was installed inside the building by the ceiling. The distribution ducting was a complex "tree" form to allow fresh air to homogeneously reach throughout the large space. Figure 7-33 shows the systems schematic as built including all the components and ducting route. Both TSCs are connected internally to a central duct which splits into five double delivery distribution ducts. The recirculation inlet is placed after the two TSC output ducts connection and before the fan. An attenuator and filters are also placed before the fan and a secondary attenuator is installed after the fan. Access to the moving parts and filters is allowed for maintenance through a 2800mm panel.

Table 7-13 TSC – systems Integration and challenges for the experimental cases studies, author (continued overleaf).

No.	Experimental case study name	Integrated to	Integration challenges
1	**SEDA Ltd. Blackwood, production hall**	2 separate HVAC with existing inlets and recirculation	• TSC output to reach HVAC with minimum duct losses • HVACs controls and TSC controls should collaborate • Turn old inlet to bypass
2	**B&Q store Cyfarthfa, retail store**	Natural ventilation	• Install a new distribution system • Integrate a fire alarm to fan and dampers
3	**Lampeter School, main hall**	Natural ventilation	• TSC output to reach space with minimum external duct losses • Install a new distribution system
4	**Lampeter School, cloakrooms**	Natural ventilation	• TSC output to reach space with minimum external duct losses • Deliver to two cloakrooms
5	**Glan Clwyd School, theatre**	HVAC with existing fresh air inlet and heat recovery	• TSC output to reach HVAC with minimum external duct losses • HVAC controls and TSC controls should collaborate • Turn old inlet to bypass
6	**Glan Clwyd School, corridors**	Natural ventilation	• Deliver to two floors
7	**Saxon Court residence, corridors**	Natural ventilation	• Deliver to three floors • Consider duct aesthetics
8	**Rhondda House (terraced)**	Natural ventilation	• Minimise duct losses in the attic • Utilise attic space to include bypass and recirculation ducts

No.	Experimental case study name	Integrated to	Integration challenges
9	**Solcer house (detached)**	Exhaust air source heat pump with MVHR	• Collaborate with a system that has similar operation priorities • Minimise duct losses in the attic • Consider duct aesthetics
10	**Rhondda House (end-terraced)**	MVHR inlet	• Collaborate with a system that has similar operation priorities • Minimise duct losses in the house • Consider duct aesthetics

Figure 7-33 Lampeter cloakrooms; external duct installation and insulation (left) and supply grills integration (right), author.

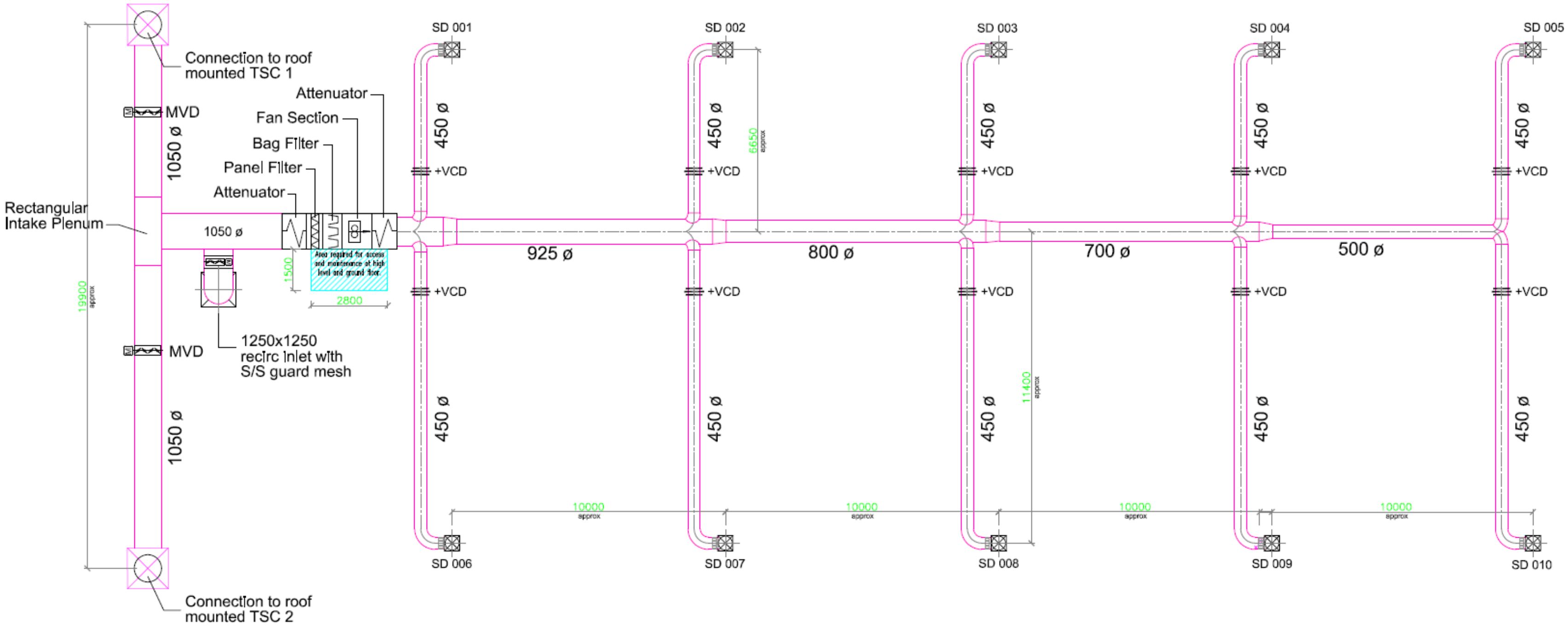


Figure 7-34 B&Q store; TSC ducting and system, TATA steel for SBED project.

The building integration in Rhondda terraced required to utilise the attic space to transfer heat from the back of the two panels to the habitant space. The task was complicated as the installation included recirculation and bypass ducting to be routed into the delivery ducts before the fan. The summer bypass inlet was installed to the north roof to utilise lower temperatures during summer (Figure 7-35). All the ducts were highly insulated, and the supply duct entered the house from the first-floor ceiling at the staircase area following the principles of a Positive Input Ventilation system.

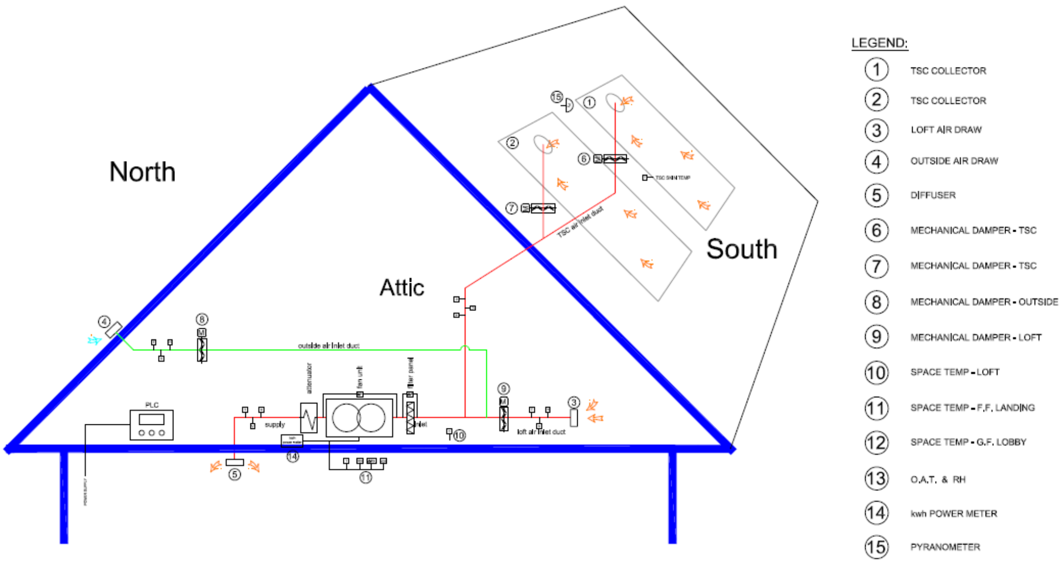


Figure 7-35 Rhondda terraced; TSC System and ducting design drawing, SBED project.

The SEDA and Glan Clwyd installations were very similar as in both cases the TSC was connected to an HVAC AHU. The complexity in terms of the physical connection for both cases was that the old fresh air inlet should become the summer bypass as the new air inlet for the gas boilers would be connected to the TSC. This was done by dampers control in the mixing box. In both buildings heat recovery pre-existed; in SEDA through physical mixing (recirculation) and in Glan Clwyd through heat exchanger between supply and extracted air. The TSC internal ducting in SEDA was not insulated as recirculation and duct heat exchange would allow for heat recapturing similarly to B&Q, whereas in Glan Clwyd theatre, the external duct from the TSC to the HVAC was highly insulated. In Figure 7-36 the TSC duct connects to a new intake box (intake plenum) where the TSC replaces the old fan louvre which is now re-installed on the side of the box as a summer bypass intake.

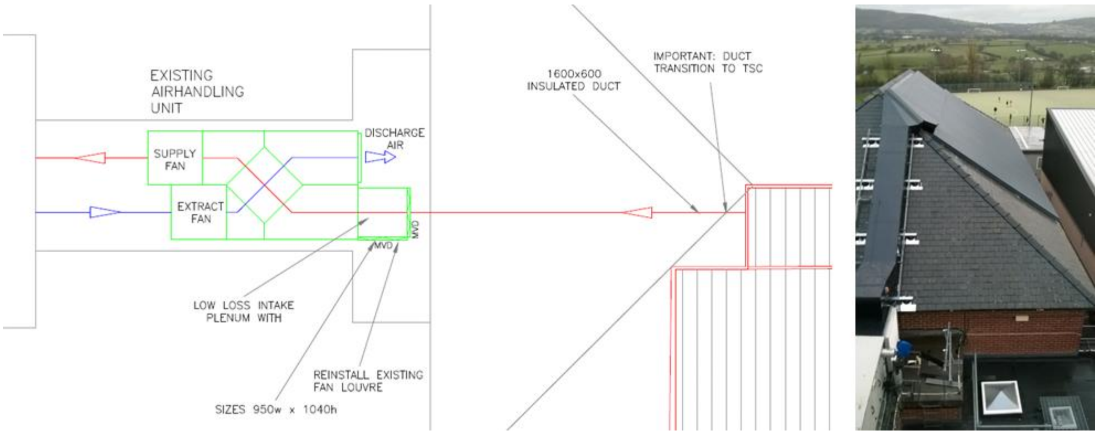


Figure 7-36 Glan Clwyd theatre; from right to left: a photo with the TSC and the TSC insulated ducting; a sketch with the ducting driving the air to the new entrance box which is the air inlet of the AHU unit which includes the supply and extract flows, sketch by TATA steel, photo by author.

Solcer and Rhondda end-terraced are different in terms of the heating system integration; however, they both integrate to an MVHR unit. Solcer house also integrates an exhaust heat pump to the MVHR unit whereas Rhondda end-terraced has a separate not integrated gas boiler. As seen in Figure 7-37, in Solcer house the TSC feeds the MVHR with preheated air. If the temperature is below the extracted, the heat exchanger will further increase the temperature and finally the heat pump through the condenser will bring it up to the desired temperature for space heating. In the meantime, heat will be removed from the exhaust air, meaning that a TSC heat would increase, through the heat exchanger, the temperature of the exhausted air before the evaporator. Without the heat pump (Rhondda end-terraced), when the TSC preheats above the extracted temperature, the heat exchanger should be bypassed to allow all the heat to be supplied to the space rather than most of it (depending on the HE efficiency) to be exhausted through the heat exchanger. The equations behind this are analysed in 6.2.1.

TSC ducting in the Rhondda end-terraced house was straightforward as the TSC output and the MVHR where both in the attic and 3 meters apart; all ducts were insulated. In Solcer house, ducting was more complicated as the TSC output was in the attic and the heat pump on the ground floor, meaning that a 10 meters route was designed. The first 6 meters of the duct in the attic were not initially insulated. The idea behind this was that the semi-transparent roof and the PV heat losses could provide extra heat to the exposed ducting in the daytime and stack effect would also heat the attic and provide recapturing heat to the ducts in the night-time. This was revised in the commissioning-optimisation stage in 7.1.4.2.

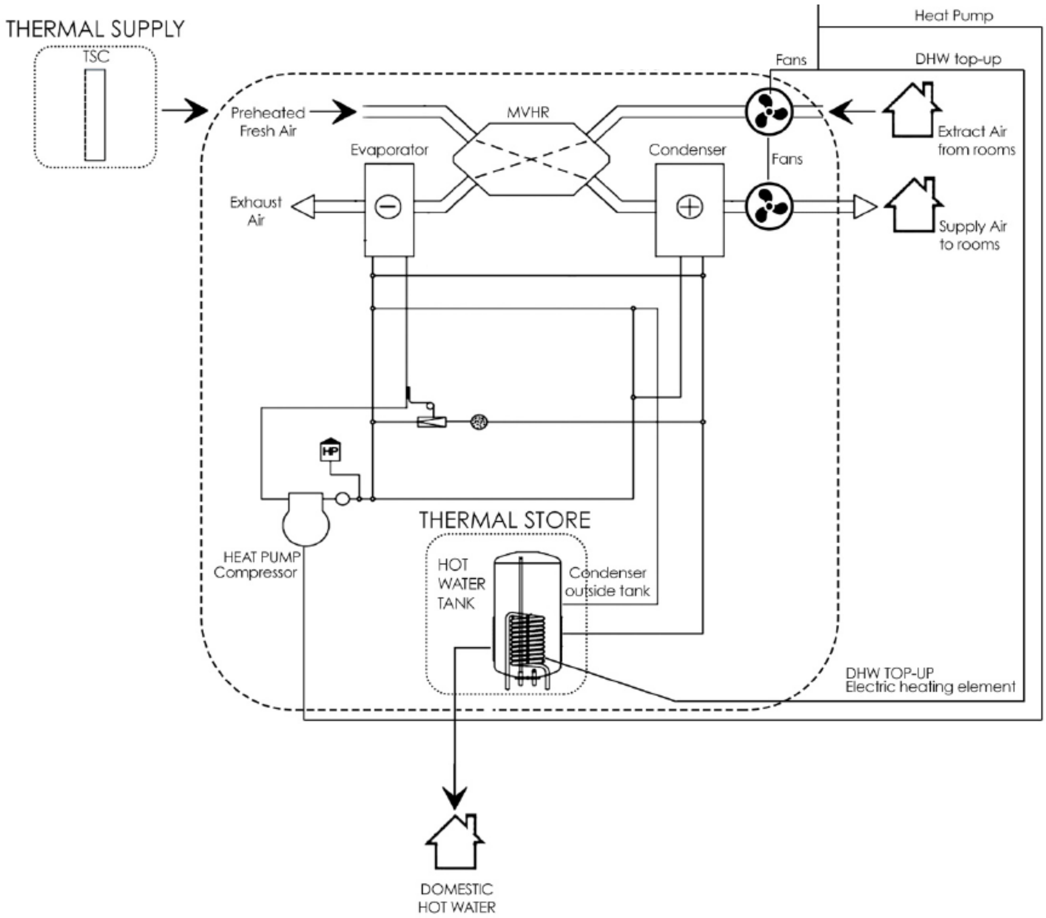


Figure 7-37 Solcer house; TSC integrated to an MVHR and an exhaust heat pump, sketch by Dr. Ester Coma Bassas, LCBE project.

7.1.3.3 Controls

The controls of the TSC aim to operate the TSC according to all the design parameters discussed in the framework. The control strategy intends to fulfil the following three principles:

- Fulfil heating and ventilation demand
- Response to existing systems
- Optimise TSC variants' capabilities

The controls descriptions below aim to present the control equipment and explain operation settings selected in response to the control strategy. The first example refers to Lampeter cloakrooms as this is a straightforward TSC system variant with one collector, one fan and two spaces of delivery without any physical integration to any other HVAC system (Figure 7-38).

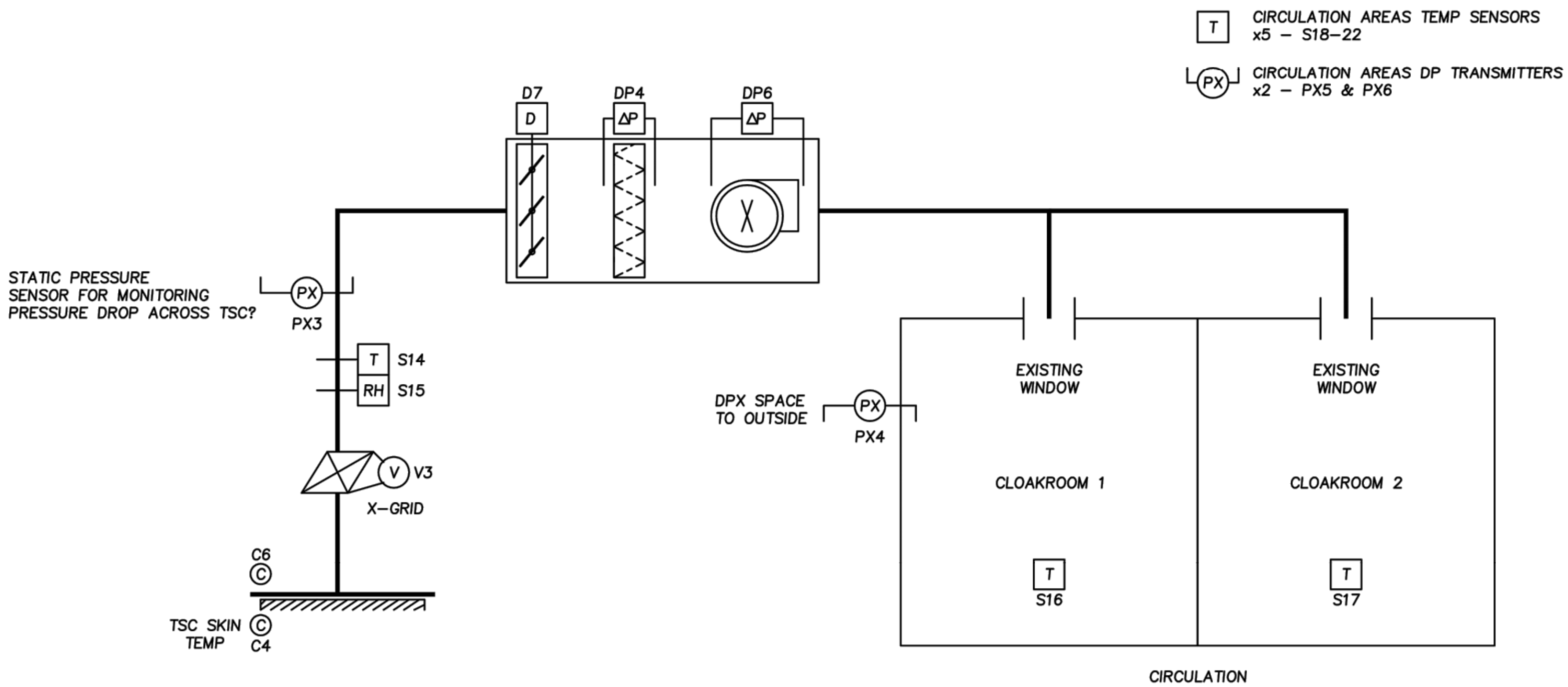


Figure 7-38 Lampeter cloakrooms; Controls schematic, Building Technology Systems and TATA steel for SBED project.

The schematic (Figure 7-38) includes the following variable settings:

S16 & S17	T_{space} (Average of two sensors)
S1	T_{amb}
S14	T_{TSC}
C4	T_{coll}
D7	TSC output damper
X	Fan

The controls of the Lampeter cloakrooms include the following initial settings:

Time schedule TM = 1 for Mon-Fri 7am-7pm, according to the school's timetable

TM = 2 for Sun-Thu 12am-5am, for night-time purge

Time delay TD = 5min, delay to avoid short cycling state of moving parts

TSC design flow rate V_{TSC} = 0.4 m^3/s, based on ventilation needs (Table 7-3)

TSC max flow rate $V_{TSC\ max}$ = 0.7 m^3/s, based on figure 8-5

Setpoint $T_{space\ SP}$ = 18°C, according to section 6.1.2 and client's desire

$T_{space\ SP+}$ = 24°C, according to figure 8-5 and client's desire

TSC supply $T_{TSC\ min}$ = 12°C, to avoid cold drafts

$T_{TSC\ max}$ = 36°C, to avoid hot drafts

Summer temperature $T_{afternoon\ amb}$ = 20°C, average ambient temperature from 12pm to 18pm

$T_{afternoon\ space}$ = 22°C, average space temperature from 12pm to 18pm

The main strategy is for the TSC to deliver warm air by comparing the delivery temperature (S14) to the space temperature (S16 & S17). This raises the question on how the system starts up as the delivery temperature, which in this case is the TSC output temperature, will not be affected by the TSC when the system is OFF. To address this issue, the initial driver is a skin temperature sensor (C4) which will activate the system when its temperature is + 2°C. higher than the space temperature. The additional 2°C is a precaution that ensures that any variations or losses through the ducting would not trigger the TSC to start delivering at below space temperature. This starting strategy is only enabled within the occupancy time schedule and within space heating season. The space heating season mode has a set point at 6°C degrees higher to the ordinary (18°C) which allows the space to be thermally charged using free renewable heat without causing discomfort as discussed in 6.1.2.1.

The set point depends on ambient temperature. If the ambient is greater than 20°C (set point plus 2°C) then it is unlikely that we are in the heating season and the desired set point can remain the same. If the ambient is lower than the set point, then it is beneficial to use the $T_{space\ SP+}$ at 24°C to maximise renewable heat delivery.

If the TSC delivery temperature remains above the space temperature, then the flow rate can increase up to a maximum that does not cause discomfort and unwanted drafts. If the delivery temperature is below the space temperature, then the flow rate will remain at the design value. The system will remain on for delivery temperatures above the minimum supply (12°C) to avoid cold drafts and above the ambient plus a minimum temperature lift of 4°C to ensure that delivery is significantly above infiltration of ambient.

The night purge mode shall be activated when cooling demand is needed. The prerequisites for the night colling is for the average ambient afternoon temperature to be above 20°C and for the average space afternoon temperature to be above 22°C. If the afternoon condition is fulfilled then between 12am and 5am, the TSC should be activated only if the current ambient is above 14°C and cooler to the space and the space is above the 18°C set point thus cooling would be beneficial.

All the above translate into the below algorithm:

If TM=1 and $T_{room} < T_{space\ SP+}$ and $T_{coll} > T_{space} + 2°C$, then D7= 100% and X = V_{TSC} and TD=5min

If $T_{amb} > T_{space} + 2°C$, then $T_{space\ SP}$ = 18°C

Else $T_{space\ SP}$ = 24°C

If $T_{space} < T_{space\ SP}$, then

  If $T_{TSC} > T_{space}$ and $T_{TSC} < 36°C$, then X = $V_{TSC\ max}$ and TD=5min

  Else If $T_{TSC} > 12°C$ and $T_{TSC} > T_{amb} + 4°C$ and $T_{TSC} < 36°C$, then X = V_{TSC} and TD=5min

  Else X=0 and D7= 0%

Else X=0 and D7= 0%

If TM=2 and $T_{afternoon\ amb} > 20°C$, and $T_{afternoon\ space} > 22°C$ and $T_{amb} < T_{space}$ and $T_{amb} > 14°C$ and $T_{space} > 14°C$, then D7= 100% and X = V_{TSC} and TD=5min

Else X=0 and D7= 0%

The strategy described above was used for the SBED sites. The bypass addition would replace the OFF mode when overheating This means that when the space temperature was above the set point and the ambient was below the space, then the bypass damper would be activated to provide cooling. The recirculation addition is used when there is a demand for heating (i.e. space temperature < space temperature setpoint) yet, the external conditions prohibit any heat gains from the TSCs. A mixture of fresh TSC air and recirculation was programmed when destratification was a priority (e.g. in B&Q store). In which case, the temperature controller to activate the recirculation damper is based on the temperature difference between a high-level and low-level point indicating temperature stratification.

A different approach in terms of strategy is needed when the TSC is applied to an MVHR unit. To better understand the control needs, a table with different scenarios is presented in Table 7-14. Also, a sketch describing the TSC with the MVHR is presented in Figure 7-39. The application is for Solcer house; however, if the evaporator and condenser (HP) are ignored, Figure 7-39 applies to Rhondda end-terraced as well. The scenarios assume balanced air flow rates and a 90% heat exchange with zero losses within the unit. Four scenarios are presented: deep winter with high and medium irradiation, shoulder months with high irradiation and summer with high irradiation. In all scenarios, TSC causes a significant increase of the exhaust temperature. This is irrelevant to Rhondda end-terraced as the exhausted air is of no use but is highly relevant to Solcer house as the exhaust heat pump will have significantly less work to heat up the condenser. In terms of the supply, in all scenarios the TSC is slightly beneficial except the summer scenario where a summer bypass and a heat exchanger bypass is needed for both Rhondda and Solcer house. During the shoulder months, when sunny, the TSC will provide at higher to the space temperatures (30°C in the scenario), meaning that if heating is required, a heat exchanger bypass would be beneficial for the Rhondda end-terraced house to allow the warm incoming air in the house. This is not necessary the case with the Solcer house where the heat exchanger is not needed to be bypassed during the shoulder months because the exhaust air temperature will rise facilitating the heat pump to provide heat for space heating and hot water as discussed in 6.2.1.

Table 7-14 Projected results of a TSC to the supply and exhaust of an MVHR for different weather scenarios, author.

Scenario		MVHR Temperatures without TSC	MVHR Temperatures with TSC	Projected Result
Deep winter and high irradiation	T_{amb} = 0°C T_{room} = 20°C $T_{room\ SP}$ =22°C	T_{inlet} = 0°C $T_{extract}$ = 20°C **T_{supply} = 18°C** **$T_{exhaust}$ = 2°C**	T_{inlet} = 20°C $T_{extract}$ = 20°C **T_{supply} = 20°C** **$T_{exhaust}$ = 20°C**	• Supply will slightly increase • Exhaust will highly increase
Deep winter and medium irradiation	T_{amb} = 0°C T_{room} = 20°C $T_{room\ SP}$ =22°C	T_{inlet} = 0°C $T_{extract}$ = 20°C **T_{supply} = 18°C** **$T_{exhaust}$ = 2°C**	T_{inlet} = 10°C $T_{extract}$ = 20°C **T_{supply} = 19°C** **$T_{exhaust}$ = 11°C**	• Supply will slightly increase • Exhaust will moderately increase
Shoulder months and high irradiation	T_{amb} = 10°C T_{room} = 20°C $T_{room\ SP}$ =22°C	T_{inlet} = 10°C $T_{extract}$ = 20°C **T_{supply} = 19°C** **$T_{exhaust}$ = 11°C**	T_{inlet} = 30°C $T_{extract}$ = 20°C **T_{supply} = 21°C** **$T_{exhaust}$ = 29°C**	• Supply will slightly increase • Exhaust will vastly increase
Summer months and high irradiation	T_{amb} = 20°C T_{room} = 25°C $T_{room\ SP}$ =22°C	T_{inlet} = 20°C $T_{extract}$ = 25°C **T_{supply} = 24.5°C** **$T_{exhaust}$ = 20.5°C**	T_{inlet} = 40°C $T_{extract}$ = 25°C **T_{supply} = 26.5°C** **$T_{exhaust}$ = 38.5°C**	• Supply will slightly increase • Exhaust will vastly increase • Bypass is needed

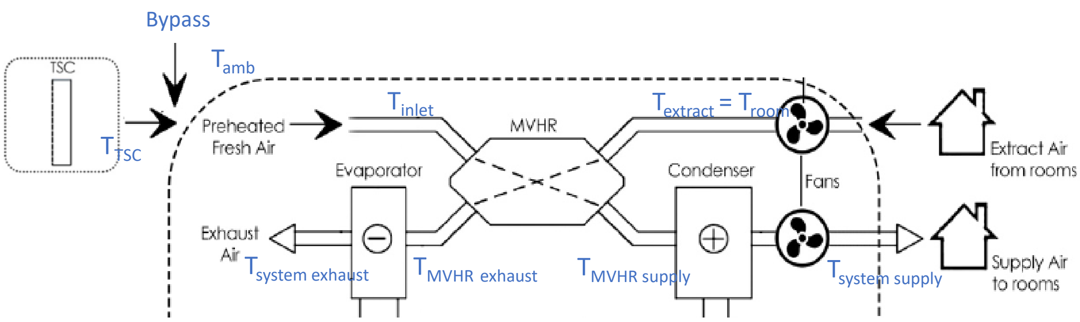


Figure 7-39 TSC inlets an MVHR; applies to Solcer house where an exhaust heat pump is included and to Rhonda end-terraced if the condenser and evaporator are ignored, initial sketch by Dr. Ester Coma Bassas, LCBE project, amended by author.

Based on the above a bypass was set driven by a thermostat for ambient greater than 20°C acknowledging that internal gains will cause room temperatures higher to the ambient. To control that high internal gains will not be transferred to supply, a heat exchanger bypass was set at 27°C when TSC bypass is ON (25°C). For Rhondda end-terraced the heat exchanger bypass is also activated when T_{TSC} > $T_{extract}$.

The automations analysed in this Section, require resources such as extra space and funds for design, programming, equipment, installation and procurement. These need to be calculated in the total cost of the installation. For the SBED project an IQ3 Series DDC BMS controller was used accompanied by a Trend IQ VIEW 4 touch screen display for easier control and demonstration purposes. Two alarms were set for temperature limits and maintenance cleaning time of TSC. In B&Q, TSC and recirculation dampers were connected to a fire alarm to ensure the fresh air supply is stopped in the event of a fire. The damper actuators were the Belimo SM24-SR for the SBED projects (No1-8, Table 7-3) and the Belimo NM24A for the Solcer house and Rhondda end-terraced. The actuators in SBED project were triggered by the controller which was connected to temperature sensors whereas in Solcer house and Rhondda end-terraced, the actuator was controlled by thermostats.

7.1.4 Commissioning and Optimisation

7.1.4.1 Testing and commissioning adjustments

All the ventilation systems were commissioned according to Building Regulation F (122). A balanced ventilation was set for both Solcer house and Rhondda end-terraced. Table 7-15 shows the commissioning flow rate values for both extract and supply for the Rhondda house. The target was for 61.2 m^3/h (17l/s) as discussed in 7.1.2.3 but a 5% deviation is allowed in the regulations. The balometer used for the test was a Testo 417 Vane Anemometer with a funnel set.

Volume flow rate sensor such as the balometer above was also used for sampling heat transfer measurements based on the heat transfer equation introduced in Section 2.1.2.4. Two temperature sensors were used for measuring the temperature difference between the TSC delivery and external ambient. The results were compared against the manufacturer's TSC performance specification for temperature rise and heat delivery against different mass flow rates (Section 6.1.2.1). The reference pyranometer used for the Solcer and Rhondda was a Kipp & Zonen CMP3. For bigger ducting systems instead of a balometer, pressure and velocity meters were used following methods that will be described in the instrumentation Section 7.2.2..

Some set points were re-adjusted based on real life measurements to consider duct losses, stack effect, drafts etc. Replicating summer extreme conditions was not always viable thus some of the testing was done by triggering the dampers manually and/or by changing the thermostat temperature set points and studying the responds in a different range. All tests were carried out after getting a stable weather forecast to ensure relative stable sunshine and ambient temperature.

Table 7-15 Rhondda end-terraced; volume flow rate commissioning measurements, author.

Supply m^3/h		Extract m^3/h	
Living room (GF)	22.3	Kitchen (GF)	29.7
Main Bedroom (FF)	25.7	Bathroom (FF)	29.5
Second Bedroom (FF)	13.0		
Ground Floor	22.3	Ground Floor	29.7
First Floor	38.7	First Floor	29.5
Total	**60**		**59.2**

7.1.4.2 Long term commissioning and optimisation

In most of the sites, long term commissioning measures were applied responding to findings from the evaluation stage or after discussions with building owners/users. Table 7-16 shows the optimisation actions taken for each experimental case study.

A common observation was that the bypass activation set point has to change especially when ducts would recapture heat between the bypass damper inlet and delivery point. This difference was measured during the summer at 1.6ºC in Rhondda end-terraced where ducts were insulated, and inlet was 3 meters away from the MVHR unit. In Solcer house, this was measured at 6.7ºC with uninsulated ducts, transparent PV-roof and a long distance between the inlet and the MVHR+HP unit. This was beneficial in the winter months in sunny cold days but caused an overheating problem in warm sunny days; thus, all attic ducts were insulated and the summer bypass activation set point was decreased to 18ºC.

Table 7-16 Recommissioning and optimisation actions for the experimental case studies, author.

No.	Experimental case study name	Finding	Optimisation Action
1	**SEDA Ltd. Blackwood, production hall**	TSC damper would not go to “OFF” position in summer mode	Recommissioning of the control system
2	**B&Q store Cyfarthfa, retail store**	Unbalanced flows coming from the two collectors	Recommissioning of the control system
3	**Lampeter School, main hall**	Heat loss from external ducting and noise from fan	Insulating all external ducting and installation of diffuser
4	**Lampeter School, cloakrooms**	Heat loss from external ducting	Insulating all external ducting
5	**Glan Clwyd School, theatre**	-	-
6	**Glan Clwyd School, corridors**	Aesthetics reservations	System boxed-in
7	**Saxon Court residence, corridors**	Aesthetics reservations and cold drafts	System boxed-in and flow was adjusted. The system was put on hold from 2019.
8	**Rhondda House (terraced)**	Cold drafts complaints	Flow was readjusted and “low flow-hight temperature” approach was adopted. The system was put on hold from 2020.
9	**Solcer house (detached)**	Overheating in summer months, and unbalanced flows	Summer bypass thermostat was readjusted. Internal attic ducts were insulated. Supply and extract flow were readjusted after filter change
10	**Rhondda House (end-terraced)**	Overheating in summer months, HE bypass triggered by extract and unbalanced flows	Summer bypass thermostat was readjusted, and HE bypass was triggered by inlet temperature. Supply and extract flow were readjusted after filter change

Exposed ducts in residential or institutional buildings were boxed in for aesthetics reasons after discussions with the users. Two of the systems were put on hold, the Rhondda terraced and the Saxon court one. In both cases, TSC was not connected to a heat recovery medium meaning that would ensure elimination of the cold drafts. Saxon Court system did not include a recirculation system and residents would feel an unwelcome breeze under weather specific conditions. Rhondda terraced included an attic recirculation which is a form of heat recovery but is not stable as the heat is recovered from un-serviced space (attic). When the flow rate was reduced, the tenants would only complain about a couple of cold drafts per year which however is sufficient risk for a housing association (client) to put the system n hold).

7.1.4.3 Handover

In Solcer house the handover was designed for the TSC-MVHR-HP system all together. In Rhondda end-terraced a handover was given to the housing association and a house user manual was shared with the tenants. This is included in the Appendix VII.

A summary of the Rhondda end-terraced house handover is presented below:

A. **Scope of works:**

   4m^2 of Opus200 TSC from Euroclad was designed by the LCBE WSA Cardiff University team and installed by Vale Roofing and Cladding on the south triangular gable end wall of the end-terraced house. The collector preheats the ambient air by using renewable solar energy. The TSC feeds into a Titon HRV 1.25 Q Plus Eco MVHR unit installed by Quest 4 and is set to deliver fresh preheated air to and extract polluted air from the house at a balanced flow.

B. **Inventory of components and suppliers:**

   TSC related inventory:

   - Euroclad Opus Plank 200mm module 3mm gap in HPS 200 Ultra plastisol finish. Colour RAL 7016 Anthracite by Euroclad Limited.
   - Drip, ridge, verge and eaves flashings in HPS 200 Ultra plastisol finish. Colour RAL 7016 Anthracite by Euroclad Architectural.
   - Gutters and downpipes in HPS 200 Ultra plastisol finish. Colour RAL 7016 Anthracite by Euroclad Architectural.
   - Sills in HPS 200 Ultra plastisol finish. Colour RAL 7016 Anthracite by Euroclad Architectural.
   - Fixings and sealants by Ash and Lacy Building Systems.
   - Design and drawings by Severn Draughting services of Weston Super Mare consulted by Cardiff University, LCBE team.

More details on the MVHR inventory for Rhondda ned-terraced can be seen in Appendix VIII.

C. **Instructions**:

The MVHR-TSC system is set at rate at 17m^3/h supply and extract with a +20% boost mode. Boost is activated automatically through a humidistat at 70% RH in the extract duct or manually through boost switch installed in the kitchen and outside the bathroom with an automatic timer at 30min. The summer bypass of the TSC is set at 18ºC ambient temperature. The heat exchanger bypass will disengage the heat exchanger when $T_{TSC} > T_{ext}$. The bypass will also disengage for $T_{ext} > 27$ºC. The system is controlled by a 16A switch on the consumer unit.

More details on other experimental case studies can be seen in Appendix IX.

D. **Maintenance guide:**

The TSC does not need any maintenance other than annual collector cleaning and check of the bypass damper. Cleaning should be carried out utilising a floor-operated water lance cleaning system. The MVHR will need 6-12 months filter change for both the supply and extract within the MVHR unit.

A note from Tata steel, SBED (No1-8, Table 7-3) case studies can be seen below:

- "There is no pedestrian access permitted onto the solar collector at any time."
- "Only experienced & competent persons are permitted to undertake any inspection, maintenance, cleaning or disposal works."
- "It remains the clients' responsibility at all times to ensure that any inspection, maintenance, cleaning or disposal works are undertaken in accordance with the current Health & Safety at Work Act in making provision for the appropriate risk assessments, safe methods of access and working practices."

E. **Commissioning data:** This includes a certificate with the latest commissioning air flow data described in 7.1.4.1 for Rhondda end-terraced house.

F. **Life cycle information**:

An LCA assessment can be found in Colorcoat Prisma® pre-finished steel coil Environmental Product Declaration (275) which applies to the SBED projects (No1 to No8, Table 7-3). An end-of-life material disposal can be seen in Appendix X.

G. **Design and "as built" drawings**:

An "as built" design can be seen in Figure 7-40. For further details please see Appendix XI.

H. **Warranties:**

TSC and cladding system include a 10years warranty and a 2-year workmanship warranty. The MVHR system and workmanship include a 3-year warranty

I. **Appendix:**

Extra supporting documents for the controller the display as well as the instrumentation can be found in Appendix XII.

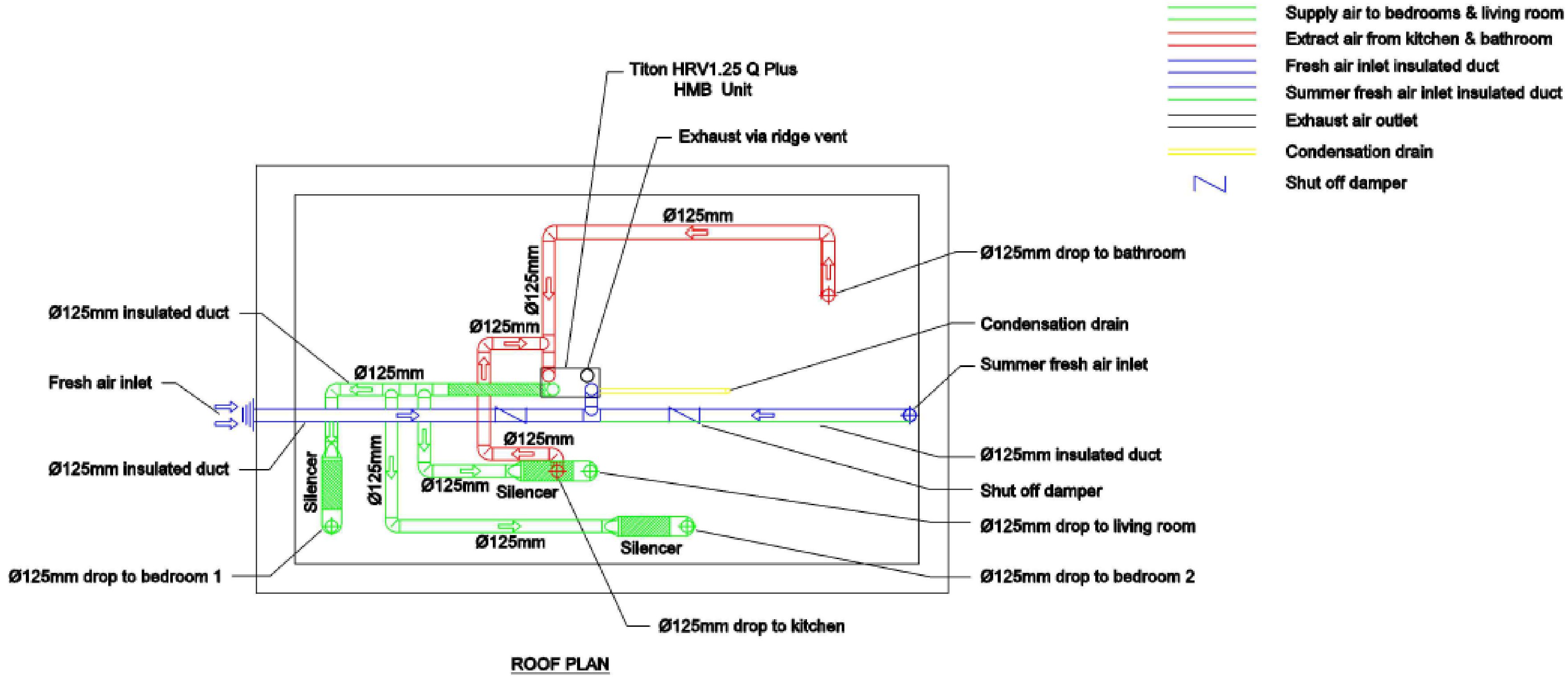


Figure 7-40 Rhondda end-terraced house; MVHR-TSC design prepared by Quest4 Systems LTD consulted by LCBE research project.

7.2 TSC Performance evaluation

In this part, the application of the second part of the framework (6.2) on the experimental case studies will be presented. Again, Rhondda end-terraced will be the main narrative character but other case studies will be used where needed. Performance indicators, instrumentation and data processing Section will present how the evaluation plan (6.2) was applied, whereas in the data analysis section, results from the experimental case studies will be presented and discussed.

7.2.1 Performance indicators

Data collection on existing systems was used in all the experimental studies. In the SBED case studies the collection focus was on existing or (for new-build) designed heating and ventilation systems to evaluate feasibility and inform modelling. In the Rhondda end-terraced, site information and 1-year weather data were captured prior to the intervention. This was agreed with the clients to inform and calibrate modelling and explore the combination of Solar thermal and solar PV. Weather data was also captured after installation to facilitate comparison and normalisations None of the schemes included a governmental initiative requiring monitoring but in SBED sites the controller included in situ and remote monitoring and system visualisation capability. The fundamental performance indicator agreed in all case studies was the TSC heat delivery in monthly and annual totals. Supplementary performance indicators were agreed on a case-by-case studies. SBED project deadlines would not allow for in-depth analysis. However, this was possible in Solcer house and Rhondda end-terraced investigations reflected the performance of the systems components.
The fundamental heat transfer equation was used (Equation 6.4) but the temperature rise was split into two where needed as described in the controls Section (7.1.3.3):

$$T_{rise} = T_{TSC} - T_{amb} \quad for \ \dot{V} \leq V_{dem} \qquad \text{Equation 7-1}$$

$$T_{rise} = T_{TSC} - T_{space} \quad for \ \dot{V} > V_{dem} \qquad \text{Equation 7-2}$$

Where T_{rise} is the air temperature rise because of the TSC (K)

T_{TSC} is the TSC output temperature in the delivery duct (K)

T_{amb} is the ambient air temperature (K)

T_{space} is the temperature in the space by the thermostat (K)

$\dot{V}$ is the TSC air delivery volume flow rate

V_{dem} is the demanded designed ventilation flow rate

The contribution of the different benefits and different parts of the systems were calculated using the equations 6-13, 6-14, 6-15 and 6-16. The ducts, MVHR and heating system contribution was calculated in Solcer house and Rhondda end-terraced. The percentage of the TSC contribution to the total space heating savings or/and delivery was calculated on a monthly and annual basis. Comparison against modelling data was made by using historic weather data for normalisation purposes. Extensive comparison between historic and in situ weather data for horizontal and for TSC plane irradiation was made to increase data comparability and validate data sets used.

The efficiency equation (6-17) was used and applied on averaged and sampling values to identify seasonal conversion of solar to TSC delivery space heating. The fan consumption was calculated for reference but not subtracted from the total heat delivery when mechanical ventilation was the designed ventilation method as discussed in Section 6.2.1.

Additional cavity evaluation based on the test rig was applied to the Rhondda end-terraced house TSC to understand the cavity temperature variations of a triangular collector.

7.2.2 Instrumentation

7.2.2.1 Monitoring Plan

The monitoring plan for the full retrofit of the Rhondda end-terraced in shown in Appendix XIII whereas the part that refers to the TSC study is shown in Figure 7-41 below. The sketch indicates the instruments used for the long-term monitoring named “dynamic” as the variability was captured through the monitoring. There were instruments used for both pre and post retrofit evaluation period as monitoring techniques were used to inform design study as explained in 6.1 and applied in 7.1. Further monitoring was used post-retrofit that refers to the exploration of the TSC and retrofit systems such as the MVHR in the Rhondda end-terraced case study. Figure 7-41 also includes non-dynamic in situ measurements used as one-off tests in evaluating the fabric (pre and post-retrofit) and commissioning stage (balometer). The figure also includes some data collection methods used that do not involve instrumentation but are part of the broader monitoring study.

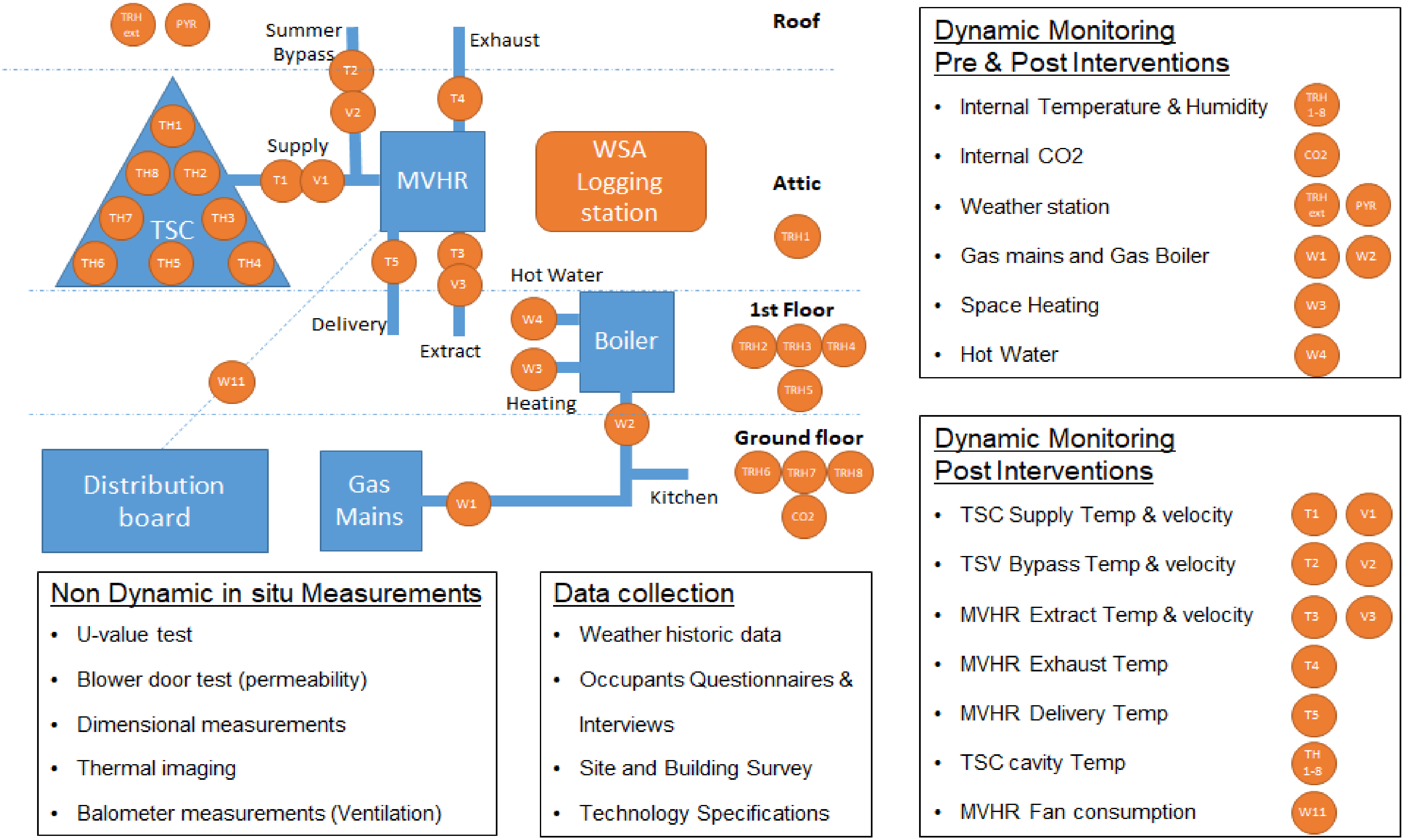


Figure 7-41 Rhondda end-terraced house; TSC and related systems monitoring plan, author.

In more detail, historic weather data were collected from three sources indicated below for intercomparison reasons:

- CIBSE 25 years historic data (243) from a weather station 28km away.
- degree-days-net 5-year data (241) from a weather station 20km away.
- PVGIS-SARAH2 16 years historic data (244) adjusted for specific site's landscape.

PVGIS was used for initial solar irradiation studies as including landscape morphology adds accuracy to the incident solar study.

Occupants and owners were interviewed before and after the retrofit. A timeline schematic (Figure 7-42) illustrates both the works and monitoring scheduling. Occupants were interviewed in early December to capture their view during the heating season and still able to recall the summer and autumn seasons. A semi-structured interview included qualitative and quantitative information for the whole house retrofit. Most of the questions were about building comfort, space heating status and behavioural responses which assisted the heating and ventilation study. A part of the questionnaire created by LCBE team including responses can be found in Appendix XIV.

The site, building and systems survey occurred early in 2017 accompanied by some dimensional measurements and fabric testing. For the dimensional measurements a LEICA DISTO D110 Laser distance measurer was used, whereas Google Maps was used for orientation in combination with a compass. For U-value testing, a bespoke system was designed by the author using four Hukseflux HFP01 heat flux sensors accompanied by eight type-T class A thermocouples, four Tinytags plus two waterproof temperature sensors and a Campbell CR1000X logger. The air permeability testing equipment used in this study was a Minneapolis blower door and fan Model 4 with a DG-700 dual micromanometer following BS EN 13829 and ATTMA TSL1 protocol and using TECTITE Express UK 4.0 software. Different fans can be used for different building floor area. The test was accompanied by thermal imaging analysis of fabric air gaps by using a FLIR i7 camera and TESTO 405NTC telescopic anemometers. U-value testing was used for wall gains recapturing as described in equation 8-16. The balometer used for commissioning the ventilation system and for additional testing was a Testo 417 vane anemometer with a funnel set.

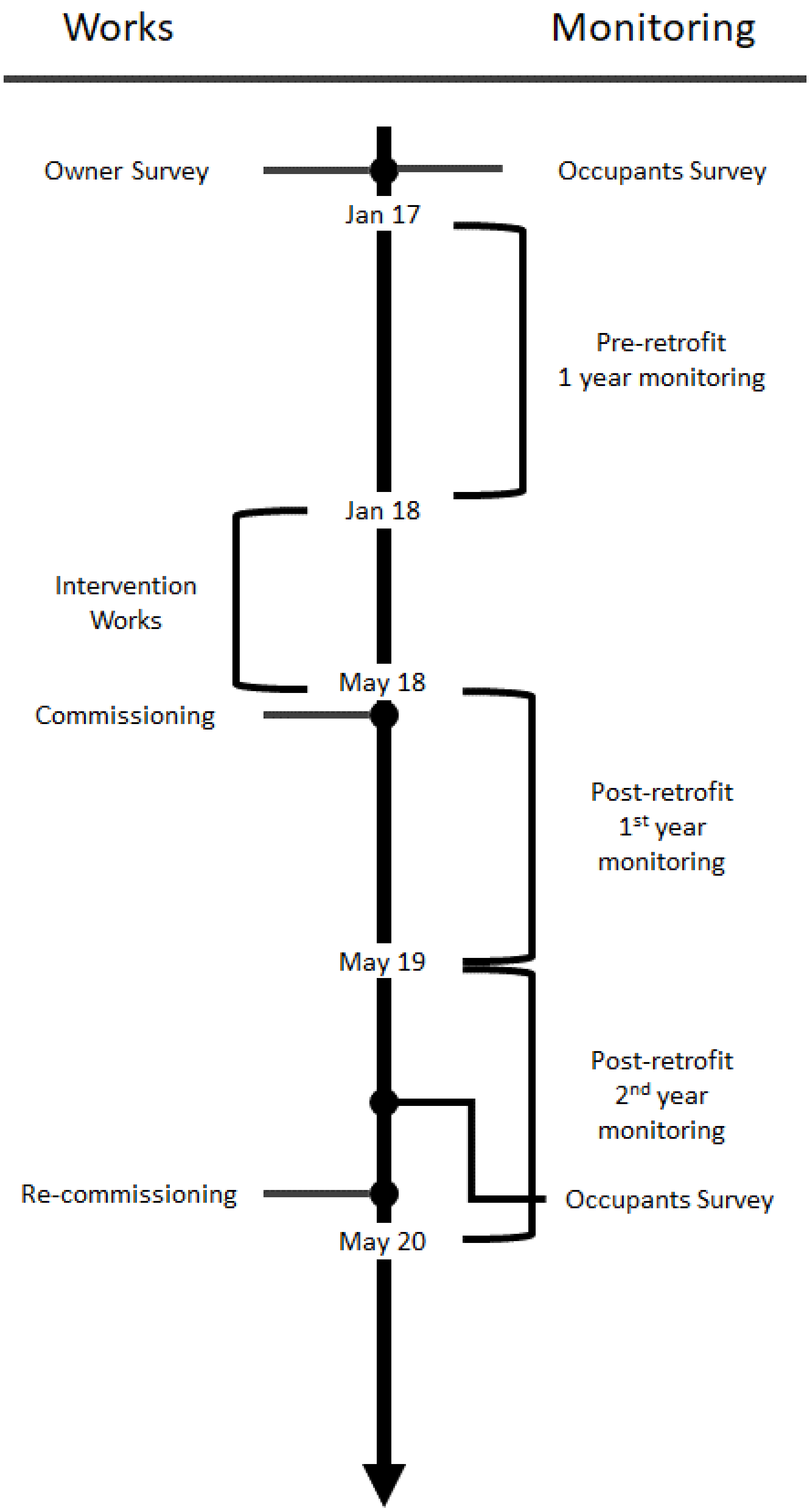


Figure 7-42 Rhondda end-terraced; timeline for both intervention works and monitoring, author.

The long-term monitoring principle was to use high accuracy sensors that are fit for purpose and do not have major compatibility limitations but still do not disturb the occupants. For this reason, wireless or local loggers were selected for the pre-interventions and a wired holistic system was preferred for post-retrofit or new builds in all the sites. The wired system was installed during the intervention to minimise disruption and was hidden in risers and suspended ceiling as much as possible.

A bespoke weather station including Campbell Scientific components was designed and programmed by the author. The station included a CR1000X logger connected to a battery and PV panel for full autonomy. A HC2S3 Rotronic temperature and humidity probe was used in a RAD10E Stevenson screen shield. A Young 05103 wind monitor was used to capture wind velocity and direction. A CMP3 Kipp & Zonen pyranometer was used to mirror the TSC plane - vertical in Rhondda end-terraced. A weatherproof enclosure was used in some of the sites such as the Glan Clwyd School to enclose the logging station.

In terms of thermometers a combination of types was used which is not ideal as the accuracy and thermal response is different. Thermocouples were used in the TSC cavity and PT 100s were used in the ducts and delivery space. Wireless tiny tags sensors-loggers with encased thermocouples and relative humidity sensors were used for internal space temperature and humidity distribution for pre and post retrofit. Also, a Flamefast CO_2, Temperature Sensor with a screen was used for visualisation but was connected to the logger as well. The reasoning behind these choices and sensors parameters will be further explored in the next Section (6.2.2.2).

Itron G4 Secondary gas meters were installed by certified engineers on the main and gas pipe before and after the kitchen branch to monitor the gas consumed by the boiler (W1 & W2 in Figure 7-41). Sontex Supercal 539 Heat meters were installed by certified engineers on the boiler outputs; one for space heating and one on hot water (W3 & W4 in Figure 7-41). Electricity fan consumption was measured after the retrofitting by measuring the corresponding circuit on the consumer unit by using a DDS 353 50A DIN rail meter (W11 in Figure 7-41) installed by certified electricians. All the above energy meters were procured to produce pulse outputs that were connected to local Tinytag pulse loggers (TGPR-1201) for pre-retrofit monitoring and to the logging station for post retrofit monitoring.

The velocity meters used to capture the flow rate in the ducts were a combination of a low differential pressure sensor and two multi point velocity probes from Titan Products Ltd. (V1, V2, & V3 Figure 7-41). The probes were micro perforated to capture the flow pressure drop before and after the flow whereas the pressure sensor would convert the pressure difference into velocity and converted into a signal to be transferred to the data logger (Figure 7-43). These probes were used to capture a cross-Sectional “cross” of pressure variation as described in 6.2.2. The velocity then combined with simultaneous temperature measurements and dimensional measurements of the cross-Sectional area would allow calculating the volume flow rate included in the heat transfer equation as suggested in 6.2.1 and 6.2.2. The probe length was adjusted according to the diameter of the ducts using a variation from 100mm to 1000mm for the experimental studies. As seen in Figure 7-41, V1 and V3 were used for the two main velocities for supply and extract respectively, whereas V2 was used for the summer bypass. V1 and V2 measured the velocity created by the same supply fan but V1 was approximately 2% lower due to the extra TSC pressure drop creating an extra friction in the system. The third velocity meter was used for experimental purposes in Rhondda end- terraced; in all the other experimental sites, the number of velocity meters was determined by the number of fans of the ventilation system.

Figure 7-43 Pressure probe (left) and pressure-velocity sensor/transmitter (right), (299).

7.2.2.2 Sensors factors

Following the Rhondda end-terraced monitoring plan shown in Figure 7-41, the instrumentation parameters were determined according to the framework suggestions. For the non-dynamic in situ measurements the instruments used are shown in Appendix XV accompanied by their main specifications including accuracy. The U value plates and thermometers came with a calibration certificate. The aim was to keep the combined uncertainty below 5% and ensure waterproof external sensors. The external sensors waterproof cover also reduced radiative components from reflections. Also, the temperature sensors were selected based on their time response; for example, the thermocouples selected were bare to avoid any shielding inertia.

The blower door selected is well-known in the sector and was calibrated before and after the experiments. Again, the aim was to keep the uncertainty below 5% thus ATTMA guide was used capturing 10 values per testing ensuring linearity and repeatability (123, 124).

The laser distance measurer was used to ensure high accuracy for a range of measurements, from duct diameter to wall and roof dimensions. With a 1.5mm accuracy the uncertainty for 100mm duct (smallest measurement) was ±0.75%.

The thermal imaging camera was used for indicative thermal and air bridges thus, high resolution was not a priority. Similarly, the aim of the Testo 405NTC anemometer was to indicate draft windows and doors and other leaky areas thus, high accuracy was not a priority however low velocity capturing was considered in selecting appropriate low velocity range. On the contrary, a high accurate ventilation anemometer (Testo 417) was used to measure supply and extracts inlets and outlets volume flow rate. Building Regulations request for a ±5% maximum variation when commissioning meaning that the instrument used should be significantly better.

For the dynamic long-term monitoring, the instruments used are shown in Appendix XV accompanied by their main specifications including accuracy.

The weather station temperature and solar radiation sensors were selected to be of high accuracy as both quantities are part of the fundamental heat transfer and efficiency equations. The response time of such instrument is high (approximately 20s) which does not match the response time of the bare sensors. It has to be considered that a change in weather would impact air temperature in the ducts at a time lag affected by air velocity and thermal response of the skin. Testing, using the Bute building test rig, revealed that clouds would impact duct temperature after approximately 12 seconds. The inertia in sensor response had potential to cause synchronisation issues – this was addressed by averaging within the logging time interval. This will be further explained in the logging setting in the next Section (7.2.2.3)

PT100s were used for measuring temperature for all the KPIs to increase accuracy as their ±0.15ºC accuracy would allow for less than 5% uncertainty for a 3ºC temperature difference. To further reduce uncertainty, the 4-wire connection was used to create a bridge circuit which completely eliminates the influence of the wire resistance and asymmetries. Very thin tip shield was used to reduce the time response; however, testing measurements by using the Bute roof test rig indicated that the type T would typically capture a change in 1s whereas the PT100s would need approximately 10s. For this reason, type T were used inside the TSC cavity to map simultaneously the temperature homogeneity. The Flamefast instrument was selected to monitor CO_2, temperature and humidity close to the thermostat for three reasons; the first was that it included an easy to read screen to inform occupants; the second was that it included an 0-10V output allowing for connection to the logging system and the third was that all the integrated sensors had appropriate accuracy to ensure uncertainty below 5%. the In Rhondda end-terraced house where temperature variation of the rooms was measured by tiny tags us wiring up all the spaces to monitor the air temperature in different rooms was not a viable option. In all the other case studies, PT100s were used to capture room/spaces temperature.

It was essential that energy meters had a pulse output resolution of at least 1 pulse per 1 Wh (allowing 10 pulses to be captured for 10W consumption within 1 hour). This was needed in order to create an hourly profile which would show the 10-30W fan consumption for the residential applications.

The flow-velocity meters were extensively tested at the Bute-building test rig where flow grids, multi point probes and point single-directional sensors where tested. Omni-directional sensors where not tested as they were very expensive and some of them would disturb the flow significantly. Flow grids were also expensive and intrusive. Single-directional / single-point velocity sensors were not accurate as they were struggling with turbulent flow within the duct. A fair compromise was the use of multi point probes described in 7.2.2.1 and their 3% accuracy ensured low uncertainties. To increase accuracy two probes were used averaging two perpendicular multi point pressure drop measurements.

All the above long-term sensors were selected to have a terminal output (voltage or current) that is compatible with a logger directly or through current or voltage conversion modules.

7.2.2.3 Logger selection and settings

The main logging system that was used in all the experimental case studies was the Campbell Scientific Ltd CR1000 logging station (Figure 7-44). An upgrade, the CR1000X was used in SOLCER house and Rhondda end-terraced house. This logging system was selected as it fulfilled all the requirements set in 6.2.2.3. Also, the system is fully programmable, can be connected to a variety of wired sensors with appropriate conversion modules, has extensive expansion capabilities, and supports a wide range of communication protocols. Also, the system is very low powered, can be connected to solar power and batteries. It has a remarkably high accuracy at

±0.04% and significant storage expansion capabilities. It has a cold junction embedded which is a prerequisite for measuring thermocouples accurately.

Figure 7-44 CR1000 (up) and CR1000X (bottom); the data logger from Campbell Scientific used in all the experimental case studies, author.

The CR1000X version has 16 single-ended or 8 differential and individually configured inputs (0-5V); 4 of the 8 differential inputs can be programmed for I/O and pulse ports whereas another 10 digital ports can work as I/O and pulse counters. The logger has four extra excitation terminals that can provide voltage excitation to sensors such as PT100. The expansion peripherals used in this study were the following:

- AM16/32B: This is a 32-channel relay multiplexer used in this study to accommodate up to 16 4wire PT100, or 32 differential voltage inputs such as velocity sensors.
- AM25T: This is a 25-channel solid-state thermocouple multiplexer specifically design to accommodate up to 25 multiplexer that includes an on-board platinum resistance thermometer that serves as a reference junction.

- SDM-IO16A: This is 16-channel I/O and pulses expansion unit used in this study as multiple pulse counter.

In order to facilitate installation, the author created wiring diagrams that are easy to read by a range of construction professionals. The diagrams replicate the logger and peripherals terminals and indicate the wiring connections for each sensor accompanied by comments and wiring colours. A full logging terminal-wiring diagram for Saxon Court residence case study can be seen in Appendix XVI. This case study was preferred to Rhondda end-terraced to present the wiring diagrams as The Rhondda includes further retrofitting monitoring equipment that are irrelevant to this study. This visualisation method got positive feedback in facilitating communications with both colleagues and installation electricians on site.

Loggers' setting-up require visual or coding programming depending on the logging device. In this study, CR Basic language (coding) that is compatible with Campbell Scientific loggers was used by the author to program the terminals, intervals, first layer of data processing, storing and transmission of data. An example of the program used for Saxon court can be found in Appendix XVII. In the design stage, Tiny tags were used to capture energy and comfort data. To program these sensors, Tiny tag explorer visual programming was used.

The time interval used in the experimental case studies was 30 minutes for the pre-intervention data-gathering stage which matches the UK smart metering interval (300). The time interval used for the post-intervention evaluation stage was 1 minute to increase the resolution of monitoring; however, hourly averages and totals were used in the analysis stage when transient phenomena investigation was not a priority. This means that the Campbell program (Appendix XVII) would run and store the timestamped data set every minute. Some of the loggers were not connected to the internet and annual visits were needed to download the stored data before filling the logger's memory capacity. The loggers in Solcer house and Rhondda end-terraced house were connected to the internet through an ethernet connection, and a local router as seen in Figure 6-20. The data sets then were called by Cardiff University server set by Dr Simon Lannon and stored as raw data in monthly bins.

7.2.2.4 Installation

Wireless sensors such as tiny tags were used for pre-intervention monitoring for retrofitting. In the Rhondda end-terraced house, comfort sensors/loggers could not be placed exactly at the centre of the rooms and at chest height as this would disturb occupants. The instruments were placed at the most reasonable place representing the sense of the measured quantity. All temperature sensors were installed away from heating sources and direct sunlight. Extra relative humidity sensors were placed by the west wall where damp had been observed as discussed in 7.1.1.4. Gas meters, boiler heat meters and electric DIN rail meters with pulse outputs were installed by certified professionals and then the author connected the pulse output to battery powered pulse counters (pre-retrofit) and Campbell logger (post-retrofit).

In all case studies, a wired monitoring system was preferred for post-retrofit monitoring. All the installation details were planned before the construction phase to allow for installers to apply the monitoring plan in conjunction with the TSC equipment and controls and hide all wiring. In Solcer house, the risers and suspending ceiling housing the ducting and controls were also used for hosting monitoring as seen in Figure 7-45. An opening to the riser was designed and hidden behind the bathroom mirror. In Rhondda end-terraced house, wires were also hidden in risers, but the velocity transmitters were installed in the attic (Figure 7-45) where the main logging system was also installed.

Figure 7-45 Installation of air velocity pipes and transmitters. Left: Solcer house installation hidden within risers. Right: Rhondda end-terraced visible installation in the attic, author.

The probes for the pressure velocity measurements were installed at the straightest part of the ducts allowing for a minimum of 2 duct diameter length before and after the installation to minimise turbulence. The bespoke setting designed by the author was a compromise between a flow grid and one probe and is visualised in Figure 7-46. Instead of one probe, two probes were used to capture two perpendicular diameters of circular (or rectangular) ducts as seen in Figure 7-46. The probes were then connected through pipes to average the pressure and then connected to a velocity transmitter. This arrangement was tested at the Bute roof rig and was preferred to one probe arrangement as accuracy was increased without using very expensive and intrusive flow grids.

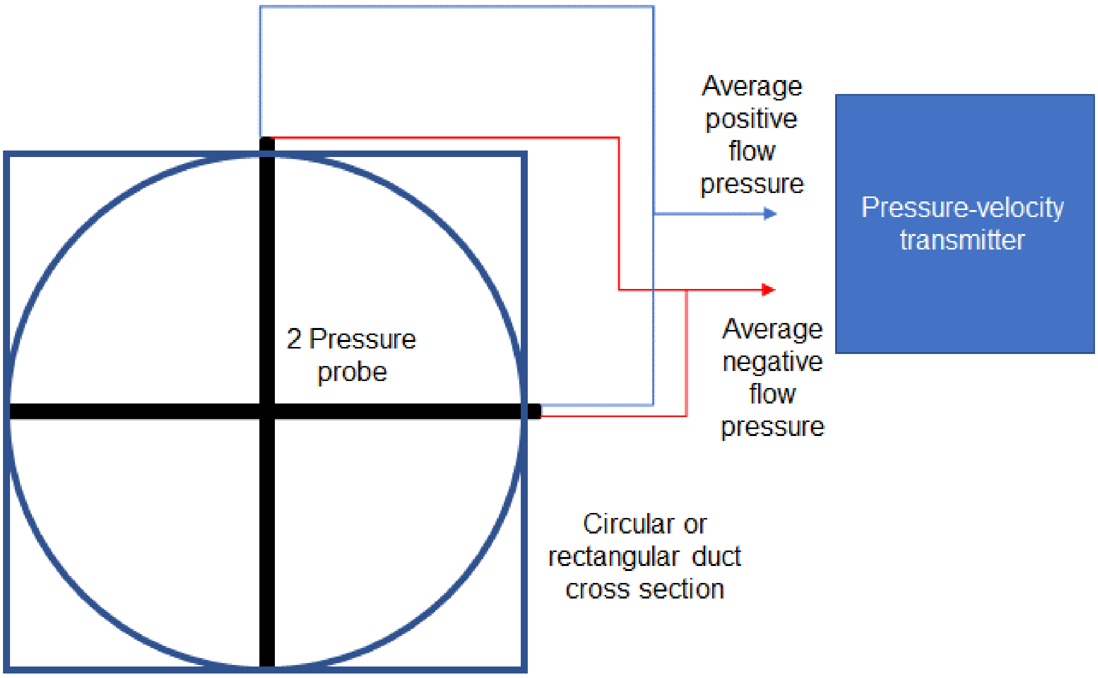


Figure 7-46 Double pressure probes arrangement to capture the cross-Sectional pressure-velocity distribution within the TSC ducts, author.

The logging stations were installed in most of the cases internally to be protected by weather. In large installations, the loggers were installed near or in the control enclosures and sometimes (Glan Clwyd school) outside in waterproof (IP68) enclosures (Figure 7-47). Most of them were powered by mains, however solar powered CR1000X loggers were successfully tested at Bute roof test rig and also used In SEDA for powering the weather station. SEDA was the only site that the weather station was not connected to the main CR1000; instead, a separate CR1000 was used due to installation limitations Figure 7-48. The two loggers were synchronised through server programming.

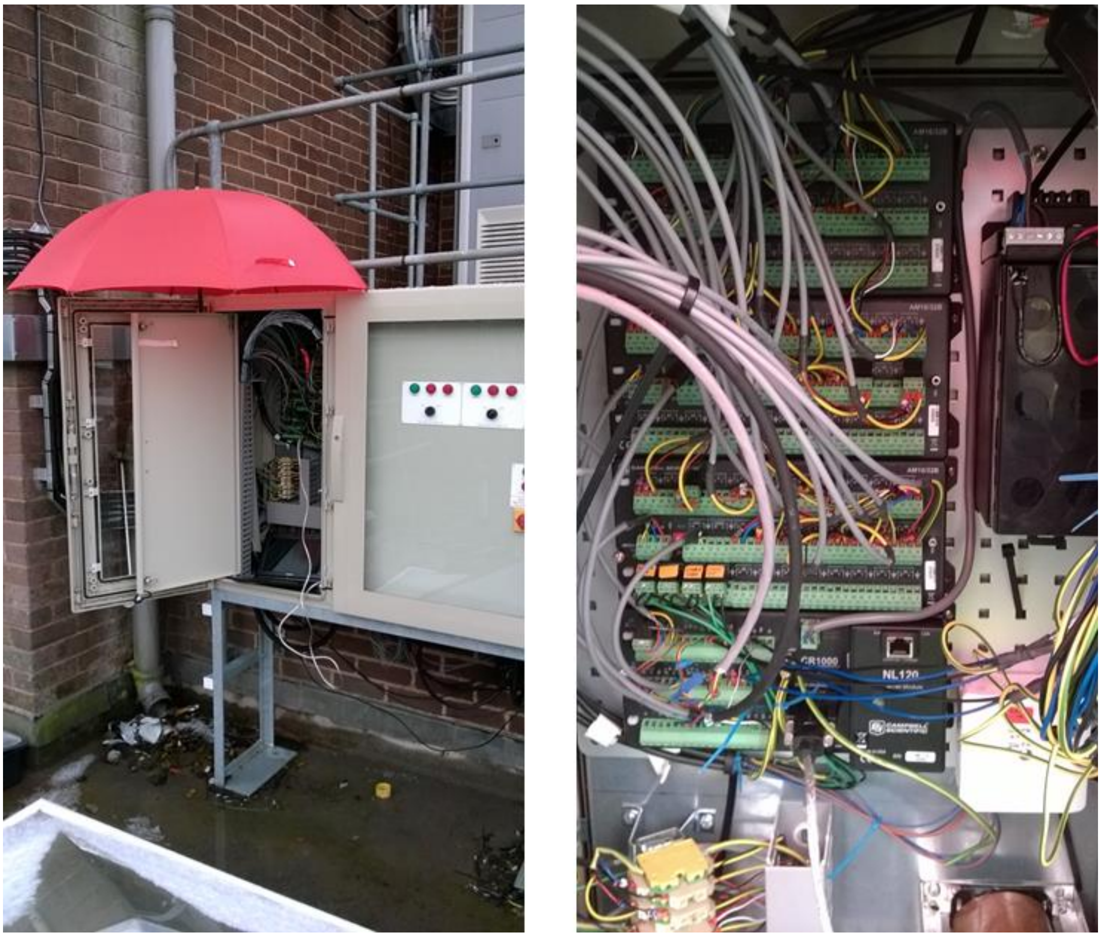


Figure 7-47 Glan Clwyd School. Left: external waterproof control and monitoring enclosure including data logging and peripherals. Right: installation of CR1000 and three extension multiplexers, author.

The weather station was installed on a pole with a tripod and was secured by three ropes. From bottom to top, as seen in Figure 7-48, the weather station in SEDA factory included:

- A rain gage installed away from the pole and level in parallel to the ground
- A CR1000 logger with a battery backup facing north to avoid direct sunlight, enclosed in a IP68 box.
- A temperature and relative humidity sensor protected by direct sun in a Stevenson screen which allows air to pass through.
- A photovoltaic panel sized to power up the logger and charge the battery ensuring 1 month autonomy with no sun.
- An antenna used to increase data transmission
- Two pyranometers installed to mimic SEDA TSC plane and horizontal plane for reference. They were placed at 5 meters to avoid shading from surrounding buildings.

- A wind set including wind velocity and direction instrument installed at 5m height to mimic TSC installation height and avoid close to surface wind variations.

Figure 7-48 SEDA factory. Left: autonomous, solar powered weather station. Right: Waterproof enclosure to accommodate CR1000 logger and battery; author.

7.2.3 Data processing

The CR1000 and CR1000X can capture digital or analogue signals within 0-5V including all types of pulses within this range. The instruments that generate signals outside this voltage area, or generate different forms of signals such as current (e.g. 4-20mA), need a conversion mechanism to transform the generated signal to readable signal. For example, the pressure-velocity meter used (Titon) has a 0-10V output; thus, a resistive transformer module was used to change the range to 0-5V. A further layer of processing includes the translation from the 0-5V range to units that correspond to the actual measuring quantity. This translation can happen at the logger, the server or at the end terminal. In any of these cases, a multiplier or an equation was used to convert signal to actual rational values following the instruments' specifications. Within the experimental case studies, both raw signal and raw value were stored after they were timestamped as two different forms of raw data. Data were stored at Cardiff University servers and any further processing was done to a copy. The files used for analysis were 5 min interval files for each month for each site averaging the 1 minute interval used on the logger sampling. An exception to the above refer to the performance evaluation of transient phenomena such as the Rhondda end-terraced TSC temperature variation within the cavity where 30 seconds time interval was used on the logger and the server.

All the error detection mechanisms were applied asynchronously by using Excel software. The first testing was counting rows of data by comparing expected number of rows to received number of rows. For example, in January, 8928 rows were expected at 5 min interval. When less than 10% was missing, then values would be normalised for expected total. In a few cases in the beginning of the first monitoring sites, data loss was greater to 10%. When transmission methods and programming was optimised, the losses decreased to less than 1%. The second error detection test including a range check for all the values within each row. This was used extensively during the monitoring commissioning phase to ensure use of appropriate conversion factors and wiring connections. Grouping was performed according to 6.2.3.3 Hourly averages and totals were used accompanied by min, max and standard deviation calculations. Also, logic equations were used when need, for example were data needed to be summarised during sun hours, "sum-if" and similar formulas were used

7.2.4 Data analysis

7.2.4.1 Space heating savings

As described in Figure 7-42, the pre-retrofit year for the Rhondda end-terraced house was 2017. Works took place for the first four months of 2018 and post retrofit monitoring started in May 2018. In Table 7-17, average ambient temperatures for pre- and post-retrofit years are presented in comparison with historic data basis used in the design stage. The table shows that the post-retrofit monitored averaged air temperature was higher to the pre-retrofit for the first monitored year and slightly lower for the second monitoring year. The same pattern is followed when comparing monitored years to historic data. Also, similar findings are shown when looking at the heating season where average of the post retrofit monitoring is higher to historic data. Another interesting output is that the second post-retrofit monitored ambient temperature for the heating season has very little variability from Nov 2019 to March

2020. The average monthly ambient temperature for that period was very similar. As ambient temperature is an important factor of the TSC heat transfer (Equation 6-4), the degree days normalisation process used in the design phase will be used in the performance evaluation phase so that the TSC contribution responds to historic weather conditions.

Table 7-17 Rhondda end-terraced; Monthly ambient temperature averages monitored for pre and post retrofit years and compered against historic weather data, author.

Month	Pre-retrofit measured 2017 (°C)	Post-retrofit measured 1st year (°C)	Post-retrofit measured 2nd year (°C)	CIBSE historic (°C)	PVGIS historic (°C)
January	4.8	4.7	6.6	6.2	4.4
February	5.6	6.6	6.6	4.9	4.7
March	8.2	7.8	6.4	6.6	6.1
April	8.8	10.3	9.3	8.5	8.8
May	13.0	13.4	10.6	12.2	11.2
June	15.4	16.8	13.9	14.0	14.0
July	16.1	18.6	16.8	16.1	16.0
August	14.8	15.6	15.8	16.1	15.4
September	12.8	13.1	14.1	13.9	13.9
October	12.2	10.3	10.1	11.2	10.9
November	7.4	8.2	6.7	8.6	8.0
December	5.7	7.8	6.3	6.7	6.1
Average All year	10.4	11.1	10.3	10.4	10.0
Average Heating season	7.5	8.0	7.4	7.5	7.0

Figure 7-49 shows the pre- and post-retrofit monthly daily averages and annually total gas use including boiler losses. It follows the pattern of Figure 7-19 for comparison reasons. The figure indicates the space heating decrease for the 2 post-retrofit monitored years from 11,016 to 7,239kWh which is a 3,777kWh (34.3%) reduction. This reduction comes from fabric changes and the MVHR+TSC system assuming for similar weather conditions. The graph indicates the monthly average ambient temperature for each pre- and post-retrofit month.

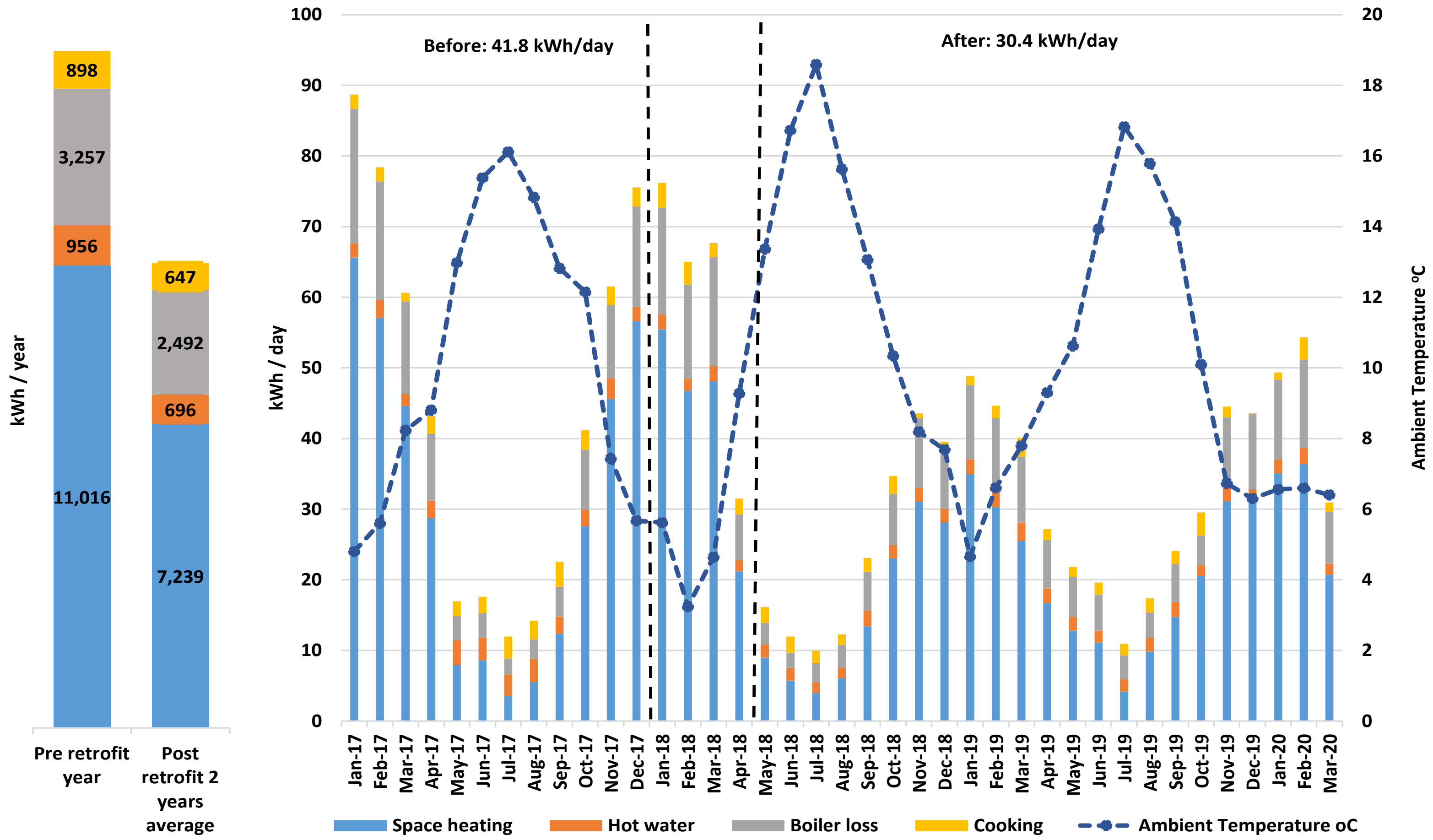


Figure 7-49 Rhondda end-terraced house; pre- and post-retrofit daily averages per month and annual total gas consumption break down including losses and average monthly ambient temperature, author.

The monthly analysis does not account for the four months of works (Figure 7-49). The total annual gas use (daily average) dropped from 41.8kWh to 30.4kWh, where 19.8kWh was the space heating delivered from the gas boiler. The ambient weather line indicates the variation showing a warmer summer for the 1st post-retrofit year in comparison to the pre-retrofit. It also shows a long cold five-month period which is also indicated in Table 7-17 above.

As monthly average ambient temperature shows a significant variation during the three monitoring years, space heating should now be normalised for historic weather data. Also, the 3,777kWh space heating savings should be broken down to the retrofitting measures taken which include the fabric changes and the MVHR+TSC system. Another parameter to be considered is that the monitored gas boiler losses is at 21.4% as explained in the building demand survey (7.1.1.3) This means that the 11,016kWh space heating was delivered by 14,015kWh of gas for pre retrofit and the similarly 7,239kWh was delivered by 9,210kWh. In other words, the 3,777kWh of a space heating savings correspond to 4,805kWh of gas savings, equals to £577 savings annually (£0.12/kWh 2022 Oct - gas cap from Ofgem (265)).

Figure 7-50 shows pre- and post-retrofit space heating daily averages per month and annual total, normalised for CIBSE historic heating degree days as described in 6.1.1.1 and 6.2.4.2. The pre-retrofit annual normalised space heating is only 0.11% higher than the monitored data showing a good match between CIBSE historic and pre-retrofit data, something that was evident from the heating degree days in Table 7-1. The post retrofit annual normalised space heating is 0.37% higher than the monitored showing again a good match between CIBSE historic and post-retrofit 2-year data. The graph also includes the ambient (external) and the lounge (internal) monthly average temperatures. A warmer summer affects the internal temperature without dropping the space heating used. This could happen as occupants were asked to use the thermostat at a desired set-point rather than using it as on ON-OFF switch. This helps the gas boiler to operate smoothly in the winter, but the thermostat can be forgotten at “ON” during summer. This was an observation that was confirmed by the post-retrofit occupants’ survey.

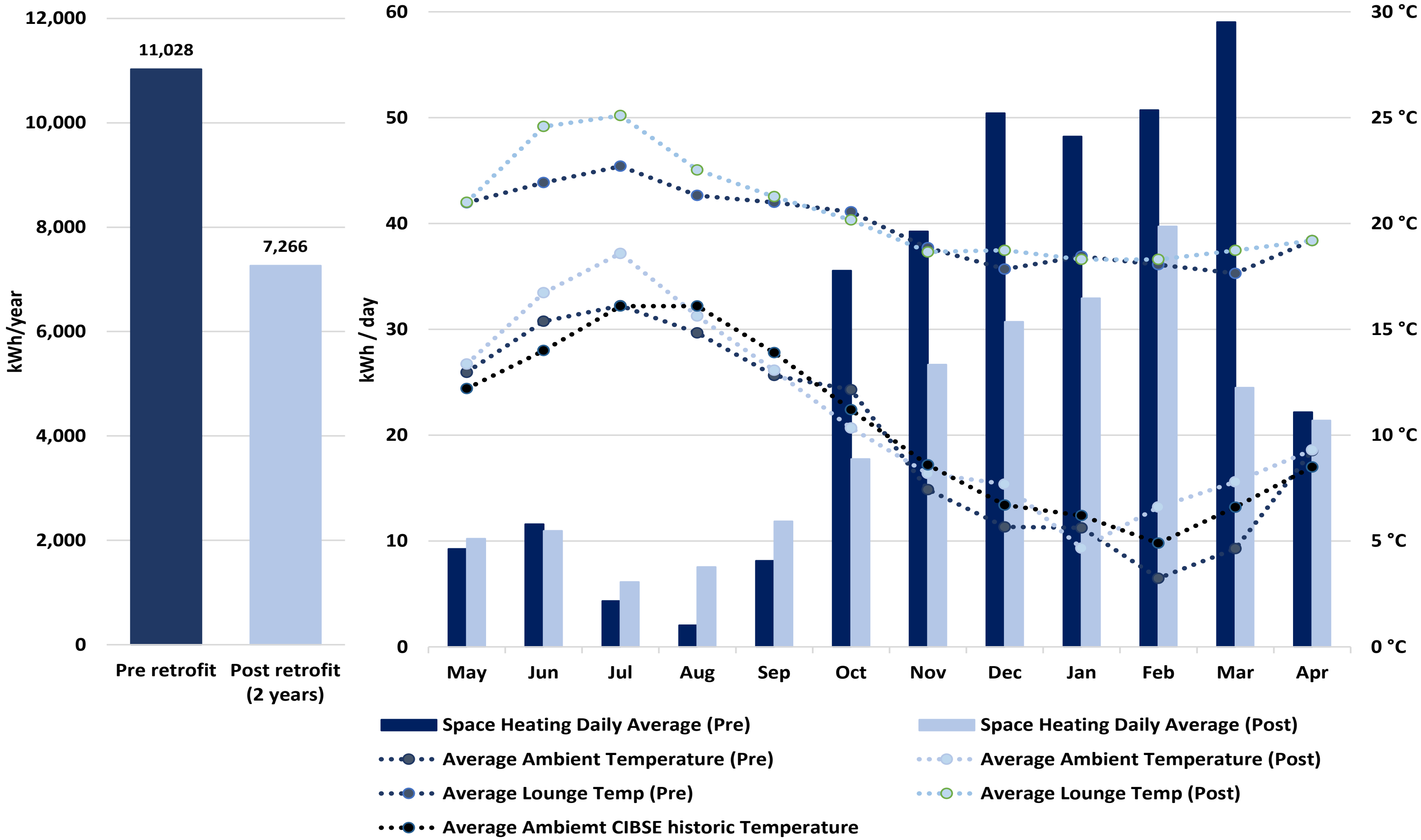


Figure 7-50 Rhondda end-terraced house; pre- and post-retrofit space heating daily averages per month and annual total including average monthly ambient and internal temperature, author.

Before analysing the TSC contribution, it is useful to observe the total energy used in the Rhondda-end-terrace house to have an overview of the significance of space heating reduction. Figure 7-51 visualises the gas consumption and electricity balance including electricity covered by renewables (PV and battery).

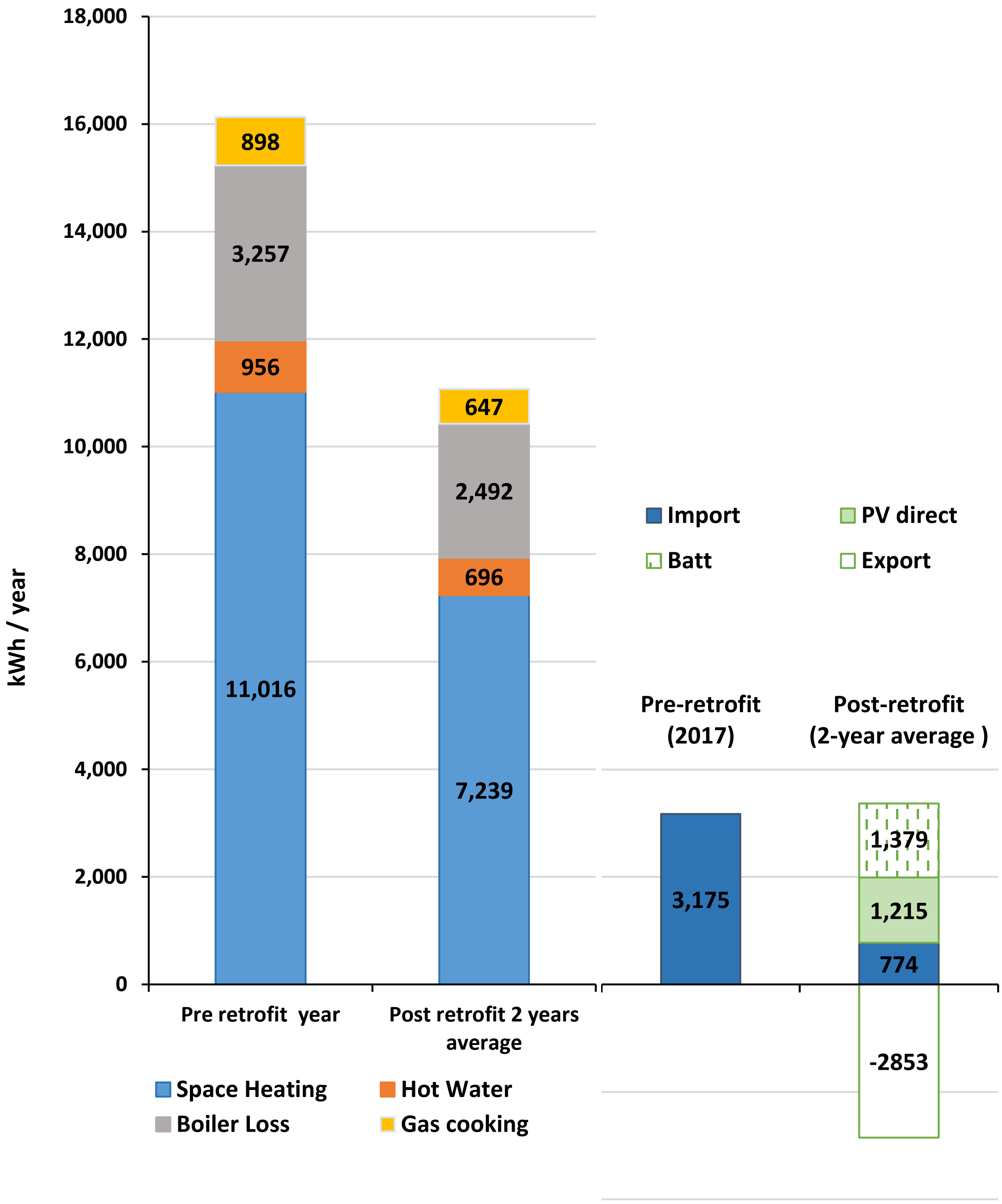


Figure 7-51 Rhondda end-terraced; annual energy balance for both gas and electricity for pre and post retrofit including savings from space heating and PV plus battery, author.

It can be observed that the post-retrofit electricity consumption was slightly increased. This is a result of three factors:

- The electric shower was used more especially during sun-hours as suggested to the occupants. This resulted to a 27% reduction on gas boiler hot water use.
- The battery includes some charge and discharge losses.
- The MVHR fan consumes electricity.

This last one is more relevant to this study and accounts for approximately 6% (Figure 7-52) of the total energy consumption at approximately 20Wh each hour.

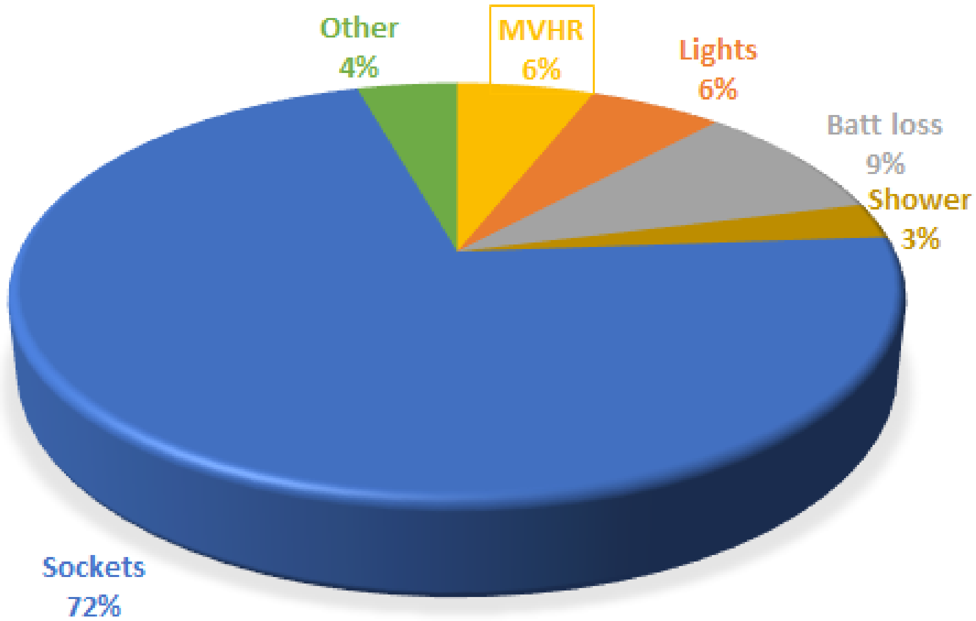


Figure 7-52 Rhondda end-terraced; Electricity consumption break down showing the impact of the MVHR using two years of post-retrofit monitoring data; author

7.2.4.2 Key performance indicators

The following graph (Figure 7-53) compares the monthly total vertical solar radiation measured through the pyranometer for both post retrofit years against the modelled vertical solar radiation calculated though PVGIS and through SWIFT using CIBSE horizontal solar data.

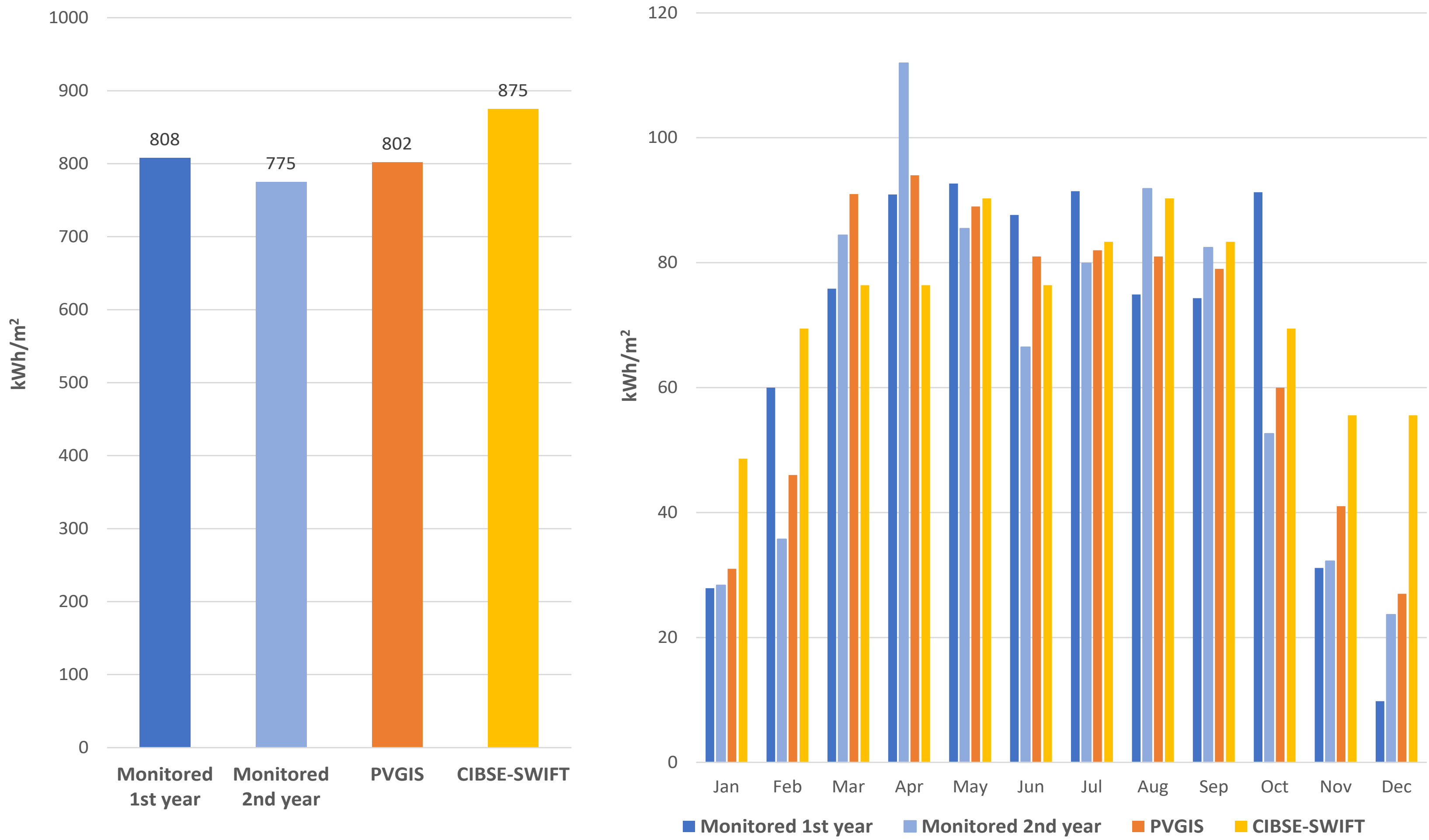


Figure 7-53 Rhondda end-terraced; vertical solar radiation annually and monthly as monitored on site for two post-retrofit years and as modelled by PVGIS and CIBSE-SWIFT, author.

Despite monthly variability, the annual monitored data are close to the PVGIS historic data with the first monitored year to have 0.8% higher solar radiation than the PVGIS whereas second year has 3.4% lower. The average of the two monitored years is 1.3% lower than the PVGIS historic and 9.6% lower than CIBSE-SWIFT. It must be noted that the CIBSE-SWIFT vertical radiation winter months are on average 40% higher than the monitored. The reason for this deviation lies to the fact that PVGIS considers the local landscape whereas CIBSE does not as seen in the outline of Rhondda end-terraced horizon in Figure 7-3. This can cause some overestimation to the TSC modelling performance as CIBSE historic weather data were used in the modelling process because the pre-monitored ambient air measurements were very close to the CIBSE, and solar radiation data were not gathered in the pre-retrofit stage. The above indicates that solar radiation monitoring before installation can assist in historic data selection especially when landscape cause shading to low solar paths

The next figure (Figure 7-54) shows the TSC-MVHR system performance for the Rhondda house. The graph includes monthly and annual data as well as temperature monthly averages. The calculations are based on equations 6-4 and 6-5, Section 6.2.1. The total heat delivery of the system is 1,276 kWh with 74% delivered during the 7-month heating season (Oct-April). The TSC contributed 38.2% to the TSC+MVHR system or 488kWh. This is very close to the 37.8% contribution of the TSC to the MVHR+TSC system in Solcer house. However, and as described in 6.2.1, equations 6-4 and 6-5 can be used for Solcer house where the exhaust heat pump would use any heat coming from the TSC whereas in Rhondda end-terraced, the TSC contribution is not all useful as, part of the heat that it delivers, would have been delivered by the MVHR without the TSC existing. The TSC useful heat, when connected to an MVHR only without the presence of any exhaust heat pump, is described in 6.2.1, equation 6-9, 6-10 and 6-11. Figure 7-55 shows the TSC useful contribution which accounts only for 33% of the 488kWh delivered by the TSC. The 160kWh of TSC useful heat come from 104kWh of heat delivered up to the extract temperature and 56kWh above the extract temperature. The first (160kWh) refers to TSC heat that the heat exchanger cannot deliver due to efficiency (76%) limitations and the second (56kWh) refers to TSC heat if there is a demand for delivering above extract temperature and the HE is bypassed as described in 6.2.1.

The temperature variations in Figure 7-54 shows an expected relation between the ambient and the TSC delivered temperature. The MVHR HE smoothens up the temperature coming out of the MVHR-TSC system through the heat exchanger. The temperature in the lounge follows the delivery temperature from an average of 18.3^{o}C in January up to 25.6ºC in July. These temperatures are monthly averages, meaning that instantaneous overheating during the daytime could be significant (Table 7-18). Overheating can be addressed by lowering the TSC bypass temperature set point for the no-heating season mode.

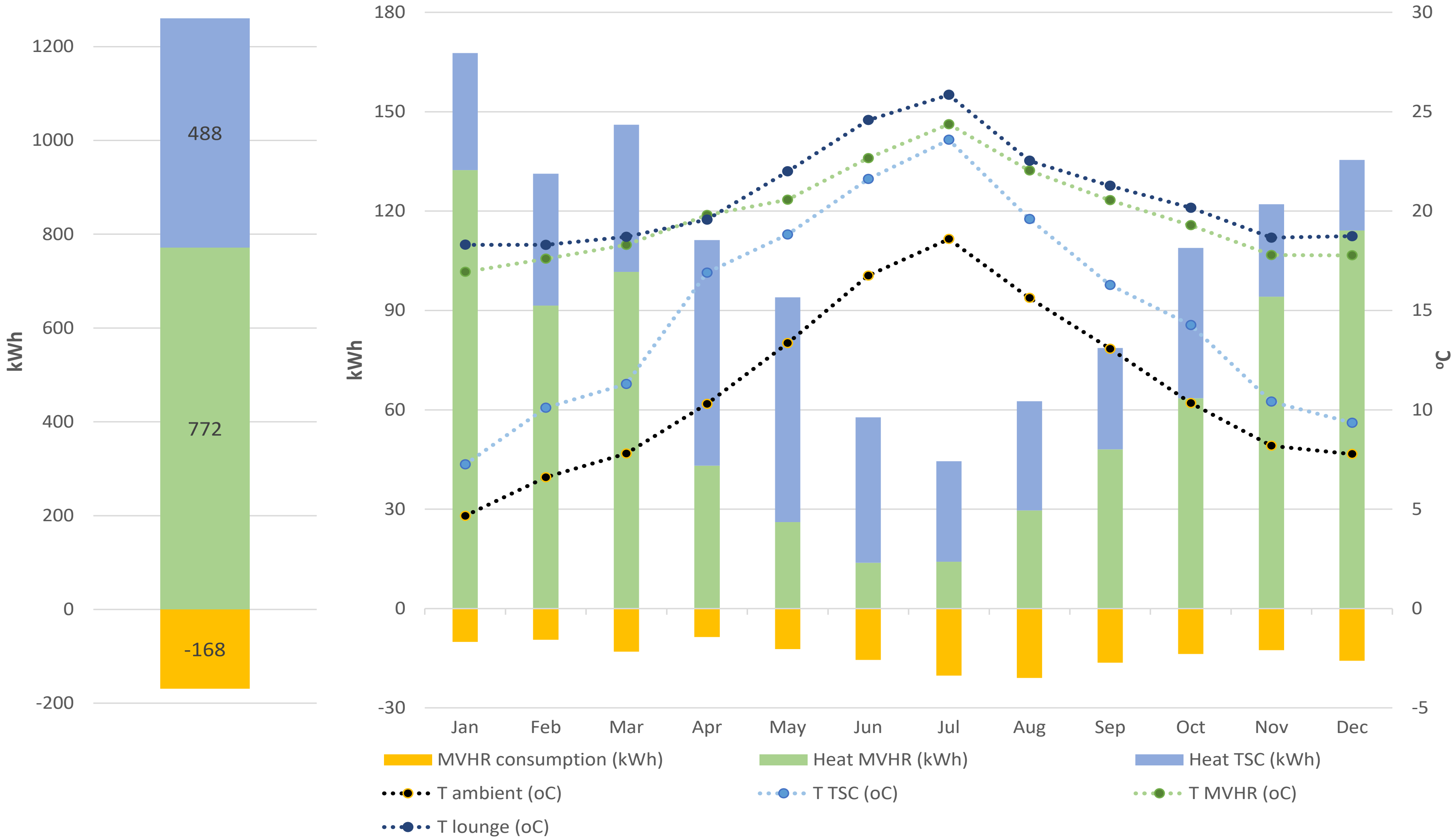


Figure 7-54 Rhondda end-terraced; MVHR and TSC contribution monthly and annually accompanied by relevant average temperatures, author.

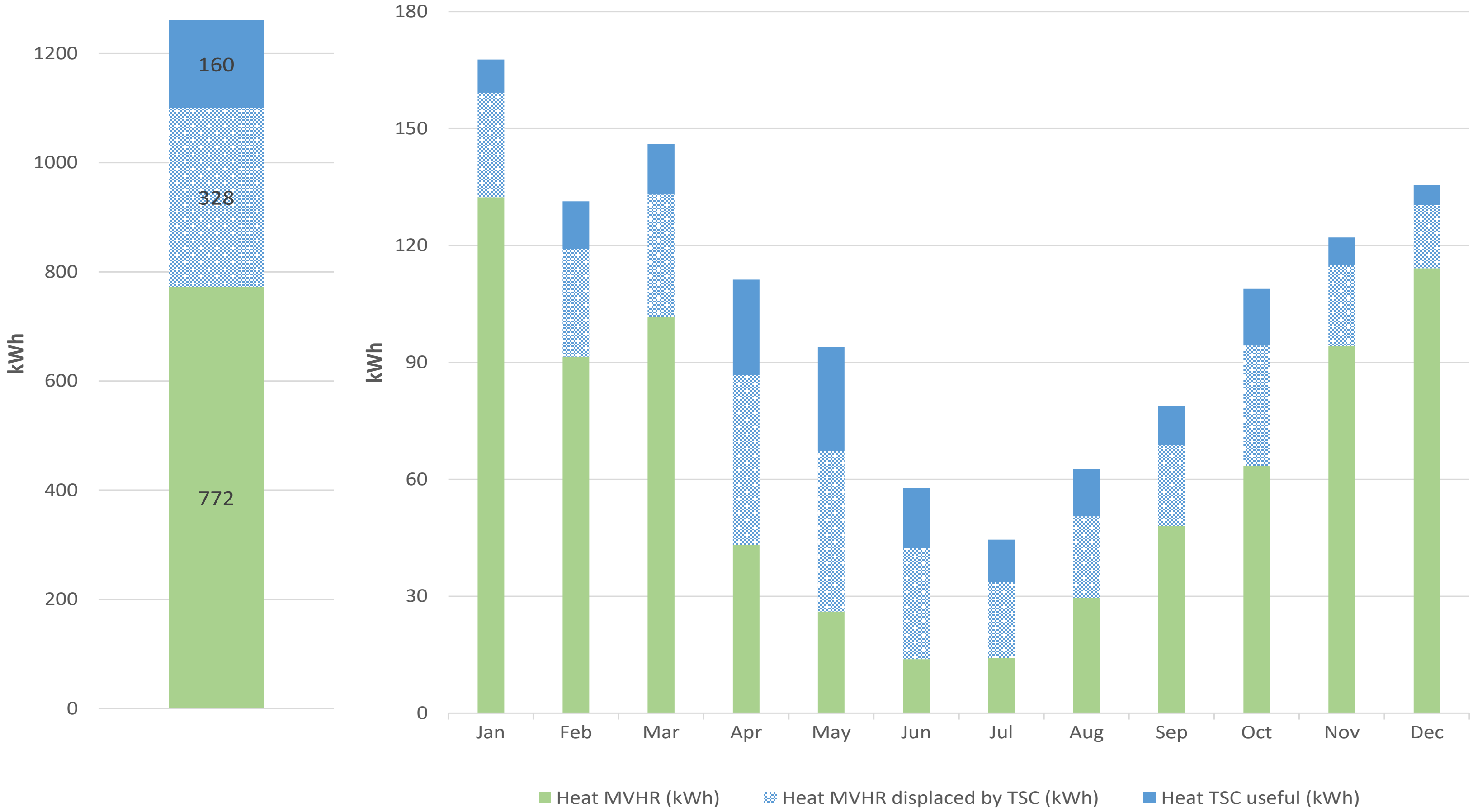


Figure 7-55 Rhondda end-terraced; MVHR and TSC contribution monthly and annually where the TSC contribution splits into heat that displaces some MVHR heat potential and TSC useful heat, author.

The monitored TSC heat delivery can be compared with the modelled predictions. HTB2 and SWIFT were used to model TSC performance as described Section 7.1.2.3 and visualised in Figure 7-27. The figure below shows the monitored data broken down to delivery during heating and non-heating season. There is approximately an 24% and 27% performance gap comparing monitored and modelled HTB2 and SWIFT respectively. This is caused by three reasons that are all related:

- the solar radiation used was from CIBSE data without a correction for landscape causing shading during winter months (as described earlier in this Section and presented in Figure 7-53 and in Figure 7-3).
- the solar radiation is associated with an overestimation of the SWIFT model indicating TSC temperature rise that are higher than monitored. This is evident in Table 7-18 which brings together data from Table 7-12 and monitored data.
- the flow was measured flow at 53.4m^3/h whereas 61m^3/h was predicted in the modelling. This was adjusted in the second commissioning.

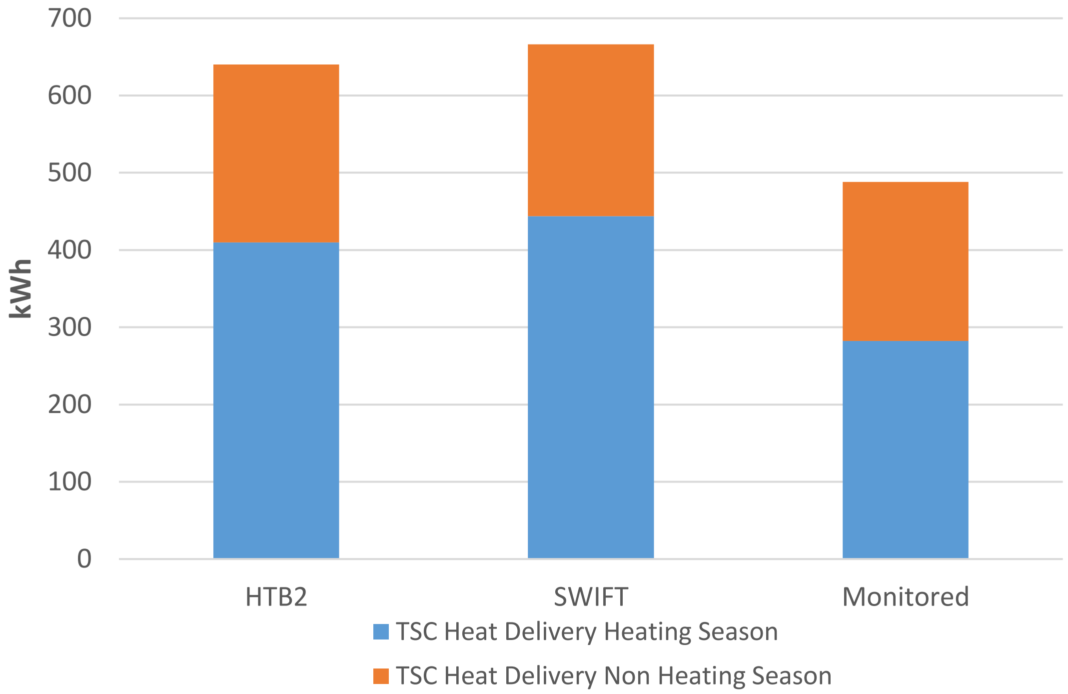


Figure 7-56 Rhondda end-terraced; modelled and monitored heating season TSC Heat Delivery, author

The deviation between modelled and monitored TSC temperatures rise is not significant during summer months but is significant during heating season and especially November to February. The modelled average temperature rise for the year is 7.9°C whereas 6.0°C was monitored. The temperature rise for the same flow is an indication of TSC heat delivery difference (equation 6.4), meaning that the 24% difference in temperature rise matches the difference found in Figure 7-56.

Table 7-18 Rhondda end-terraced; Monthly average daytime ambient and TSC rise temperature, monitored and modelled using CIBSE historic data and SWIFT, author.

Months	CIBSE average Ext Air Temp daytime (°C)	Monitored average Ext Air Temp daytime (°C)	SWIFT/CIBSE average TSC temp rise daytime (°C)	Monitored average TSC temp rise daytime (°C)	Monitored average supply temp daytime (°C)
Jan	6.6	5.8	8.1	5.3	11.1
Feb	5.6	8.4	10.6	6.4	14.8
Mar	7.6	8.7	8.5	6.6	15.3
Apr	9.4	12.0	7.9	7.7	19.7
May	12.8	15.0	7.0	7.1	22.1
Jun	14.7	18.3	5.7	6.1	24.4
Jul	16.8	20.3	6.0	6.3	26.6
Aug	17.0	16.9	7.1	6.9	23.8
Sep	15.1	14.7	8.2	6.3	21.0
Oct	11.8	12.1	7.7	5.4	17.5
Nov	9.3	9.2	8.7	5.2	14.4
Dec	7.4	8.6	9.5	2.7	11.3
average	**11.2**	**12.5**	**7.9**	**6.0**	**18.5**

Another noticeable outcome from Table 7-18 is found in the last column where the average monitored supply temperature during daytime is presented. The July daytime average is 26.6°C which indicates overheating. For all the other summer months the temperature is between the 23-25°C range suggested by CIBSE (87). In theory this was not expected as the summer bypass was set to be triggered for ambient external temperature at 20°C. In practice though, duct heat recapturing especially in warm attics would transfer heat to the delivered air. For this reason, the bypass thermostat was readjusted to 18°C during the second commissioning.

The next analysis presents the MVHR+TSC contribution to the total space heating delivered and saved through the retrofitting. The interventions in Rhondda end-terraced that affected the space heating apart from MVHR+TSC system, included insulation and sealing. The windows remained the same and the ground floor was not further insulated. The attic was additionally insulated changing the U-value from 0.25 to 0.11 W/m^{2}K (values based on modelling). The external walls were also insulated reducing the U-value significantly from 1.40 to 0.49W/m^{2}K (values based on monitoring). Sealing around windows, doors and attic hatch together with the insulation, reduced the permeability from 6.8 to 5.1 $m^3/(h.m^2)$@50Pa. Figure 7-57 shows the breakdown of the 3777kWh (3762kWh for historic weather normalisation) space heating reduction. The MVHR+TSC system is responsible for 1/3 of the savings with the TSC alone for 13%; however, only 4% was the useful TSC contribution with no exhaust heat pump or similar system connected. For 0.12£/kWh as discussed in the sizing Section (7.1.2.3) the TSC monitored cost savings per year was £58.70 and MVHR savings at £92.70. However, this does not account for improved comfort and the drastic reduction in CO_2 emissions and especially in relative humidity and damp. The relative humidity in the lounge dropped on average 14.3% from 69.0% to 54.7% as shown in Figure 7-58 resulting to significant improvement to occupants' asthma conditions. Similar results were measured in the bedrooms.

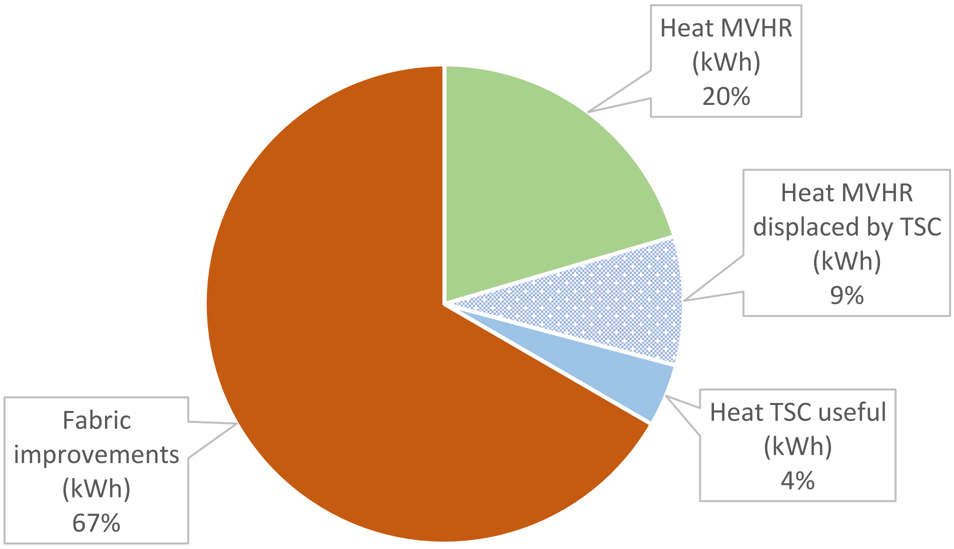


Figure 7-57 Rhondda end-terraced; contribution of retrofitting actions to space heating savings, author.

The pre-retrofit relative humidity was not peaking in the summer months probably indicating an impact of the adjacent river as occupants used to open the west door very frequently. The post-retrofit variation of the relative humidity is very small (st. dev. at 2.6) and peaks in August whereas the pre-retrofit variation is much higher (st. dev. at 5.9). This means that the relative humidity was not only decreased to recommended levels CIBSE (87)) but was also stabilised due to mechanical ventilation. CO_2 levels were measured for long term post-retrofitting. The CO_2 levels would drop around 420ppm in the night. However, daytime CO_2 level average was at 880ppm peaking in January at 982ppm. It has to be mentioned that the adults were unemployed and the children were home-schooled meaning that the family would spend very long hours in the lounge.

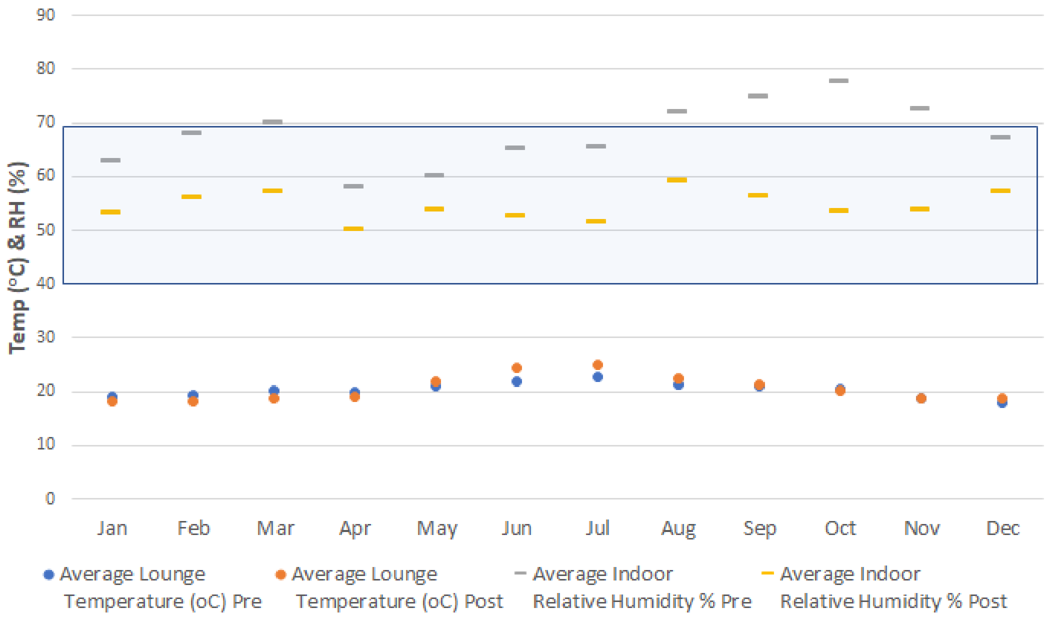


Figure 7-58 Rhondda end-terraced; pre and post retrofit lounge monthly average temperature and relative humidity for including a CIBSE suggested range for relative humidity (40-70%) (87), author.

7.2.4.3 Supplementary performance indicators

The average seasonal efficiency of the TSC was calculated using Equation 6-18 from Section 6.2.1. The measured value was at 17.5% which is slightly lower than the 19.0% which was modelled for the same area of TSC (4m^2) as seen in Figure 7-25. The obvious reason for this deviation is the difference between modelled and measured volume flow rate; 61.2 versus 53.4m^3/h, respectively.

In Figure 7-59, a sketch of the the triangular TSC shape including seven sensors in the cavity is visualised. Sensor 2 was placed by the MVHR intake duct and was considered as the reference sensor and any deviations were calculated against this sensor. The annual average temperature difference between the reference and the other six sensors was calculated and is indicated for each sensor in Figure 7-59. This calculation was done for both the whole day (24h) and daytime. Daytime temperature was calculated by avearging the temperature only when using solar radiation was greater than zero. A radiation offset (20W/m^2) to avoid artificial sand sky kighting. The next set of observations summise the findings:

- The sensors by the edge of the panel (1, 3, 5 and 7) are colder than the reference sensor during a 24 hours comparison which is explained by the reduced heat being absorbed by the surrounding area that includes edging strips and sealing finishes.

- However, during the daytime, sensor 1 average temperature equals the reference temperature. This is a result of the stack effect occuring during the heating time as the warm air tends to rise and the air that is not instantaniously extracted will influence sensor 1.
- Sensors 4 and 6 have slightly higher temperature than the reference for both day and 24-hour. During the day they get heated and the air behind the cavity stalls for a while as it is not dragged as rapidily as for sensor No2 which is very close to the extraction. During the night a similar but less intense phenomenon occurs through the back wall heat gain.
- The colder part of the cavity is at the bottom as there is no stack effect to heat them up and at the bottom part there is insulation that would prevent significant heat recapturing through the wall. This is in addition to the effect of the sensors being close to the edges mentioned previously.

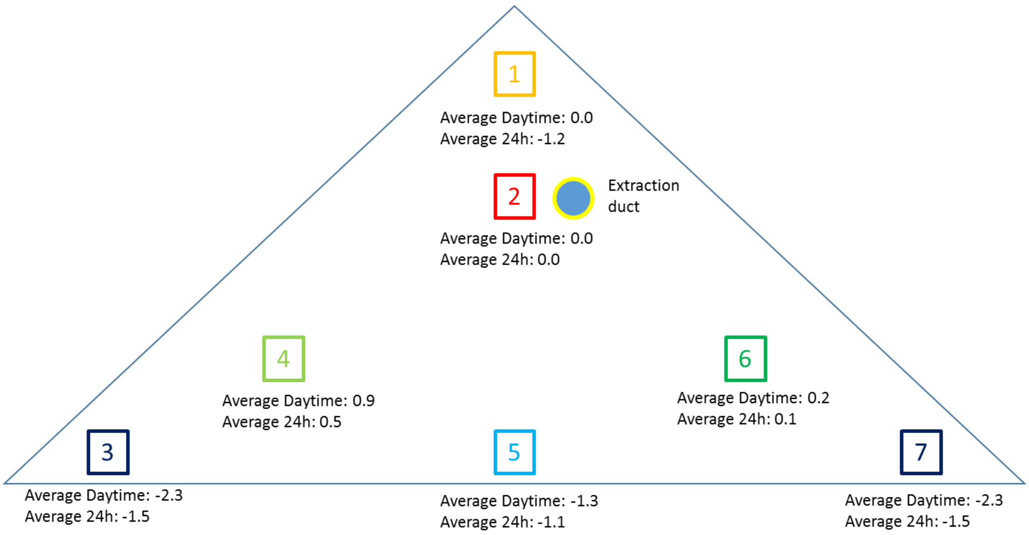


Figure 7-59 Rhondda end-terraced; triangular TSC, temperature variations in the cavity, author.

Temperature near the panel edge tends to be lower than the centre; this means that a TSC with high area to perimeter ratio would perform better. A circular TSC would get less heat loss from the perimeter than a rectangular and a rectangular less than a triangular. On the other hand, stack effect is benefitted from the chimney triangular shape leading warm air naturally to the extraction duct.

7.2.4.4 TSC performance across all the experimental case studies

In order to compare the TSC heat delivery for all the experimental case studies, a normalisation per area of TSC is needed. It has to be noted that the TSCs would also have a different orientation, inclination, controls and volume flow rate, which makes comparisons challenging. A comparison that is quite straightforward is between Rhondda end-terraced and Solcer house as they have similar orientation, inclination, controls and set points. They also have a similar flow per square meter of TSC ratio which makes them comparable when normalising per volume flow rate and area. Figure 7-60 shows the MVHR and TSC heat contribution with the TSC contribution difference at approximately 4%.

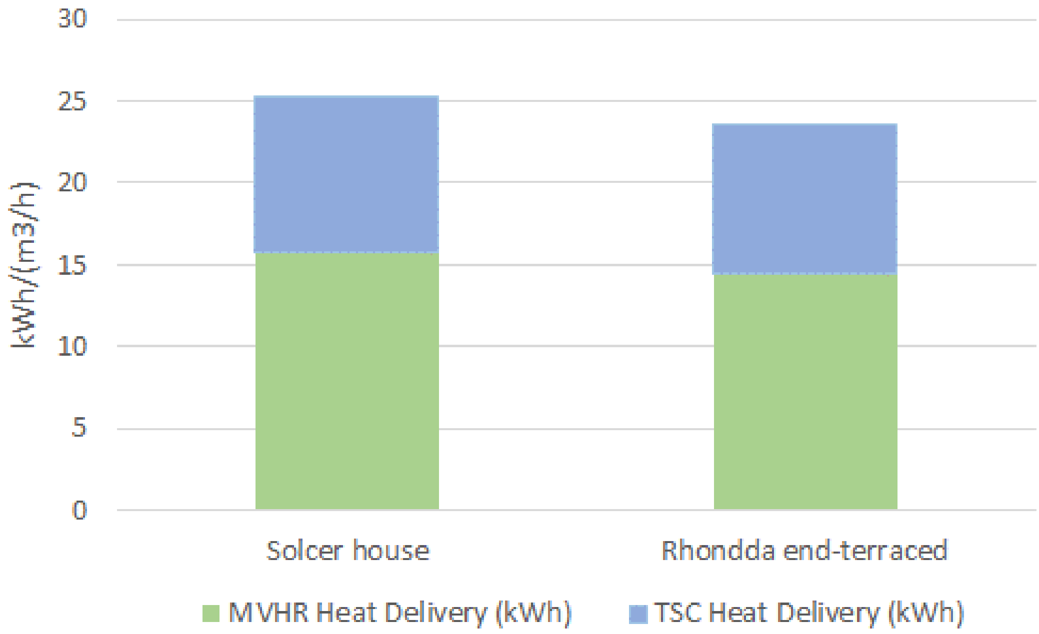


Figure 7-60 Solcer house and Rhondda end terraced TSC heat delivery comparison for flow and TSC area normalisation, author.

The next figure shows a TSC performance comparison between all the experimental case studies monitored in this work. Figure 7-61 visualises the annual TSC heat delivery for the 10 buildings. The delivery has been normalised per m^2 of TSC. The panels all have south orientation but different inclinations. The buildings have been grouped in four different categories according to the level of controls. Group A only includes the SEDA factory, with minimum control. The TSC delivers in high flows from September to May and overheating is rarely an issue as the factory transport doors are always open. Group B includes the two school transitional spaces with again minimum control but with operational working hours set. Group C includes buildings with moderate controls where flow is adjusted to reduce drafts and temperature rise becomes a priority. Group D includes highly controlled residential buildings where low flow and hight delivery temperature are prioritised together with residential thermostats and bypasses. Rhondda terraced (Group C in the graph) was recommissioned after complaints about high drafts and the flow was adjusted. As seen in Figure 7-61, the more control the less the heat delivery; also, the reduced flow reduces heat delivery - this is a necessary compromise in residential application.

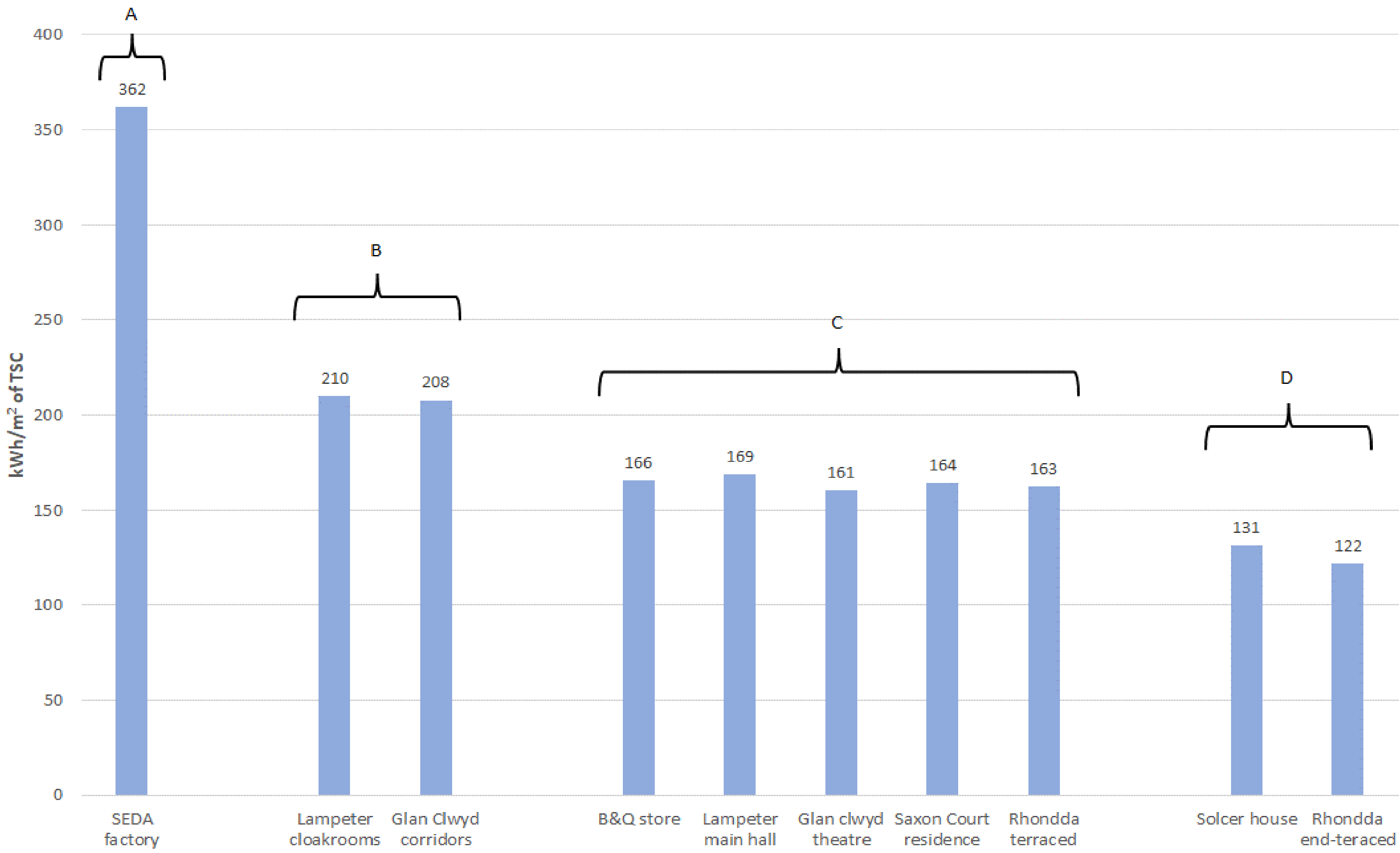


Figure 7-61 TSC heat delivery for all the experimental case studies monitored in this work grouped according to different control settings, author.

8 Discussion: from literature to the framework application

The purpose of this Chapter is to discuss how research gaps identified (Chapter 4) in existing literature on TSC integration and evaluation (Chapter 3) were addressed theoretically through the framework (Chapter 6) and in practice through the experimental results (Chapter 7). Also, the applicability and challenges of the different steps of the framework will be discussed. The structure of this Chapter will replicate framework and results Chapters (6 & 7). The narrative explores what happened in the literature case studies, what was adopted, evolved or changed in the framework and how the framework was applied.

8.1 TSC Design

The research gap identified in Chapter 4, was the lack of a coherent design approach that would include different building types and systems and serve both heat and ventilation demand. This situation is exacerbated by fragmented information which does not allow the designer to follow a holistic design process when integrating a system to the building. The framework follows the steps below that form a holistic design narrative used in this study:

- Make sure it is feasible (8.1.1)
- Design the integration (8.1.2)
- Integrate (8.1.3)
- Make sure it works (8.1.4)

8.1.1 Feasibility Study

A concise feasibility guide is presented below Figure 8-1 to assist decisions making in early stages without the use of Swift modelling. The guide does not require extensive knowledge of tools allowing for a spectrum of users to assess if a TSC installation is feasible for a specific context. The section also includes a discussion of the feasibility study.

Does it match the climate?

- Find historic/future weather file for the location (PVGIS, CIBSE Meteonorm or other)
- Adjust file for microclimate particularities: temperature and wind can be adjusted through monitoring; radiation can be adjusted through shading, orientation and inclination calculation (PVGIS). If the adjusted solar availability for the selected plane is < 500kWh/m^2 annually or wind speed average is>5m/s the TSC is not applicable.
- Calculate or find Heating Degree Days (HDD) for the site. This may include the need for temperature normalization for specific microclimate. If HDD<1000/year then TSC is not applicable.

Does it match the envelope?

- Assess existing/new building available planes. Planes that are perpendicular to the heating season solar angle work better (vertical is preferable to horizontal for UK). Feed this to solar availability calculations (PVGIS).
- Assess aesthetics and consult the client and planning permission requirements.
- Air tightness should be <10 $m^3/(h.m^2)$@50Pa .
- Attaching plane should comfortably support TSC weight (10kg/m^2).

Does it match demand?

- Assess/design ventilation strategy and calculate needs. If the building is designed for natural ventilation, then TSC can only work as an over-pressurisation mechanism to prevent infiltration of cold air. This is not applicable in domestic and small buildings.
- Assess and calculate heating demand. If heating demand hours do not match solar availability then TSC in not applicable.
- If there is already an MVHR in place then TSC useful delivery will be reduced by approximately 60%.

Is it cost effective?

- Divide maximum design building ventilation rate by minimum acceptable TSC flow rate (15m3/h). This is the maximum TSC area; check if this area is available on the selected envelope plane.
- Calculate annual TSC heat delivery by multiplying the heating season solar availability by the minimum average TSC efficiency (15%).
- Calculate the cost of TSC heat delivery considering the fuel cost that would generate equal amount of heat. Extrapolate this cost over TSC lifespan (10-20 years) and calculate payback considering the real price of TSC. Estimated current (2022) price for TSC is £230/m^2.
- Further considerations may include extra cost for design detailing, monitoring, integration challenges such as distribution ducting , existing MVHR etc.

Figure 8-1 Concise feasibility guide

8.1.1.1 Climate and site analysis

There is a lack of site and climate analysis in the literature case studies. Some weather data such as solar radiation, ambient temperature and wind speed were measured during the evaluation stage (185), but not prior to the installation to inform TSC design. In Maurer's study (210), TRNSYS was used to look at the potential for TSC installation in warmer climates than where they are typically installed. The US DoE guide (18) suggests that locations with short heating seasons should be avoided. The framework recommends detailed analysis to: 1) explore if the climate and site microclimate is suitable for TSC applications, and 2) inform design decisions and simulations. CIBSE, PVGIS or similar historic data should be used as representative data only if the weather station used for gathering this data set is close to the site and with similar microclimate characteristics. If this is not the case, site weather data can be collected and compared against historic weather data site. PVGIS historic data has the advantage of including landscape shading within the data set which is important for solar technologies. When evaluating similarities through heating degree dates, the base temperature should be the same as it can be different for different climates (15.5^{o}C for the UK). The purpose of climate classification and HDD analysis in the feasibility study is not to quantify heating demand of a specific building but to establish if the location is (in principle) compatible with TSCs. Horizon and local solar availability can be completely different in deep winter depending on the landscaping of the site. Study of horizon should be considered especially when exploring higher latitudes where solar elevation is lower, or sites are surrounded by hills and mountains. This is evident in the result section when the outline of the horizon was different for sites in the Welsh valleys such as the Rhondda end-terraced (Figure 7-3) where solar availability in deep winter was minimal.

The site and climate analysis suggested, ensures that the site is suitable for TSC installations and inform design-decision increasing credibility to performance projections.

8.1.1.2 Building envelope exploration

In the literature, the building envelop exploration is minimal. The US DoE (18) suggests that multiple-storey buildings should be avoided because of possible problems with fire codes. In the same guide, it is claimed that TSC application to be suitable for south-facing wall or a wall within 45° of true south. The inclination was vertical or nearly vertical in all the case studies whereas, in most cases the orientation of the TSC panels was solar facing or nearly solar facing. In two cases(144, 185), the orientation was south-east due to the initial footprint of the building envelope. Shading had a performance impact in some case studies such as the house in Judgeford (217). Kutscher (155) claimed that tilted TSC would perform slightly better than the vertical ones; however, only the TSC in the Wal-mart building was slightly inclined (216). There were no horizontal or roof-integrated applications in the literature.

The framework suggests a full exploration of building envelope starting from legal, structural and aesthetics considerations. In the UK, TSC installation do not need planning permission unless system needs to protrude more than 0.2m above the roof slope or when the site is in a conservation area or the building is listed (250). A structural feasibility study is suggested and applied in the experimental case studies and potential experimental studies. TSCs were not implemented in two potential cases due to structural risks. An initial exploration of the envelope aesthetics is communicated between the clients and designers through communication tools such as interviews, questionnaires etc. such as the ones presented in 6.1.1.4 and 6.1.2.2. Clients may object to install TSCs on specific facades with architectural interest such as stone or brick cladding. Any feedback in the early design phase will allow the designer to proactively explore the envelope in retrofits or adjust the envelope in new building considering TSC-envelope integration as a priority. The framework suggests that heating season solar potential should be evaluated for inclined and vertical facades within 90° of true south which is a wider orientation range than previously suggested by US DoE (18). This is backed up with evidence from the results where the East 34º roof in Rhondda end-terraced has only 6% less solar potential to the South 90º wall during heating season. Predominant wind velocity and direction should be evaluated in response to the potential solar facades orientation and inclination as discussed in 3.2.4.3. As TSC is a ventilation system, building envelope airtightness is suggested to be explored accompanied by an evaluation of leaks. This will determine feasibility of mechanical ventilation and will quantify the infiltration rate which is important when TSC is used together with natural ventilation strategies.

The building envelope exploration suggested, ensures TSC is legally, structurally and aesthetically feasible. Also, it quantifies the solar potential to inform façade selection in the design process and relates airtightness to mechanical ventilation effectiveness.

8.1.1.3 Building demand Survey

There is no evidence in the literature that a heating or ventilation demand survey was carried out as part of the feasibility study. This raises some concerns as there are claims that the design intention (will be discussed in 8.1.2.1) was for the TSC to fulfil both ventilation and heating demand. Hastings (140) argues that the main design parameter is the necessary ventilation rate implying that this should be known.

Both modelling and monitoring techniques are described in the framework section (6.1.1.3) to quantify ventilation and heating demand accompanied by suggested design values extracted from 2.1 and 2.2. In terms of heating, a range of tools was demonstrated and applied to the experimental cases studies. Static and dynamic modelling informed by building survey was presented for Rhondda end-terraced and Solcer house indicating a good agreement between HTB2 and SAP2012. Monitoring the space heating delivered and the energy used to generate this heat is another tool to quantify actual usage; however, a close look to the comfort data will indicate if needs were covered. Also, normalising monitored space heating for historic weather data used for modelling would ensure that monitoring reflects representative values. The annual data for Rhondda end-terraced showed a strong agreement with the Welsh average house space heating demand. Monitoring data compared with modelled shows a 15% performance gap despite the average indoor monitored temperatures being lower than modelled during heating season. The gap was explained by the qualitative information extracted from the occupants semi structured interview where occupants scheduling, and habits increased the heating demand. That increase was also identified by monitoring a daily heating profile which indicated a significant space heating demand around midday which is a good match for the TSC potential. Also, gas usage for space heating was monitored and compared against potential heat displacement due to TSC. The challenge is that cost savings projections are related to the heating system meaning that existing or potential heating systems study is important at early stage.

In the framework, a building demand survey will ascertain whether a TSC is needed and then inform modelling exercises in the sizing step. Monitoring the building, identifying current systems and discussing occupancy patterns can address modelling performance gap and enable cost benefits projections.

8.1.1.4 Further considerations and cost

Literature does not seem to include a cost analysis guide in the early stage. Also, there are no literature evidence on compatibility of TSCs with other systems or further consideration regarding risks such as access. US DoE (18) suggests that heat recovery systems are not to be used with TSCs; however this study aimed to quantify TSC useful heat when working with other systems including heat exchanger especially when the exhaust heat is input to a heat pump. Initial data on existing systems is needed to assess compatibility with TSC. This informs design decisions and facilitate strategy selection and drawings for presentation to the client.

Data on integration feasibility were also gathered; for example, in Saxon Court residence, some of the slopes were eliminated due to accessibility. In Rhondda end-terraced, a PV feasibility study indicated that the two roofs were a better fit for the PV than the south wall which was a good fit for the TSC.

The framework suggests an early-stage step-by-step guidance on cost quantification which is also applied for Rhondda house indicating a theoretical payback time for different heating systems' fuel savings. The challenge in such exercise is that installation cost includes major uncertainties related to market maturity, size of installation, deadlines, initiatives, logistics etc. An indicative cost was suggested by NREL in Chapter 3 and adjusted for 2022 inflation at £230/m^2 of TSC. Solar availability can be converted to TSC output using rule of thumb process summarised in Figure 8-1, For non-heating season TSC output can calculate using the same process, however, potential losses of storing low gradient heat could be significant as discussed in 1.3.4.2.2.

8.1.2 Design Integration

8.1.2.1 Design intention and strategy

Cali et al. (185) claim that any application that requires the heating of outdoor air could benefit from a TSC application. However, Hastings (140) argues that the main design parameter is the necessary ventilation rate, and it can thus be assumed that ventilation provision is the main design intent of such applications. Tata steel implies that the design intent of the use of the specific product in buildings is solar heated air for ventilation and space heating (206). In the literature case studies the design intention was in most of the cases unclear as seen in design driver table (Section 3.3.1); however, heating cost reduction was an aim in some studies. Also, available area on the solar-facing wall in conjunction to aesthetics was considered priority in some existing case studies such as (140, 185, 301) and questionnaires (159, 238). This is also shown in demonstration buildings such as the TATA steel Sustainable Building Envelope Centre in Shotton or the WSA Cardiff University Solcer house in Bridgend UK.

The framework suggests that the designer and the client should together set the priorities responding to feasibility study and also discuss aesthetics criteria and services singularities. The relation between flow and temperature rise should be communicated to the client. In order to set the priorities, opportunities and challenges as an outcome of the feasibility study applied to all experimental case studies (Table 7-7, Table 7-8, Table 7-9). When aesthetics leads collector selection and sizing, compromise on heating delivery and ventilation as well as cost may occur. The framework correlates TSC strategy with volume flow rate and heat delivery. This is visualised in Figure 6-5 where useful heat is defined as meeting ventilation demand and causing space temperature rise up to the temperature set point. The exception to this is to provide higher flow rates only within a comfortable temperature range which is determined by the current space temperature and the set point temperature. Another consideration from the framework is that design intent would determine if maximum flow per TSC area or maximum temperature rise is the priority. For the same TSC area, maximising flow would maximise heat delivery but minimising temperature rise (discussed 6.1.2.1) which may cause discomfort drafts especially in residential applications. The integration of the TSC to other systems and envelope also include strategic decisions especially when bypass and recirculation variants are discussed as the variants will also affect collaborative heating and ventilation systems. Table 7-10 relates deign intentions to appropriate strategies for all the experimental projects indicating that different approach to different intentions.

8.1.2.2 Variants, collector selection and aesthetics

TSCs can be connected to an existing HVAC (PHV) or work in parallel with a heating system (DHV). The can have a bypass or a recirculation add on connected through dampers. Seven out of fifteen literature TSC systems investigated, included a summer bypass function. Most of these were industrial, whereas the only residential one did not have a summer bypass which raises overheating concerns. Recirculation was broadly used in the literature. This raise concerns around the possibility of polluted air being recirculated in buildings especially in/after the Covid-19 era. There are some information about the TSC collector in the case study but lack of reasoning on how the collectors parameters were selected. Especially when it comes to the profile types, case studies do not relate selection to aesthetics.

In the framework and the results, the importance of summer bypass was highlighted especially for residential application to control overheating. Also, recirculating is not recommended for residential where or other building types, recirculation control and filtering is suggested. Dampers can be controlled to ensure that the fresh air ventilation demand is met and still get the supplementary benefit of heat recirculation and destratification. Alternatively, a heat exchanger can be used to capture the heat without any risk from recirculating air.

The framework suggests a decision-making flow chart on selecting appropriate TSC variant (Figure 6-7) where the selection is related to the existence of an HVAC and the flow-temperature rise priorities. The framework also sets operational limitations when a TSC is connected to an MVHR unit. Controls are suggested to ensure that the two systems do not compete. The co-existence of the TSC and MVHR is facilitated by the presence of an exhaust heat pump, which can absorb the exhausted which is further explained in the systems integration (6.1.3.2 & 7.1.3.2).

The framework sets collectors' parameters based on the analysis in Chapter 3 and discusses profile types Also, by using a questionnaire, the framework assesses aesthetics variations featuring colour, profile and area choices by using a typical terraced house as an example (238). The results highlight that black TSC colour and area size that gives an impression of a complete architectural element are the preferred options. Similar questionnaires can be used by the designer to understand clients preferences; however, it has to be communicated that different TSC profiles have different performance characteristics. In the results section (7.1.2.2), the TSC the panel geometry was optimised according to section 3.5.2. Also, the TSC profile and colour for all the experimental case studies were selected to mimic the surrounding envelope elements, however dark colour only used for high absorptivity.

8.1.2.3 Sizing, modelling and cost

US DoE (18) states that sizing is based on fresh air requirement but also on the available south-facing wall area which was the driver for most of the literature case studies. Hastings (140) applies a more detailed approach where the collector area is determined by the collector type, the air flow rate, any restrictions on the inlet temperature, the performance prediction from simulation tools and the cost of the collector. Tata steel (206) focuses collector design and sizing on the ventilation requirement of the building and the selection of the TSC flow rate. Other design factors include the internal dimensions of the space to be heated, the thermal efficiency of the envelope's fabric, the actual space heat demand, the orientation of the building, any shading effects and the available space for the TSC installation. These approaches have been considered in the development of the framework. The framework highlights that performance (prioritizing heating and ventilation needs and delivery flow rate of the TSC), aesthetics and cost should be considered when sizing the TSC collector. This approach enables sizing to be informed by both feasibility study and design integration parameters. The sizing starting point for the framework is the total ventilation volume flow rate.

A variety of TSC flow rate per m^2 of TSC were suggested by literature design guides. In Hastings's (140) guidance sizing is related to the temperature rise needs which is also echoed by this framework. The framework suggests modelling tools such as SWIFT (171) to be used for creating a graph indicating appropriate TSC areas in response to annual heat delivery and temperature rise (Figure 7-24) for a standard ventilation demand. This graphic information aids selection of an appropriate area for optimising high temperature, high flow rate or a compromise between the two. This finding should be accompanied by aesthetics and cost parameters to enable final decisions. This is evident in the results section where for Rhondda end-terraced, the cost and performance optimisation were indicating a $2m^2$ TSC application, however, architectural integration drove the decision for a $4m^2$ application even though it increased the projected payback time by 40%.

8.1.3 Building integration

8.1.3.1 Envelope integration

US DoE (18) indicates that a support grid of perforated vertical and horizontal Z-channels is typically used for the TSC integration to the structural wall. The framework adds sealing and water drainage considerations. It also suggests that any bracket attachments should happen before any external back wall sealing to avoid cold bridges. Hastings (140) suggests a maximum plenum width of 300mm and an optimal at 170mm for air velocity in the plenum at 3m/s for specific product porosity. However, in UK, 200mm wall or roof add-on is the maximum allowed as a permitted development without making a planning application. Badache et al. (165, 182) has a more sophisticated approach which relates plenum width to heat transfer, as decreasing width will increase convective heat transfer but also increase fan power requirement to drag the air. This is the approach adopted by the framework. This approach in a low flow system allows the plenum width to be reduced to maintain at least 25Pa pressure drop at the holes which avoids flow reversals in the cavity. Hastings (140) suggests that tall narrow collectors perform better due to stack effect and suggest cavity output to be drilled at the middle of the wall on the top part of the installation. This is ideal but could be challenging as for example in Rhondda end-terraced, where a middle point output was not possible due to structural stability issues. This affected the distribution as seen in the cavity temperature mapping (Figure 8-60). In this application, stack effect works as expected; however, temperature by the edges is lower. To reduce this, Cali (185) suggests high porosity at the edge and low porosity by the cavity outlet (fan inlet) which is an interesting concept but challenging in fabrication.

8.1.3.2 Systems integration

Hastings (140) presents three distribution options for a DHV and also refers to the possibility for connecting a PHV to heat storage. In addition to the above alterations, the framework highlights the different approach when the TSC integrates to an already naturally ventilated space when over-pressurization could reduce infiltration of cold air. The framework also highlights the building airtightness prerequisite when mechanical ventilation is designed. It also explores further integration with MVHR and MVHR-exhaust heat pump, referring to extra controls required to avoid systems competing with each other.

The application of the framework also aims to resolve practical integration challenges. It highlights the need for waterproof insulation for any external ducts. Insulation should also be applied for internal ducts when installed in unheated spaces. It suggests communications with the users to decide if the visible ducts should be boxed in. The application refers to the possibility of using small windows for duct entrance which is cost effective but it may compromise lighting levels. Also, when installing to an existing, roof, waterproofing is a challenge. In the results (7.1.3.2) it is suggested the removal of tiles and the use of trays would allow a duct outlet from the middle of the tray without compromising waterproofing.

8.1.3.3 Controls

Hastings (140) guide presents a thorough analysis on TSC controls. It states that system controls can be driven by a temperature sensor, a solar radiation sensor or a timer. The guide also introduces different operation modes such as winter and summer. TATA steel (206) elaborates by providing controls information relating temperature to TSC, recirculation and bypass dampers. CA Group Roll Mill (212) provided a full algorithm using scheduling, the ambient temperature, the TSC duct temperature, and the room/space temperature. The framework includes a fourth temperature in the basic algorithm which is the delivery temperature after the mixing box (Figure 6-12). This enables the controller to respond to changes that happen due to the recirculation and bypass dampers or connected ducts and HVAC system. This sensor also facilitates adjustments during commissioning as it assists in setting the thermostats exact temperature in relation to the delivery temperature.

The framework also explores the controls required when an MVHR and an exhaust heat pump is connected to the TSC. Four different scenarios are investigated indicating that TSC and MVHR can work together but both bypass controls and MVHR HE controls should be applied.

One of the main control challenges addressed by the framework is the activation of the system at zero flow when the system is OFF or when the cavity flow is zero due to scheduling or summer bypass mode. The framework suggests a temperature sensor (initiator) which should be attached to the TSC inner skin. This is an indirect but effective method to understand if there is enough solar irradiation to activate the system. After a few minutes, control can be transferred back to the TSC temperature. The addition of the above, controls have a cost impact which has to be explored in early stages.

8.1.4 Commissioning

8.1.4.1 Testing and commissioning adjustments

Hastings (140) highlights the need for testing within the commissioning as the absence of commercial “all-in-one” controller does not allow for “fit-for-all” settings. The framework aims to encompass regulations for ventilation and heating system commissioning by using Building Regulations (136), ISO 9806 (270) and BS EN/12975 (271). The last two are test guides for heating solar collectors which are partially applicable for TSC installations. The priority for the framework is to ensure that the desired ventilation rate is achieved on site. This is important as flow rate is part of the design in all occasions and also a vital component of the heat transfer equation. The second step is to test system response for different design scenarios. The framework highlights the importance of stable weather conditions when running a test. In practice, it is not possible to create conditions to test all modes and scenarios. A way to overcome this, is to model the controller response for different scenarios using both real and simulated inputs. Anther practical way is to monitor the real long-term performance of the system and re-adjust in a later stage.

8.1.4.2 Long term commissioning and optimisation

If the TSC system was a mature and off-the-shelf technology, the commissioning process would be standardized. However, bespoke TSCs require bespoke testing and commissioning. If the TSC is installed in the summer, the in-situ testing is difficult as creating winter conditions is challenging. Also, TSC is a low gradient heating system, meaning that a small change/input of heat such as heat captured or lost in a long duct would impact delivery. For the reasons above, the framework suggests a long-term commissioning protocol. This was mentioned as control optimisation within a few literature case studies (Table 3-9). In Ford Assembly Plant and GM Battery Plant (185) major systems modifications were performed (fans, ducts) whereas in NREL Facility and Göttingen Plant (185) control adjustments were made to optimise the performance.

It should be noted that optimised design increases confidence in the commissioning stage. The framework suggests one year long commissioning monitoring with a high frequency interval data logging (i.e. 1min) to capture transient phenomena. Clearly, this has a major cost implication; however, the control instruments can be connected to a logger to also monitor performance. For this reason, proactive procurement would ensure that instruments selected for control could also support long term commissioning.

8.1.4.3 Handover

Literature does not cover the importance of handover documentation; however, experimental case studies examples underline the value of such an output. The framework handover aims to be inclusive in terms of the information shared with the clients. For this reason, a handover list was created and included in the framework (6.1.4.3) after discussions with the stakeholders of the experimental case studies. The aim is for the client to understand the system, its maintenance and expected performance including warranties. Also, life cycle information is recommended so that the client can have TSC end-of -life disposal instructions.

8.2 TSC Performance Evaluation

8.2.1 Performance indicators

Although not clearly stated, in most of the literature case studies, it can be inferred that the aim in using monitoring was to quantify the system's performance and/or cost savings. The framework intends to explore a broader aim in introducing measuring and monitoring techniques in both pre and post-intervention for retrofits. The framework highlights the importance of data collection to take informed design decision prior to application.

Eleven out of the fifteen literature case studies monitored the heat delivered by the TSC whereas as six calculated the cost savings. Five of the studies calculated the % of the heat supplied by the TSC and the same number of studies calculated the TSC efficiency whereas some of the studies correlated the efficiency to different variables such as flow, solar radiation, wind speed, temperature variations and modelled efficiency. A full list of literature KPIs and SPIs and how many case studies included them in their analysis can be found in Appendix XVIII. The framework analyses the mathematical and physical components of the KPIs and SPIs by breaking down all the indicators to equations and the equations to elements. The intention is for the reader to be able to use appropriate tools to quantify the indicators. The framework focuses on a series of challenges that are not addressed by the case studies literature such as:

- Measuring mass flow rate in a duct, where different approaches are discussed including limitations.
- Evaluating the useful rather than the delivered heat of the TSC, especially when this is connected to a heat exchanger.
- Relating usefulness to ventilation rate, highlighting that when the TSC delivers at rates above the ventilation demand, the useful temperature rise is only the delivery above the space temperature (Equation 7-1 & 7.2)
- Defining when fan energy consumption should be considered as it may compromise energy savings.
- Evaluating comfort considerations related to drafts, reduction of relative humidity and CO_2.

Also, the framework sets three comparison exercises that would respond to different evaluation questions:

- Pre-retrofit vs post retrofit
- Monitored vs modelled
- Monitored vs benchmarks

Information that feeds into the feasibility study is considered necessary for design and should be costed. This may mean that small scale applications may not be feasible due to significant cost increase.

8.2.2 Instrumentation

Hastings (140) design guide includes valuable information about the temperature sensors controls that were applied for monitoring use. Some case studies included instrumentation information, especially the Judgeford house (217) and CA Group Roll Mill (212) which assisted in the development of the framework. Also, the test rig in Bute building was used by the author as an instrumentation TSC lab. The framework approach was to design a monitoring plan that would include pre and post retrofit monitoring with the addition of in situ data gathering (Figure 6-16). This holistic approach facilitates future evaluation exercises as the monitoring temperature can be used in parts or as a whole depending on particular performance questions. The Framework assists in the selection by relating KPIs and SPIs to the instruments and also analysing the sensors parameters, the logging devices and settings and the installation challenges. This last part is highlighted in both the framework (6.2.2.4) and the results (7.2.2.4) where practical installation guides are provided. Factors such as range, accuracy and time response are discussed with the view to choosing appropriate instruments. Time response is a challenging parameter as heat transfer is a transient phenomenon where data capturing synchronisation is vital. The study addresses the synchronisation by using responsive sensors and by averaging values when possible. Also, the study deals with challenges related to measuring turbulent flow within the duct by exploring all possible solutions and suggesting a hybrid double cross-sectional probes system with multiple pressure/velocity measuring points.

Another interesting question is about the appropriate time interval as the literature case studies use logging intervals from 15sec to 15min with the Judgeford house (217), CA Group Roll Mill (212) at 3 and 5 min respectively. 15sec interval was used for Wheatley Campus Retrofit (218) however the context of the experiment was very lab oriented as wall heat transfer and conduction losses study would require very dense data logging. The framework does not adopt one time interval as a case-by-case assessment is required; however, the experimental case studies used a 5min interval but averaging 1min values except from transient heat studies in the cavity where a 30sec interval was used.

In Judgeford house (217) it was suggested that the system should be wireless to eliminate disturbance. The framework explores pros and cons of wired and wireless systems, establishing that wired can be used when the monitoring design is embedded into the TSC design so that cables can be hidden during installation. The framework also emphasizes the importance of remote monitoring as it was applied in most of the experimental case study facilitating real time evaluation and error detection, while minimising disturbance of the occupants.

8.2.3 Data Processing

Data processing was not discussed in the literature case studies. The framework analyses the data processing from the sensor's signal to the stored meaningful value as the aim is for readers with different background to be able to replicate the process. The study deals with challenges in storing raw data, converting signals into data and data into information and also in cleaning and grouping the data. Appropriate analysis tools and techniques are suggested. One of the most demanding tasks is when dealing with data loss. Proactive approach is the most effective solution, and the suggestion is to test the monitoring performance during the commissioning stage. Remote data gathering facilitates early data/instrument error detection. Most of the errors can be sorted by adjusting the sensor or sensor wiring or by updating the logging programming; thus, remote access to logging programming is helpful. Also, data interpolation/extrapolation is possible but should be applied cautiously.

8.2.4 Data Analysis

The literature case studies had variable approaches in analysing TSC and visualising data in terms of performance indicators type, seasonality, comparisons and visualisations (Appendix XVIII). In terms of seasonality, most of case studies them provided annual figures whereas some provided monthly and some daily. The framework approaches data analysis using a seasonality that is appropriate to the output being presented. As an example, for TSC energy and heat delivery, results are presented in annual total or monthly daily average. Where required, analysis is presented based on heating and non-heating season. The monthly daily average was preferred to the monthly total as months do not have the same number of days.

The literature case studies also used a variety of methods and visuals to compare monitoring against modelling and to compare different TSC performance for different modes. The framework aimed to group the performance indicators that would include comparisons and also describe data normalisation process for each occasion. Also, the framework indicated visualisation methods that would communicate better the performance indicators and information. A challenge addressed in the results section was to combine appropriate correlated information to one graph without overloading the graph. Thus, a series of hybrid graphs were used in the results section for example when combining temperature (dots) and energy (bars) variation (Figure 7-54).

The results were discussed within the results Chapter (9), however there are summarised findings in terms TSC system, panel, savings and comparisons that are discussed below:

Overheating could be addressed by changing the bypass thermostat setting; thermostat temperature set point does not represent delivery temperature especially in the example of long ducting recapturing heat in the attic. This is something to be considered in the commissioning and optimisation. The energy consumed by the fan should not be considered and subtracted from the TSC useful delivery unless natural ventilation was the designed ventilation method that fulfils the design ACH.

The TSC cavity temperature variation is driven by the outlet position and velocity, stack effect, turbulence and losses at the edging strips and sealing finishes. All the above can be optimised but further research can be done on appropriate measures. The optimal TSC shape is circular in terms of reducing the TSC perimeter to area ratio thus reducing losses trough the edges.

For space heating savings, a HDD normalisation techniques was used to normalise both pre and post retrofit space heating use as well as TSC heat delivery. The TSC delivery is not always the same as TSC useful delivery as the usefulness refers to the heat displacement and savings should be calculated for the useful heat displacement. Also, when calculating savings, heat displacement should be related to fuel used to deliver this amount of heat. This means that when the TSC displaces heat that would be delivered by a gas boiler, it also displaces the losses of the gas- to-heat conversion. On the other hand, when TSC displaces heat from renewables or from heat recapturing, then, this displacement is not useful. When calculating cost savings, energy prices should reflect fuel prices that would be used to deliver the TSC useful heat. The challenge is to use future price projections; warranty duration can be used for projections

When comparing monitoring against modelling, performance gap should be considered. When comparing pre-retrofit monitoring against post-retrofit monitoring, occupancy should be kept the same including set points, schedules, rituals, no of occupants etc. When this is not possible, extending the monitoring duration to two or more years will increase the data confidence levels. When comparing heat delivery of different TSC systems in a similar weather context, normalisation per m^2 is the most appropriate. However, comparisons should only be made for similar flows per TSC area as low flow systems would be used for high temperature rise that would compromise the heat delivery whereas high flow systems would be used for high heat delivery that would compromise tempature rise.

8.3 Framework workflow

This section summarises the framework decision-making process after discussing its attributes and application. The following flow chart (Figure 8-2) aims to visualise the step-by-step process in a contained format in order for the framework user to be able to navigate when designing or evaluating a building integrated TSC. The visual can also be seen in Appendix XIX in A3 print format.

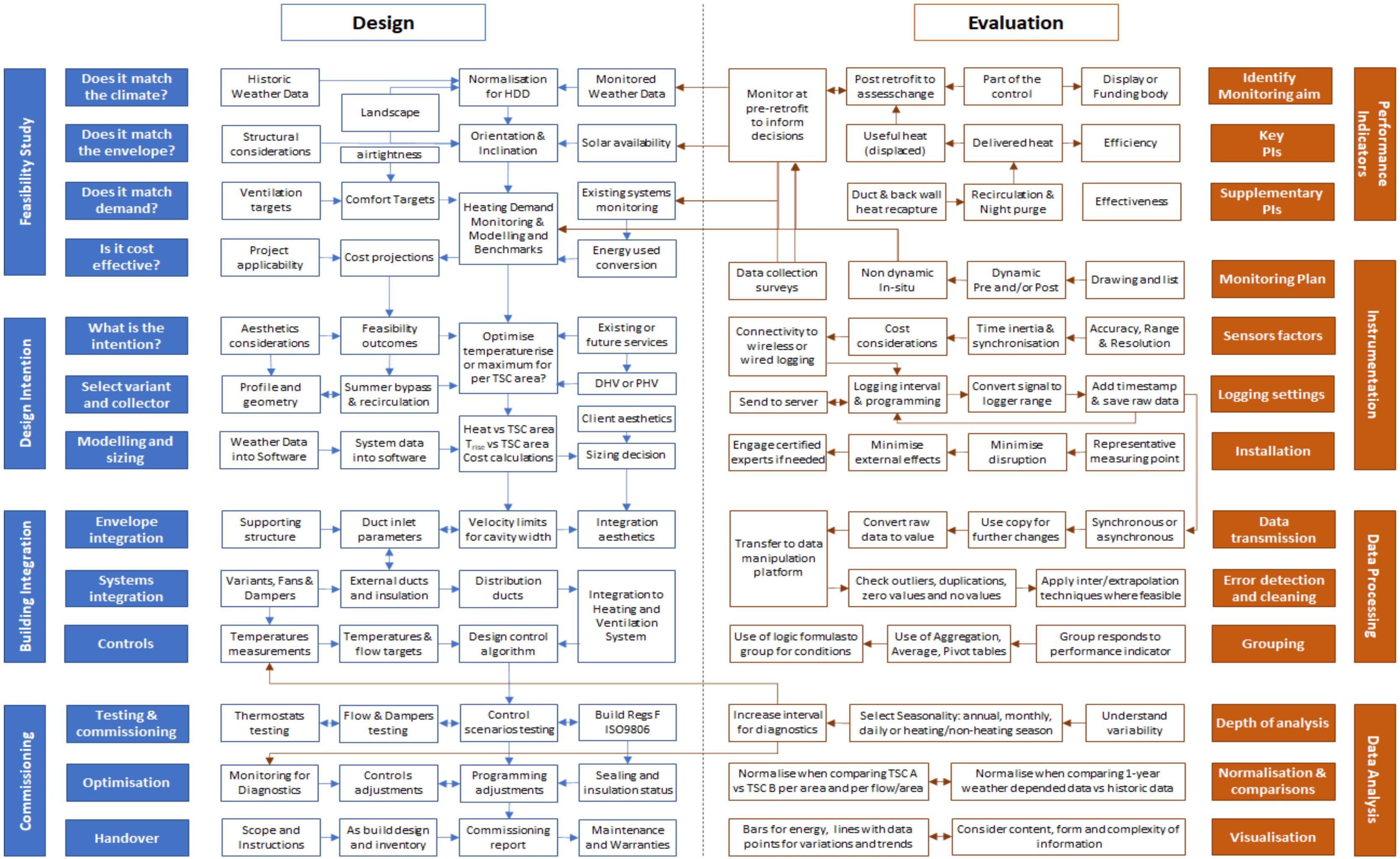


Figure 8-2 TSC design and evaluation framework summary flow chart, author.

9 Conclusions

9.1 Response to objectives and aims

The aim of this work was to develop a design and evaluation framework to integrate Transpired Solar Collectors (TSCs) into buildings and assess their performance. The aim for the design component of the framework was to respond to heat and ventilation demand in conjunction with other traditional and novel systems. The aim for the evaluation component of the framework was to quantify the performance of real-life systems and their contribution to heat and ventilation demand.

The framework was conceived as a development beyond existing design guides (140, 185, 204-206) in order to apply a detailed and systematic approach to design and evaluation parameters. The design part of the framework is built on ventilation and heating demand principles for different building types (Chapter 2), the developments of the TSC technology and evaluation of existing design guides and literature case studies (Chapter 3). The requirement for a framework to support informed decisions on sizing and collaborative systems arises from analysis of the research gap (Chapter 4). New experimental case studies are introduced (Chapter 5) and a new step-by-step design framework was evolved (Chapter 6) using literature and experimental knowledge. Examples of the framework being applied to the case studies were presented in the results section (Chapter 7) showing its adaptability to different building types and systems. The framework was further discussed (Chapter 8) in conjunction with literature to explore its potential and limitations.

The evaluation part of the framework was initially built on physics relevant to TSCs and building integrated examples presented in the literature case studies (Chapter 3). However, literature information was fragmented with little evidence of decision making on monitoring strategy and instrumentation selection or usage of monitoring tools in design and evaluation stage (Chapter 3). The new experimental case studies as well as a test rig (Chapter 5) formed a robust landscape for the author to further develop the monitoring approach and create a TSC performance evaluation framework (Chapter 6). This includes a step-by-step guide to TSC quantification referring to elements that would also assist the design (data gathering and optimisation). This part of the framework was applied on a series of examples showing its versatility and applicability to respond to performance indicators. This was also discussed (Chapter 8) in conjunction with the literature case studies, showing new developments proposed.

Objective 1 (Section 1.1) was fulfilled as the TSC technology was analysed at collector (Chapter 3) and integration level (Chapter 4) by using existing guides and literature case studies. Both design and evaluation strategies were considered, and gaps were identified (Chapter 5) with respect to heating and ventilation principles (Chapter 2).

Objective 2 (Section 1.1) was fulfilled as the framework integrates heat and ventilation demand in the design process, in sizing, envelope and system integration and especially in controls and commissioning (Section 6.1). Also, the framework suggests an evaluation guide that quantifies the contribution of the TSC in different working modes and for different collaborative systems and contexts (Section 6.2).

Objective 3 (Section 1.1) is fulfilled as the framework has been applied to several experimental cases studies (Chapter 7). From this approach the findings were discussed, allowing comparison across the experimental examples and against literature (Chapters 7 & 8).

9.2 Contribution to knowledge

Ventilation demand is becoming a design priority in our times due to the need for airtightness (energy savings) and fresh air (moisture reduction, reduced infection risk etc). Space heating requirement and overheating avoidance are vital design priorities towards zero carbon and comfortable buildings. This work prioritises these two elements by developing a step-by step framework in designing and evaluating TSCs for a variety of building types and collaborative technologies. The literature review identified 15 case studies with integrated TSC with partial information on design and evaluation. This study presents ten additional case studies, a 67% increase in the body of knowledge. This series of experimental case studies also forms an additional benefit by showing development in expertise as each study builds on the knowledge gained from the previous one.

The work highlights the importance of early-stage feasibility studies incorporating data gathering techniques that enable informed decisions on cost and integration. The work explores the limitations of integrating TSC to systems that were not previously explored in the literature, such as MVHR and exhaust heat pumps. The data analysis shows that under specific control conditions TSC combined with these systems can be beneficial. The work also integrates strategies for control and commissioning that ensure effective implementation. Performance evaluation can work as a stand-alone framework; it presents a systematic approach on how equations are converted to measurable quantities to be measured by appropriate instrumentation to gather and analyse high integrity data.

This work is of benefit to anyone looking to integrate TSC systems in buildings, such as architects, engineers, designers and housing associations among others. Furthermore, the findings, methods and tools of this study can be extrapolated for other solar thermal systems, so it could provide additional benefits to designers and other disciplines.

9.3 Lessons learnt

The lessons learnt below reflect the authors' learning outcomes through the development and application of the proposed framework.

- A good design that performs effectively is not well-defined when integrating TSC. This is because TSC as a system is not a mature off-the shelf technology, and ventilation and space heating demand is not a clear design driver.
- A feasibility study is vital before the design stage, as if the right steps are followed, the applicability of the technology will be known in early stages and also, any variations and their impact can be discussed with the client before design and implementation.
- TSCs can be designed for maximum flow rate per TSC area or for maximum temperature rise. Both approaches have pros and cons, and the designer should be able to suggest the best fit for purpose.
- Monitoring is not only a tool to evaluate building performance; it is also a tool that adds confidence in feasibility and design stage as well as commissioning and optimisation stage.
- Commissioning is vital as there is not currently a commercial controller fit for all purposes. It is a challenging process and minor changes can have huge impact on performance and comfort.
- TSC delivered heat is not necessarily useful heat. The heat is not useful if it does not respond to building demand or if it does not displace heat delivered by fossil fuels.
- TSC does not necessarily work well with MVHR as TSC may deliver heat that the MVHR would deliver through HE heat recovery; however, with appropriate control adjustments the TSC-MVHR system can be optimised especially when the MVHR exhaust is connected to a heat pump or storage.

- When calculating TSC savings in energy, CO_2 or cost, it is fair to compare the useful TSC delivery against the fossil fuel which would be used to deliver that heat.
- When evaluating performance of different TSC installations, a normalisation process should be considered to enable fair comparisons.

9.4 Future developments

There are a number of directions which can be progressed from this research:

- The lack of a coherent design and evaluation framework was identified as a gap and has been remedied in this study. A more concise user-friendly feasibility guide was developed however a holistic design and evaluation concise guidance could be extracted in a future work.
- The experimental case study results revealed challenges and opportunities when incorporating TSCs to innovative systems such as mechanical ventilation with heat recovery, exhaust heat pumps or storage. Further experimental work could be carried out on the quantification of TSC useful heat delivery for a variety of scenarios especially within future weather data projections, short and long term storage compatibility and integration to hydronic systems.
- A discussion of embodied energy or/and carbon payback and the parameters of the above is an important study to holistically evaluate all the processes that take place in the lifespan of a TSC.
- Cost projections is a domain with significant potential given the current and likely future energy prices and the possibility of TSC use at scale.
- TSCs are not part of an incentive scheme and are not currently embedded in SAP which deters its implementation. Further studies on how this technology can be included in the governmental policies will be valuable and could potentially facilitate further TSC development.

References

1. Klein S, Alvarado F. Engineering equation solver. F-Chart Software, Madison, WI. 2002.
2. CIBSE. GUIDE C. Reference Data. Oxford: Butterworth-Heinemann; 2001.
3. Fleck BA, Meier RM, Matovic MD. A field study of the wind effects on the performance of an Unglazed Transpired Solar Collector. Solar Energy. 2001;73(3):8.
4. UK Parliament. Climate change act 2008. London, UK. 2008.
5. National Statistics. 2022 UK greenhouse gas emissions, provisional figures. In: Department for Energy Security and Net Zero, editor.: Crown; 2023.
6. Climate Change Committee. The Sixth Carbon Budget - Buildings. 2020.
7. Committee on Climate Change. Buildings London: Committee on Climate Change; 2015 [Available from: https://www.theccc.org.uk/charts-data/ukemissions-by-sector/buildings/.
8. Committee on Climate Change. Industry London: Committee on Climate Change; 2015 [Available from: https://www.theccc.org.uk/charts-data/ukemissions-by-sector/buildings/.
9. Department of Energy & Climate Change. Energy Trends section 6: renewables. 2015 November 2015.
10. The Gurdian. Renewable electricity overtakes fossil fuels in UK for first time: Guardian News & Media Limited or its affiliated companies; 2019 [updated 14.10.19. Available from: https://www.theguardian.com/business/2019/oct/14/renewable-electricity-overtakes-fossil-fuels-in-uk-for-first-time.
11. Clover I. Aging UK grid harming renewable integration, says Solar Trade Association. PV magazine/News [Internet]. 2015. Available from: http://www.pv-magazine.com/news/details/beitrag/aging-uk-grid-harming-renewable-integration--says-solar-trade-association_100019407/#axzz3t19QsrQO.
12. The Town and Country Planning (Use Classes) Order 1987, (1987).
13. The Town and Country Planning (Use Classes) (Amendment) (England) Order 2015, (2015).
14. IPF. The size and structure of the UK property market 2013: A decade of change. Investment Property Forum 2013.
15. Age of the property is the biggest single factor in energy efficiency of homes [Internet]. 2021. Available from: https://www.ons.gov.uk/peoplepopulationandcommunity/housing/articles/ageofthepropertyisthebiggestsinglefactorinenergyefficiencyofhomes/2021-11-01#:~:text=In%20Wales%2C%2039%25%20of%20homes,before%201900%2C%20at%2023%25.
16. ICE. Building Heating Systems. The construction industry knowledge base [Internet]. 2015 04/12/2015. Available from: http://www.designingbuildings.co.uk/wiki/Building_heating_systems.
17. Kreider J, Curtiss P, Rabi A. Heating and cooling of buildings: design for efficiency: CRC Press; 2009.

18. U.S. Department of Energy - Energy Efficiency & Renewable Energy. Transpired solar collector at NREL's waste handling facility uses solar energy to heat ventilation air. Federal Energy Management Program; 2010.
19. ICE. Thermal comfort in buildings. The construction industry knowledge base [Internet]. 2015 06/12/2015. Available from: http://www.designingbuildings.co.uk/wiki/Thermal_comfort_in_buildings.
20. HSE. Thermal comfort: the six basic factors. HSE guidance - temperature - thermal comfort [Internet]. 2015. Available from: http://www.hse.gov.uk/temperature/thermal/factors.htm.
21. Dodge R, Daly AP, Huyton J, Sanders LD. The challenge of defining wellbeing. International Journal of Wellbeing. 2012;2(3).
22. Awbi HB. Ventilation of buildings: Taylor & Francis; 2003.
23. CIBSE Energy Centre. Ventilation in Buildings: CIBSE Certification Ltd; 2015 [Available from: https://www.cibseenergycentre.co.uk/ventilation.html.
24. WHO. Natural ventilation for infection control in health-care settings. WHO Press: World Health Organization Publication/Guidelines; 2009.
25. British and world English [Internet]. Oxford university press. 2015. Available from: http://www.oxforddictionaries.com/definition/english/coolth.
26. Blasing TJ. Recent greenhouse Gas concentrations. Carbon dioxide information analysis center; 2014.
27. IPCC. Climate change 2007: Synthesis report. The Intergovernmental Panel on Climate Change; 2007.
28. Nordhaus WD. A question of balance: Weighing the options on global warming policies: Yale University Press; 2014.
29. United Nations framework convention on climate change, (1992).
30. IEA. World energy outlook 2010. France; 2010.
31. SBCI U. Building and climate change: Summary for decision makers. 2009.
32. Stern NH, Treasury HMs. Stern Review: The economics of climate change: HM treasury London; 2006.
33. Parliament U. Climate change act 2008. London, UK. 2008.
34. Committee on Climate Change. 2019 Progress Report to Parliament. London: Committee on Climate Change; 2019.
35. Committee on Climate Change. The climate change act and UK regulations London: Committee on Climate Change; 2015 [Available from: https://www.theccc.org.uk/tackling-climate-change/the-legal-landscape/global-action-on-climate-change/.
36. Energy Performance of Buildings Directive (recast), (2010).
37. Zero Carbon HUB. Zero carbon homes and nearly zero energy buildings. Zero Carbon HUB; 2015.
38. ICE. Carbon plan. The construction industry knowledge base [Internet]. 2015 14/12/2015. Available from: http://www.designingbuildings.co.uk/wiki/Carbon_plan.
39. The carbon Plan: Delivering our low carbon future, (2011).
40. Fixing the foundations: Creating a more prosperous nation, (2015).
41. Housing Act, (2004).
42. Building and buildings, England and Wales: the Energy Performance of Buildings (Certificates and Inspections)(England and Wales) Regulations 2007, (2007).

43. Goverrnment H. Energy Performance Certificates: Crown; 2015 [updated 07/12/2015. Available from: https://www.gov.uk/buy-sell-your-home/energy-performance-certificates.
44. Jenkins D, Semple S, Patidar S, McCallum P. Changing the approach to energy compliance in residential buildings–re-imagining EPCs. Energy and Buildings. 2021;249:111239.
45. Jenkins D, Simpson S, Peacock A. Investigating the consistency and quality of EPC ratings and assessments. Energy. 2017;138:480-9.
46. Solarwall. Case History: Ford Oakville Toronto: Conserval Engineering Inc.
47. Ofgem. Environmental Programmes: ofgem; 2015 [Available from: https://www.ofgem.gov.uk/environmental-programmes.
48. Rezaie B, Esmailzadeh E, Dincer I. Renewable energy options for buildings: case studies. Energy and Buildings. 2011;43(1):56-65.
49. Fabbri M, Volt J, Groote Md. The Concept of the Individual Building Renovation Roadmap. BPIE; 2018 January 2018.
50. Committee on Climate Change. UK Emissions by Sector London: Committee on Climate Change; 2015 [Available from: https://www.theccc.org.uk/charts-data/ukemissions-by-sector/.
51. Jones P, Li X, Perisoglou E, Patterson J. Five energy retrofit houses in South Wales. Energy and Buildings. 2017;154:335-42.
52. Welsh Goverment. Welsh Housing Conditions Survey 2017-18: Headline Report. Statistics for Wales; 2018.
53. Jermyn D, Richman R. A process for developing deep energy retrofit strategies for single-family housing typologies: Three Toronto case studies. Energy and Buildings. 2016;116:522-34.
54. Gupta R, Gregg M, Passmore S, Stevens G. Intent and outcomes from the Retrofit for the Future programme: key lessons. Building Research & Information. 2015;43(4):435-51.
55. Urge-Vorsatz D, Petrichenko K, Staniec M, Eom J. Energy use in buildings in a long-term perspective. Current Opinion in Environmental Sustainability. 2013;5(2):141-51.
56. https://www.carbontrust.com/resources/guides/renewable-energy-technologies/renewable-energy-and-combined-heat-and-power-chp/.
Renewable energy and combined heat and power (CHP) 2016 [
57. Dayan E. Wind energy in buildings: Power generation from wind in the urban environment-where it is needed most. Refocus. 2006;7(2):33-8.
58. Alter L. Are building-integrated wind turbines still "folly"? Treehugger2013 [cited 2013 12/02/2013]. Available from: http://www.treehugger.com/renewable-energy/are-building-integrated-wind-turbines-folly.html.
59. Cucchiella F, D'Adamo I, Gastaldi M, Koh SCL. Renewable energy options for buildings: Performance evaluations of integrated photovoltaic systems. Energy and Buildings. 2012;55:208-17.
60. solar Iwa. Integration Options 2016 [Available from: http://www.iowawindandsolar.com/solar-vs-wind.html.
61. Building Integrated Renewable Energy [Internet]. IDES-EDU. 2013 [cited 14/11/2016]. Available from: http://www.ides-edu.eu/.

62. Tyagi VV, Kaushik SC, Tyagi SK. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. Renewable and Sustainable Energy Reviews. 2012;16(3):1383-98.
63. Wall M, Probst MCM, Roecker C, Dubois M-C, Horvat M, Jørgensen OB, et al. Achieving Solar Energy in Architecture-IEA SHC Task 41. Energy Procedia. 2012;30:1250-60.
64. Buker MS, Riffat SB. Building integrated solar thermal collectors – A review. Renewable and Sustainable Energy Reviews. 2015;51:327-46.
65. Gram-Hanssen K. Residential heat comfort practices: understanding users. Building Research & Information. 2010;38(2):175-86.
66. Gram-Hanssen K, editor Households' energy use-which is the more important: efficient technologies or user practices? World Renewable Energy Congress 2011; 2011.
67. Hall R, Wang X, Ogden R, Elghali L. Transpired solar collectors for ventilation air heating. Proceedings of Institution of Civil Engineers: Energy. 2011;164(3):101-10.
68. Brewster A. Using the sun's energy. Building Engineer. 2010;85(6).
69. Brown C, Perisoglou E, Hall R, Stevenson V. Transpired Solar Collector Installations in Wales and England. Energy Procedia. 2014;48(0):18-27.
70. Passive House Plus. Space Heating Demand: Templemedia Ltd; 2019 [Available from: https://passivehouseplus.ie/space-heating-demand.
71. Crawley DB, Hand JW, Kummert M, Griffith BT. Contrasting the capabilities of building energy performance simulation programs. Building and Environment. 2008;43(4):661-73.
72. IBPSA-USA. Building Energy Software Tools: Best Directory; 2019 [Available from: https://www.buildingenergysoftwaretools.com/.
73. Kemma R. Average EU building heat load for HVAC equipment. Delft: VHK for European Commission; 2014.
74. Shorrock L, Anderson B. A guide to the development of BREDEM: Building Research Establishment Garston, Watford; 1995.
75. Roberts M. Why more people die in the winter: BBC MMIX; 2006 [Available from: http://news.bbc.co.uk/1/hi/health/5372296.stm.
76. Oreszczyn T, Hong SH, Ridley I, Wilkinson P, Group WFS. Determinants of winter indoor temperatures in low income households in England. Energy and Buildings. 2006;38(3):245-52.
77. Oreszczyn T, Ridley I, Hong SH, Wilkinson P, Group WFS. Mould and winter indoor relative humidity in low income households in England. Indoor and Built Environment. 2006;15(2):125-35.
78. Summerfield AJ, Lowe R, Bruhns H, Caeiro J, Steadman J, Oreszczyn T. Milton Keynes Energy Park revisited: Changes in internal temperatures and energy usage. Energy and Buildings. 2007;39(7):783-91.
79. Shipworth M, Firth SK, Gentry MI, Wright AJ, Shipworth DT, Lomas KJ. Central heating thermostat settings and timing: building demographics. Building Research & Information. 2010;38(1):50-69.
80. BRE. Mean household temperatures - EFUS 2011. Prepared by BRE on behalf of the Department of Energy and Climate Change; 2013.
81. Kane T, Firth SK, Lomas KJ, Allinson D, Irvine K. Variation of indoor temperatures and heating practices in UK dwellings. 2011.
82. Huebner GM, Hamilton I, Chalabi Z, Shipworth D, Oreszczyn T. Comparison of indoor temperatures of homes with recommended

temperatures and effects of disability and age: an observational, cross-sectional study. BMJ open. 2018;8(5):e021085.
83. Katiyo S, Dorey S, Bone A. The Cold Weather Plan for England Protecting health and reducing harm from cold weather Public Health England - NHS; 2018.
84. Designing Buildings Wiki. Overheating in residential properties: Designing Buildings Ltd; 2019 [updated 12.05.2019. Available from: https://www.designingbuildings.co.uk/wiki/Mechanical_ventilation_of_buildings.
85. Public Health England. Heatwave plan for England. In: England N, editor. London: © Crown; 2019. p. 43.
86. International Passive House Association. Passive House certification criteria 2020 [Available from: https://www.passivehouse-international.org/index.php?page_id=150.
87. CIBSE. Guide A: Environmental design. London: Charted Institution of Building Services Engineers; 2015.
88. HSE. Workplace health, safety and welfare, approved Code of Practice and guidance. In: Executive HaS, editor. Londn: Crown; 2013.
89. NUT. High Classroom Temperatures. National Union of Teachers; 2014.
90. NUT. Standard for School Premises - England. National Union of Teachers; 2012.
91. Seppanen O, Fisk WJ, Faulkner D. Control of temperature for health and productivity inoffices. ASHRAE transactions. 2004;111(LBNL-55448).
92. Lan L, Lian Z, Pan L. The effects of air temperature on office workers' well-being, workload and productivity-evaluated with subjective ratings. Applied ergonomics. 2010;42(1):29-36.
93. ERP. Heating buildings; Reducing energy demand and greenhouse gas emissions. London: Energy Research Partnership; 2016.
94. Shi X, Si B, Zhao J, Tian Z, Wang C, Jin X, et al. Magnitude, causes, and solutions of the performance gap of buildings: A review. Sustainability. 2019;11(3):937.
95. European Commission. Energy use in buildings: European Commission; 2013 [updated 19.02.2020.
96. CIBSE. TM41: Degree-days: theory and application. London: Charted Institution of Building Services Engineers. 2006.
97. Carbon Trust. Degree days: Carbon Trust; 2019 [Available from: https://www.carbontrust.com/resources/guides/energy-efficiency/degree-days/.
98. Meng Q, Mourshed M. Degree-day based non-domestic building energy analytics and modelling should use building and type specific base temperatures. Energy and Buildings. 2017;155:260-8.
99. EEA. Heating and cooling degree days. Copenhagen: European Environment Agency; 2019.
100. Kalogirou SA. Solar energy engineering: processes and systems: Academic Press; 2013.
101. BizEE. Degree Days - Handle with Care: BizEE Software Limited; 2019 [
102. CIBSE. TM46: Energy benchmarks. The Chartered Institution of Building Services Engineers. 2008.

103. CIBSE. Guide F: Energy efficiency in buildings. Chartered institution of building services engineers. 2012.
104. CIBSE. TM33: Tests for software accreditation and verification. Chartered institution of building services engineers. 2006.
105. CIBSE. AM11: Builfing Performance Modelling. Chartered Institution of Building Services Engineers; 2015.
106. Ofgem. Essential Guide to Metering and Monitoring Service Packages (MMSP). Ofgem; 2018.
107. Boiler Efficiency Database [Internet]. 2015. Available from: https://sedbuk.com/.
108. Odyssee-Mure. Consumption of household per m^2 for space heating. In: ADEME, Enerdata, Fraunhofer, editors.: Enerdata 2001-2019; 2019.
109. NEED. Summary of analysis using the National Energy Efficiency Data Framework. London: Department for Business, Energy and Industrial Strategy; 2018.
110. DECC. Building Energy Efficiency Survey, 2014-15: Overarching Report. London; 2016.
111. Clark D. What Colour is your Building?: Measuring and reducing the energy and carbon footprint of buildings: Routledge; 2019.
112. Action Energy. Energy Consumption Guide 19: Energy use in offices. 2013.
113. Wikipedia contributors. Tonne of oil equivalent: Wikipedia; 2020 [updated 26.01.2020.
114. Passive House Institute. Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standards. Passive House Institute; 2022.
115. Energy Benchmarking Dashboard [Internet]. CIBSE. 2021. Available from: https://www.cibse.org/knowledge-research/knowledge-resources/knowledge-toolbox/energy-benchmarking-dashboard.
116. Jones B, Das P, Chalabi Z, Davies M, Hamilton I, Lowe R, et al. Assessing uncertainty in housing stock infiltration rates and associated heat loss: English and UK case studies. Building and environment. 2015;92:644-56.
117. Designing Buildings Wiki. Mechanical ventilation of buildings: Designing Buildings Ltd; 2019 [Available from: https://www.designingbuildings.co.uk/wiki/Mechanical_ventilation_of_buildings.
118. Duraflow Industries. Understanding the 3 types of mechanical ventilation: Duraflow Industries; 2019 [Available from: https://www.duraflowindustries.com/understanding-the-3-types-of-mechanical-ventilation.
119. Comfortable Low Energy Architecture. Mechanical Ventilation: New-learn; 2019 [Available from: https://new-learn.info/packages/clear/thermal/buildings/active_systems/mv/index.html.
120. CleanAlert. Different types of mechanical ventilation best suited for you and your home 2016 [Available from: https://www.cleanalert.com/blog/different-types-of-mechanical-ventilation-best-suited-for-you-and-your-home.
121. Energy Star. Mechanical Ventilation: Breath easy with fresh air in the home. United States Environmental Protection Agency; 2007.
122. Ventilation, F1 Means of ventilation, (2010).

123. ATTMA. Measuring Air Permeability of building envelopes (dwellings). Techical Standard L1. Northampton: British Institute of Non-Destructive Testing; 2010.
124. ATTMA. Measuring Air Permeability of building envelopes (non-dwellings). Techical Standard L2. Northampton: British Institute of Non-Destructive Testing; 2010.
125. Emmerich SJ, Persily AK. Energy impacts of infiltration and ventilation in US office buildings using multi-zone airflow simulation. Proceedings of IAQ and Energy. 1998;98:191-206.
126. Gowri K, Winiarski DW, Jarnagin RE. Infiltration modeling guidelines for commercial building energy analysis: Pacific Northwest National Laboratory USA; 2009.
127. Jokisalo J, Kurnitski J, Korpi M, Kalamees T, Vinha J. Building leakage, infiltration, and energy performance analyses for Finnish detached houses. Building and Environment. 2009;44(2):377-87.
128. Younes C, Shdid CA, Bitsuamlak G. Air infiltration through building envelopes: A review. Journal of Building physics. 2012;35(3):267-302.
129. ICE. Mechanical ventilation of buildings. The construction industry knowledge base [Internet]. 2015 06/12/2015. Available from: http://www.designingbuildings.co.uk/wiki/Building_heating_systems.
130. environment Th. PKOM 4: Heat recovery, ventilatio, heating, cooling & doemstic hot water, all in one unit. 2018.
131. Genvex. Combi 185: Heat recovery, ventilation, doestic hot water heat pump. 2015.
132. Chopade PS, Channapatanna SV. Solar Air Preheaters Performance Evaluation Using New Design. International Journal of Engineering and Technical Research. 2016;4(2):4.
133. Noguchi M. Choice of Domestic Air-Sourced Solar Photovoltaic Thermal Systems through the Operational Energy Cost Implications in Scotland. Sustainability. 2013;5(3):1256-65.
134. Kamel RS, Fung AS, Dash PR. Solar systems and their integration with heat pumps: A review. Energy and Buildings. 2015;87:395-412.
135. Karagiorgas M, Galatis K, Tsagouri M, Tsoutsos T, Botzios-Valaskakis A. Solar assisted heat pump on air collectors: A simulation tool. Solar Energy. 2010;84(1):66-78.
136. HM Goverrnment. The Building Regulation 2010 - Ventilation. F1 Means of Ventilation. London: NBS, RIBS Enterprises Ltd; 2013. p. 63.
137. EN BS. 13779 Ventilation for non-residential buildings-Performance requirements for ventilation and room-conditioning systems. British Standard. 2007.
138. Hollick JC, inventor; Hollick John C, assignee. Method and apparatus for preheating ventilation air for a building. US1988 04.10.1988.
139. Hollick JC, inventor; Hollick John C, assignee. Method and apparatus for preheating ventilation air for a building. US1989 27.01.1989.
140. Hastings R. Solar air systems: a design handbook: Routledge; 2013.
141. Shukla A, Nkwetta DN, Cho YJ, Stevenson V, Jones P. A state of art review on the performance of transpired solar collector. Renewable and Sustainable Energy Reviews. 2012;16(6):3975-85.
142. Chan H-Y, Vinson A, Baljit S, Ruslan MH, editors. Comparison of Thermal Performances between Low Porosity Perforate Plate and Flat Plate

Solar Air Collector. Journal of Physics: Conference Series; 2018: IOP Publishing.
143. Gao L, Bai H, Mao S. Potential application of glazed transpired collectors to space heating in cold climates. Energy conversion and management. 2014;77:690-9.
144. Cordeau S, Barrington S. Performance of unglazed solar ventilation air pre-heaters for broiler barns. Solar Energy. 2011;85(7):1418-29.
145. Zheng W, Li B, Zhang H, You S, Li Y, Ye T. Thermal characteristics of a glazed transpired solar collector with perforating corrugated plate in cold regions. Energy. 2016;109:781-90.
146. Li X, Zheng S, Tian G, Zhang L, Yao W. A new energy saving ventilation system assisted by transpired solar air collectors for primary and secondary school classrooms in winter. Building and Environment. 2020:106895.
147. Vaziri R, İlkan M, Egelioglu F. Experimental performance of perforated glazed solar air heaters and unglazed transpired solar air heater. Solar Energy. 2015;119:251-60.
148. Li B, You S, Ye T, Zhang H, Li X, Li C. Mathematical modeling and experimental verification of vacuum glazed transpired solar collector with slit-like perforations. Renewable energy. 2014;69:43-9.
149. Shams S, Mc Keever M, Mc Cormack S, Norton B. Design and experiment of a new solar air heating collector. Energy. 2016;100:374-83.
150. Rad HM, Ameri M. Energy and exergy study of unglazed transpired collector-2stage. Solar Energy. 2016;132:570-86.
151. Wang X, Lei B, Bi H, Yu T. A simplified method for evaluating thermal performance of unglazed transpired solar collectors under steady state. Applied Thermal Engineering. 2017;117:185-92.
152. Hollick JC. Unglazed solar wall air heaters. Renewable energy. 1994;5(1-4):415-21.
153. Kutscher CF. An investigation of heat transfer for air flow through low porosity perforated plates: University of Colorado; 1992.
154. Kutscher CF, Christensen CB, Barker GM. Unglazed transpired solar collectors: heat loss theory. Journal of Solar Energy Engineering. 1993;115(3):182-8.
155. Kutscher C. Heat exchange effectiveness and pressure drop for air flow through perforated plates with and without crosswind. Journal of Heat Transfer. 1994;116(2):391-9.
156. Kutscher C, Christensen C, Barker G, editors. Unglazed transpired solar collectors: an analytic model and test results. Proceedings of ISES Solar World Congress; 1991.
157. Cortes A, Piacentini R. Improvement of the efficiency of a bare solar collector by means of turbulence promoters. Applied energy. 1990;36(4):253-61.
158. Gupta M, Kaushik S. Performance evaluation of solar air heater for various artificial roughness geometries based on energy, effective and exergy efficiencies. Renewable energy. 2009;34(3):465-76.
159. Alfarra H. Architectural integration of transpired solar thermal technology in building envelopes and associated technological innovation analysis: Cardiff University; 2014.

160. Gunnewiek L, Brundrett E, Hollands K. Flow distribution in unglazed transpired plate solar air heaters of large area. Solar Energy. 1996;58(4):227-37.
161. Dymond C, Kutscher C. Development of a flow distribution and design model for transpired solar collectors. Solar Energy. 1997;60(5):291-300.
162. Arulanandam S, Hollands KT, Brundrett E. A CFD heat transfer analysis of the transpired solar collector under no-wind conditions. Solar Energy. 1999;67(1-3):93-100.
163. Gunnewiek L, Hollands K, Brundrett E. Effect of wind on flow distribution in unglazed transpired-plate collectors. Solar Energy. 2002;72(4):317-25.
164. Wang C, Guan Z, Zhao X, Wang D. Numerical simulation study on transpired solar air collector. 2006.
165. Badache M, Rousse DR, Hallé S, Quesada G. Experimental and numerical simulation of a two-dimensional unglazed transpired solar air collector. Solar Energy. 2013;93:209-19.
166. Li S, Karava P, Savory E, Lin WE. Airflow and thermal analysis of flat and corrugated unglazed transpired solar collectors. Solar Energy. 2013;91:297-315.
167. Hall R, Kendrick C, Lawson RM. Development of a cassette-panel transpired solar collector. Proceedings of the ICE-Energy. 2013;167(1):32-41.
168. Januševičius K, Streckienė G, Bielskus J, Martinaitis V. Validation of unglazed transpired solar collector assisted air source heat pump simulation model. Energy Procedia. 2016;95:167-74.
169. Kuhe A, Ibrahim J, Tuluen L, Akanji S. Simulation of prototype active agricultural solar dryer with slit-type transpired solar collector. Arid zone journal of engineering, technology & environment: Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria; 2019.
170. FEMP. Transpired Collectors (Solar Preheaters for Outdoor Ventilation Air). The U.S. Department of Energy; 1998.
171. Goverment of Canada. SWIFT [Govermental Web Portal]. Canada.ca2017 [updated 02.22.2017. Available from: https://www.nrcan.gc.ca/energy/swift/7439.
172. Cho Y, Shukla A, Nkwetta DN, Jones PJ, editors. Thermal modelling and parametric study of transpired solar collector. CIBSE ASHRAE Technical Symposium; 2012.
173. Van Decker G, Hollands K, Brunger A. Heat-exchange relations for unglazed transpired solar collectors with circular holes on a square or triangular pitch. Solar Energy. 2001;71(1):33-45.
174. Sparrow EM, Ortiz MC. Heat transfer coefficients for the upstream face of a perforated plate positioned normal to an oncoming flow. International Journal of Heat and Mass Transfer. 1982;25(1):127-35.
175. Gawlik KM, Kutscher CF. Wind heat loss from corrugated, transpired solar collectors. Journal of Solar Energy Engineering. 2002;124(3):256-61.
176. Leon MA, Kumar S. Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors. Solar Energy. 2007;81(1):62-75.
177. Motahar S. An analysis of unglazed transpired solar collectors based on exergetic performance criteria. International Journal of Thermodynamics. 2010;13(4):153-60.

178. Li X, Li C, Li B. Net heat gain assessment on a glazed transpired solar air collector with slit-like perforations. Applied Thermal Engineering. 2016;99:1-10.
179. Bake M, Shukla A, Liu S, Agrawal A. A systematic review on parametric dependencies of transpired solar collector performance. International Journal of Energy Research. 2019;43(1):86-112.
180. Croitoru C, Nastase I, Voicu I, Meslem A, Sandu M. Thermal evaluation of an innovative type of unglazed solar collector for air preheating. Energy Procedia. 2016;85:149-55.
181. Abulkhair H, Collins M, editors. Investigation of wind heat loss from unglazed transpired solar collectors with corrugation. 5th Annual International Green Energy Conference, Waterloo, Ontario, June; 2010.
182. Badache M, Hallé S, Rousse DR, Quesada G, Dutil Y. An experimental investigation of a two-dimensional prototype of a transparent transpired collector. Energy and Buildings. 2014;68:232-41.
183. Croitoru CV, Nastase I, Bode FI, Meslem A. Thermodynamic investigation on an innovative unglazed transpired solar collector. Solar Energy. 2016;131:21-9.
184. Gawlik KM, Kutscher CF, editors. A numerical and experimental investigation of low-conductivity unglazed, transpired solar air heaters. ASME Solar 2002: International Solar Energy Conference; 2009: American Society of Mechanical Engineers Digital Collection.
185. Cali A, Kutscher CF, Dymond CS, Pfluger R, Hollick J, Kokko J, et al. Low Cost, High Performance Solar Air-Heating Systems Using Perforated Absorbers,. Washington: IEA; 1999. Report No.: SHC.T14.Air.I Contract No.: SHC.T14.Air.I.
186. Pesaran AA, Wipke KB. Use of unglazed transpired solar collectors for desiccant cooling. Solar Energy. 1994;52(5):419-27.
187. Gao L, Bai H, Fang X, Wang T. Experimental study of a building-integrated solar air heating system in cold climate of China. Energy and Buildings. 2013;65:359-67.
188. Engineering ToolBox. Absorbed Solar Radiation 2009 [Available from: https://www.engineeringtoolbox.com/solar-radiation-absorbed-materials-d_1568.html.
189. Weiss W, Stadler I. Facade Integration – A new and promising oportunity for thermal solar collectors. Solar Combisystems. 2001:59.
190. Munari Probst M, Roecker C, Schueler A, editors. Architectural integration of solar thermal collectors: results of a European survey. ISES 2005 Solar World Congress, Orlando, USA, August; 2005.
191. Paya-Marin MA, Lim JB, Chen J-F, Lawson RM, Gupta BS. Large scale test of a novel back-pass non-perforated unglazed solar air collector. Renewable energy. 2015;83:871-80.
192. Carpenter S, Meloche N. The Retscreen model for simulating the performance of solar air heating systems. Proceedings eSim. 2002:11-3.
193. Wang Y, Shukla A, Liu S. A state of art review on methodologies for heat transfer and energy flow characteristics of the active building envelopes. Renewable and Sustainable Energy Reviews. 2017;78:1102-16.
194. Ben-Amara M, Houcine I, Guizani A-A, Maalej M. Efficiency investigation of a new-design air solar plate collector used in a humidification–

dehumidification desalination process. Renewable energy. 2005;30(9):1309-27.
195. Tajdaran S, Bonatesta F, Ogden R, Kendrick C. CFD modeling of transpired solar collectors and characterisation of multi-scale airflow and heat transfer mechanisms. Solar Energy. 2016;131:149-64.
196. Badache M, Hallé S, Rousse D. A full 3 to the power of 4 factorial experimental design for efficiency optimization of an unglazed transpired solar collector prototype. Solar Energy. 2012;86(9):2802-10.
197. Miseviciute V, Rudzinskas L, editors. Simulation of ventilation system with unglazed solar collector and air heat pump. Environmental Engineering Proceedings of the International Conference on Environmental Engineering ICEE; 2014: Vilnius Gediminas Technical University, Department of Construction Economics.
198. Gholampour M, Ameri M. Energy and exergy analyses of Photovoltaic/Thermal flat transpired collectors: Experimental and theoretical study. Applied energy. 2016;164:837-56.
199. Semenou T, Rousse DR, Le Lostec B, Nouanegue HF, Paradis P-L. Mathematical modeling of dual intake transparent transpired solar collector. Mathematical Problems in Engineering. 2015;2015.
200. Li S, Karava P. Energy modeling of photovoltaic thermal systems with corrugated unglazed transpired solar collectors–Part 2: Performance analysis. Solar Energy. 2014;102:297-307.
201. Vasan N, Stathopoulos T. Experimental study of wind effects on unglazed transpired collectors. Solar Energy. 2014;101:138-49.
202. Perisoglou E, Dixon D. Experimental Monitoring of Different Dimensions of Transpired Solar Collectors. Energy Procedia. 2015;70:111-20.
203. Enginnering ToolBox. Air - Specific Heat at Constant Pressure and Varying Temperature 2004 [Available from: https://www.engineeringtoolbox.com/air-specific-heat-capacity-d_705.html?vA=0&degree=C&pressure=1bar#.
204. Energy USDo. Transpired solar collectors (Solar Preheaters for Outdoor Ventilation Air). 1998.
205. Hall RXW, S; Ogden, R. Design Guidance on Transpired Solar Collectors for Heating in Renovation of Residential Buildings. The Steel Construction Institute; 2011.
206. TATA steel. Colorcoat Renew SC Design guide. London; 2016.
207. Minister of Natural Resources Canada. RETScreen: Solar Air Heating Project Analysis. 2004.
208. BRE. UK's National Calculation Method for Non Domestic Buildings 2022 [Available from: https://www.uk-ncm.org.uk/index.jsp.
209. Solarwall. Solarwall - About Us 2019 [Available from: https://www.solarwall.com/about-us/.
210. Maurer CC. Field study and modelling of an Unglazed Transpired Solar Collector System. Raleigh: North Carolina State University; 2004.
211. Deru M, Pless SD, Torcellini PA, editors. BigHorn home improvement center energy performance2006; Quebec City, QC.
212. Pearson C. SolarWall^{TM} monitoring CA Roll Mill. County Durham: BSRIA Ltd carried out for CA Group Ltd; 2007.

213. Cordeau S, editor The performance of a solar air pre-heater system for the ventilation of two commercial poultry barns. Masters Abstracts International; 2010.
214. Cordeau S, Barrington S. Heat balance for two commercial broiler barns with solar preheated ventilation air. Biosystems engineering. 2010;107(3):232-41.
215. Eryener D, Akhan H. The performance of first transpired solar collector installation in Turkey. Energy Procedia. 2016;91:442-9.
216. Kozubal E, Deru M, Slayzak S, Norton P, Barker G, McClendon J. Evaluating the performance and economics of transpired solar collectors for commercial applications. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2008.
217. Heinrich M. Transpired Solar Collectors - Results of a Field Trial. Judgeford, New Zealand: BRANZ Ltd; 2007. Contract No.: SR 167.
218. Lawson M, Hall R. Field trials on a Transpired Solar Collector renovation system. SCI Steel Knowledge; 2010.
219. NREL. NREL Solar Technology Will Warm Air at 'Home': U.S. Department of Energy; 2010 [Available from: https://www.nrel.gov/news/features/2010/1522.html.
220. Pearson C. SolarWallT^{M} monitoring CA Roll Mill. County Durham: BSRIA Ltd carried out for CA Group Ltd; 2007.
221. Bere:architects. Covid-19 and the risk from air-recirculation in buildings 2020 [Available from: https://www.bere.co.uk/press/covid-19-and-the-risk-of-air-recirculation-in-conventional-buildings/?fbclid=IwAR2bu4SArlRHVJwsTRdl_u2miyXe12xqGdw8qycFACB6RK4dwaOxwphLpNs.
222. Whole Building Design Guide: U.S. Department of Energy Federal Energy Management Program (FEMP). Solar Ventilation Air Preheating: National Institute of Building Sciences; 2016 [Available from: https://www.wbdg.org/resources/solar-ventilation-air-preheating.
223. Duffie J, Beckman W. Solar Engineering of Thermal Processes, New York: John Wiley& Sons. Inc; 1991.
224. Summers DN. Thermal simulation and economic assessment of unglazed transpired collector systems: University of Wisconsin-Madison; 1995.
225. Perisoglou E, Ionas M, Patterson J, Jones P, editors. Building monitoring protocol development for deep energy retrofit. IOP Conference Series: Earth and Environmental Science; 2019: IOP Publishing.
226. Perisoglou E, Li X, Ionas M, Patterson J, Bassas EC, Jones P, editors. Evaluation of building and systems performance for a deep domestic retrofit. Journal of Physics: Conference Series; 2019: IOP Publishing.
227. Heinrich M. Transpired Solar Collectors: Results of a Field Trial: BRANZ; 2007.
228. Roggema R. Research by design: Proposition for a methodological approach. Urban science. 2016;1(1):2.
229. Webster J, Watson RT. Analyzing the past to prepare for the future: Writing a literature review. MIS quarterly. 2002:xiii-xxiii.
230. Snyder H. Literature review as a research methodology: An overview and guidelines. Journal of Business Research. 2019;104:333-9.

231. O'Haire C, McPheeters M, Nakamoto E, LaBrant L, Most C, Lee K, et al. Engaging Stakeholders To Identify and Prioritize Future Research Needs: Agency for Healthcare Research and Quality (US), Rockville (MD); 2011 2011.
232. Taylor JK, Cihon C. Statistical techniques for data analysis: Chapman and Hall/CRC; 2004.
233. De Wilde P. Building performance analysis: John Wiley & Sons; 2018.
234. Fawaier M, Bokor B, Horváth M. Wall heat loss recapture evaluation of transpired solar collectors for different climates: A European case study. Case Studies in Thermal Engineering. 2021;24:100836.
235. Deans J, Weerakoon A, editors. The thermal performance of a solar air heater2008: 5th European Thermal-Sciences Conference, The Netherlands.
236. Deans J, Weerakoon A, Richards P, McClew I, editors. Use of perforated roofing sheets as solar collectors. International Heat Transfer Conference 13; 2006: Begel House Inc.
237. Weerakoon A, Richards P, McClew I, Deans J, editors. Use of perforated metal sheets as solar collectors for building space heating. International Heat transfer Conference; 2004.
238. Drozynski C, Brown C, Jones P, Schmieder-Gaite T, Dixon D, Jenkins H, et al. Introduction of the Transpired Solar Collector into the market of the convergence areas of Wales. ZEMCH: UWE Bristol; 2018.
239. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World Map of the Köppen-Geiger Climate Classification Updated. Meteorologische Zeitschrift. 2006;15:259-63.
240. CIBSE. TM 41 Degree-days: theory and application. London: Chartered Institution of Building Services Engineers; 2006.
241. BizEE. Degree Days Calculated Accurately for Locations Worldwide 2021 [Available from: https://www.degreedays.net/.
242. The Carbon Trust. Degree days for energy management. Cambridge: The Carbon Trust,; 2012.
243. CIBSE. Weather Data 2022 [Available from: https://www.cibse.org/weatherdata.
244. PVGIS. Horizon profile: European Commission; 2020 [Available from: https://ec.europa.eu/jrc/en/PVGIS/tools/horizon.
245. ICE. Heating degree days 2020 [Available from: https://www.designingbuildings.co.uk/wiki/Heating_degree_days#:~:text=Heating%20degree%20days%20(HDD)%20are,a%20specified%20period%20of%20time.
246. PVSyst. Far shadings - Horizon 2020 [Available from: https://www.pvsyst.com/help/horizon.htm.
247. Meteonorm. Horizon Tiles: Meteotest AG; 2022 [Available from: https://meteonorm.com/en/horizon-tiles.
248. Historic England. Search the List 2022 [Available from: https://historicengland.org.uk/listing/the-list/.
249. Cof Cymru. National Historic Assets of Wales: Crown; 2022 [Available from: https://cadw.gov.wales/advice-support/cof-cymru.
250. Planning house. Do you need planning permission to install solar panels? : Planning House Group Limited; 2022 [updated 2022.05.11. Available from: https://planninghouse.co.uk/do-you-need-planning-permission-to-install-solar-panels/.

251. Google. Google Maps 2022 [Available from: https://www.google.com/maps.
252. Google. Google Earth 2022 [Available from: https://earth.google.com/web/.
253. Bassett T, Lannon SC, Waldron D, Jones PJ. Calculating the solar potential of the urban fabric with SketchUp and HTB2. 2012.
254. SBSE. Climate Consultant Software: SBSE; 2021 [Available from: https://www.sbse.org/resources/climate-consultant#:~:text=Climate%20Consultant%20is%20a%20simple,students%20understand%20their%20local%20climate.
255. Global Wind Atlas [Internet]. DTU. 2023. Available from: https://globalwindatlas.info/en.
256. Cho H, Liu B, Gowri K. Energy saving impact of ASHRAE 90.1 vestibule requirements: Modeling of air infiltration through door openings. Pacific Northwest National Lab.(PNNL), Richland, WA (United States); 2010.
257. ANSI/ASHRAE. Standard 55-2013 user's manual : ANSI/ASHRAE standard 55-2013, thermal environmental conditions for human occupancy: ASHRAE; 2016.
258. Anderson B. Conventions for U-value calculations: CRC; 2002.
259. British Standards Institute. BS ISO 9869-1:2014: Thermal insulation. Building elements. 7IIn-situ7R measurement of thermal resistance and thermal transmittance. Heat flow meter method. British Standards Institute; 2014.
260. Yao R, Steemers K. A method of formulating energy load profile for domestic buildings in the UK. Energy and Buildings. 2005;37(6):663-71.
261. Johnston D, Miles-Shenton D, Farmer D, Wingfield J. Whole house heat loss test method (Coheating). Leeds Metropolitan University: Leeds, UK. 2013.
262. Bauwens G, Roels S. Co-heating test: A state-of-the-art. Energy and Buildings. 2014;82:163-72.
263. Energy Saving Trust. Insitu monitoring of efficiencies of condensing boilers and use of secondary heating. 2009. Contract No.: GaC3563.
264. NREL. Transpired Solar Collector. National Renewable Energy Laboratory
2000.
265. Ofgem. Energy Price Guarantee: Ofgem; 2022 [Available from: https://www.ofgem.gov.uk/information-consumers/energy-advice-households/check-if-energy-price-cap-affects-you.
266. Loomans M, De Leeuw J, Middendorf G, Nielsen PV. COVID-19 and recirculation. REHVA Journal. 2020(5):5-9.
267. Perisoglou E, Bassas EC, Lannon S, Li X, Jenkins H, Patterson J, et al., editors. Steady State and Dynamic Modelling of Residential Transpired Solar Collectors Performance. 4th Building Simulation and Optimization Conference,; 2018 11-12 September 2018; Cambridge, UK: IBSA England.
268. Hirvonen J, Sirén K, editors. High latitude solar heating using photovoltaic panels, air-source heat pumps and borehole thermal energy storage. ISES Solar World Conference; 2017: International Solar Energy Society-Slovenian Section.
269. ANSI/ASHRAE/IES. Energy Standard for Buildings Except Low-Rise Residential Buildings. ASHRAE; 2019.

270. BS ISO. Solar energy - Solar thermal collectors - Test methods. BSI Standards Limited; 2017.
271. BS EN 12975:2022: Solar collectors. General requirements. British Standards Institute; 2022.
272. Tsafarakis O, Moraitis P, Kausika BB, van der Velde H, ’t Hart S, de Vries A, et al. Three years experience in a Dutch public awareness campaign on photovoltaic system performance. IET Renewable Power Generation. 2017;11(10):1229-33.
273. Borg I, Dixelius A, Östlund D. Interactive Visualization of Solar Energy Data. 2019.
274. Engineering ToolBox. Moist Air - Density vs. Water Content and Temperature 2022 [Available from: https://www.engineeringtoolbox.com/density-air-d_680.html.
275. TATA steel. TSC Specification details 2022 [Available from: https://www.tatasteeleurope.com/construction/products/renewables/active-solar-air-heating/unglazed-transpired-solar-collector.
276. Conservation of fuel and power, L, (2010).
277. Roveti DK. Choosing a humidity sensor: A review of three technologies this discussion of the operating principles of capacitive, resisitive, and thermal conductivity humidity sensors also addresses their advantages, disadvantages, and applications. Sensors-the Journal of Applied Sensing Technology. 2001;18(7):54-8.
278. European Standards. Test procedures and measurement methods to hand over air conditioning and ventilation systems. Ventilation for buildings2013.
279. Testo. Air flow measurements in ducts according to DIN EN 12599. www.testo.com.
280. Ludmilla Kosmina. Guide to In-situ U-value measurement of walls in existing dwellings. BRE; 2016.
281. Perisoglou E, Ionas M, Patterson J, Jones P, editors. Building monitoring protocol development for deep energy retrofit. IOP Conference Series: Earth and Environmental Science; 2019: IOP Publishing.
282. Tian W, Fu Y, Wang Q, Sevilla TA, Zuo W, editors. Optimization on thermostat location in an office room using the coupled simulation platform in modelica buildings library: a pilot study. The 4th International Conference on Building Energy and Environment (COBEE2018); 2018.
283. Tian W, Han X, Zuo W, Wang Q, Fu Y, Jin M. An optimization platform based on coupled indoor environment and HVAC simulation and its application in optimal thermostat placement. Energy and Buildings. 2019;199:342-51.
284. Ghanta N, Kongoletos J, Glicksman L. Comfort control and improved thermostat location in conference rooms and academic working spaces. Building and Environment. 2021;205:108192.
285. Seri F, Arnesano M, Keane MM, Revel GM. Temperature Sensing Optimization for Home Thermostat Retrofit. Sensors. 2021;21(11):3685.
286. Instrumentation Toolbox. How to Convert Thermocouple Milivolts to Temperature: Instrumentationtoolbox.com; 2022 [Available from: https://www.instrumentationtoolbox.com/2011/05/converting-thermocouple-milivolts-to.html.

287. Chu X, Ilyas IF, Krishnan S, Wang J, editors. Data cleaning: Overview and emerging challenges. Proceedings of the 2016 international conference on management of data; 2016.
288. Ilyas IF, Chu X. Data cleaning: Morgan & Claypool; 2019.
289. Met Office. UK climate extremes: Crown; 2022 [Available from: https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-extremes.
290. Bowen WP, Jerman JC. Nonlinear regression using spreadsheets. Trends in Pharmacological Sciences. 1995;16(12):413-7.
291. Ritz C, Streibig JC. Nonlinear regression with R: Springer; 2008.
292. Mackinlay J, Genesereth MR. Expressiveness and language choice. Data & Knowledge Engineering. 1985;1(1):17-29.
293. Mackinlay J. Automating the design of graphical presentations of relational information. Acm Transactions On Graphics (Tog). 1986;5(2):110-41.
294. Todorovic D. Gestalt principles. Scholarpedia. 2008;3(12):5345.
295. GFChart. How To Create Beautiful And Responsive Data Visualizations 2021 [Available from: https://gfchart.com/2021/12/wordpress-charts-graphs/.
296. TATA steel. Trisobuild® roof systems - steel insulated panels 2022 [Available from: https://www.tatasteeleurope.com/construction/products/roof/profiles/trisobuild.
297. Ventilation, F1 Means of ventilation, (2010).
298. CIBSE. Guide A, Environmental Design. London: The Chartered Institute of Building Services Engineers; 2015.
299. TITAN Products Ltd. Velocity Transmitter (TPAVT8) [Available from: https://titanproducts.com/product/velocity-transmitter-tpavt8/.
300. DECC. Smart Metering Equipment Technical Specifications
Version 2. Department of Energy & Climate Change; 2013.
301. Hollick J. World's largest and tallest solar recladding. Renewable energy. 1996;9(1-4):703-7.

Appendix I – Chapter 3: Case Study details

Appendix I presents additional technical details for the case studies presented in Chapter 4. The text in lighter colour is included in the main text of the thesis, while the text in black is further text included in this appendix to support the existing text.

1. NREL Waste Handling Facility, Colorado, US – industrial

Design

The system included 3 exhaust fans and one supply fan positioned after the heater that could be operated at two speeds. The exhaust fans were rated at 2,550m^3/h, while the supply fan at 5,100m^3/h (equalling to about 183m^3/h per m^2 of TSC). The ducts having a diameter of about 500mm led transported the air into two separate spaces. The flow capacity is approximately three times the flow per m2 recommended, but no explanation was provided by the authors on the sizing and selection of number of fans. A thermopile controller with connections before the electric heater and inside the room was used to control the addition of extra heat if necessary.

Evaluation

After initial monitoring (spring 1992 to spring 1993) some improvements in the data acquisition system took place and the site was monitored again (first two and a half months of 1994). The relationship between average day collector efficiency and average day radiation (kWh/m^2 per day) and averaged wind speed was studied (see section 3.24). The heat transfer to/from the concrete back wall was also considered through modelling and the impact was observed in monitoring data. Depending on outdoor conditions, this heat transfer to the wall accounted for about 4-10% of the total energy delivery during the heating season. The collector efficiencies averaged every 30 minutes for 10 days in February 1994 are shown in Figure 1(a). The radiation and ambient temperatures for the same period are shown in Figure 1(b). Raw and reduced collector efficiencies are presented in Figure 1(a) with the reduced one accounting for the heat transfer mechanism through the concrete wall. Values that are higher than 100% occur due to the thermal storage function of the concrete wall which incurred time delays. The two days of low efficiencies in the same graph correspond to days that are considerably warmer than the previous days (in which higher efficiencies were observed). It was found that on warmer days the concrete wall and the collector would absorb some energy from the air stream, thus impacting negatively on the measured heat delivered by the TSC. Based on this finding, it was suggested that the evaluation of the TSC efficiency is performed weekly or over longer periods of time.

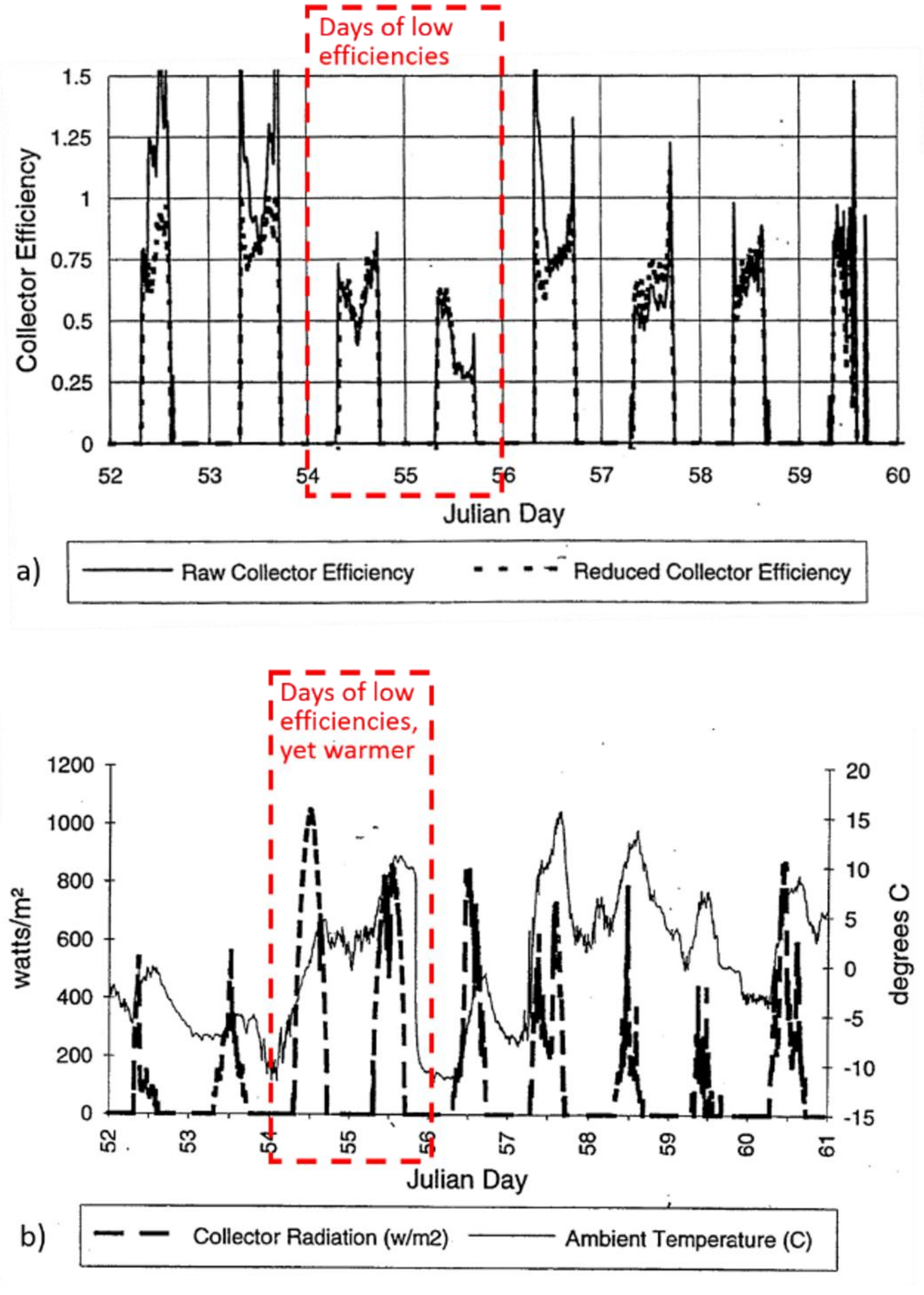


Figure 1. Data for February 1994: a) collector efficiency and b) ambient temperature and solar radiation (collated from Cali et al. (1)).

Heat savings of 513kWh/m^2 per year were estimated, corresponding to total annual savings of 14,310kWh. This amounts to about 26% of the energy requirement to heat the building's ventilation air per year (1). The cost[1] of the TSC system was ($40/$m^2$) for the materials and £49.8 ($60/$m^2$) for the installation according to Cali et al. (2), totalling £2,316 ($2,790). However, NREL revised the costs for 2005 inflation including labour for design and field supervision at $6,000 estimating a 9-year payback time (1). This is translated to $7,930 for 2020 inflation or £230/m^2 of TSC ($284/$m^2$).

2. Ford Assembly Plant, Canada – industrial

Design

In 1990 a ventilation air heating TSC system was retrofitted at the Ford Assembly Plant in Ontario, Canada (Figure 2). The TSC replaced the original glazed system (2). The TSC was chosen as it was less expensive[2] than the glazed system and also more efficient[3] (by up to 30%), as was proven through lab testing. The collector has a total area of 1877m^2 and has a hybrid ratio of perforations, namely a porosity of 1% closer to the fan and 2% on the rest of the collector area. This contributed to a more even distribution of the airflow across such a large collector area.

[1] Note that costs related to a 2005 reference were converted to USD 2020 cost accounting for USD inflation using https://www.usinflationcalculator.com/ and then converted to GBP using an exchange rate of 0.81 (USD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

[2] It was not specified whether the system was less expensive based on capital costs or operational costs or both.

[3] No specific information was provided regarding the efficiency aspects considered.

Figure 2. Part of the TSC installation at the Ford Assembly Plant in Ontario, Canada (3).

Individual gas heaters provided heat to the building independently from the solar heating system. The controls comprised constant speed fans, two recirculation dampers and a bypass damper. There were 16 fans operating in the installed TSC system, providing 119m^3/h per m^2 of collector area. The bypass set-point was 18°C (outdoor); for temperatures above this point the bypass was automatically opened, allowing warm air to escape without further heating the building. The recirculation system was controlled by a thermostat at the fan outlet to apply a pre-set minimum temperature for the air delivered in the space. The two recirculation dampers operated at the same time and would move in opposite directions, e.g., when one was open, the other one was closed. In this way, ceiling-level indoor air was mixed with collector outlet air to maintain that pre-set minimum temperature (Figure 3).

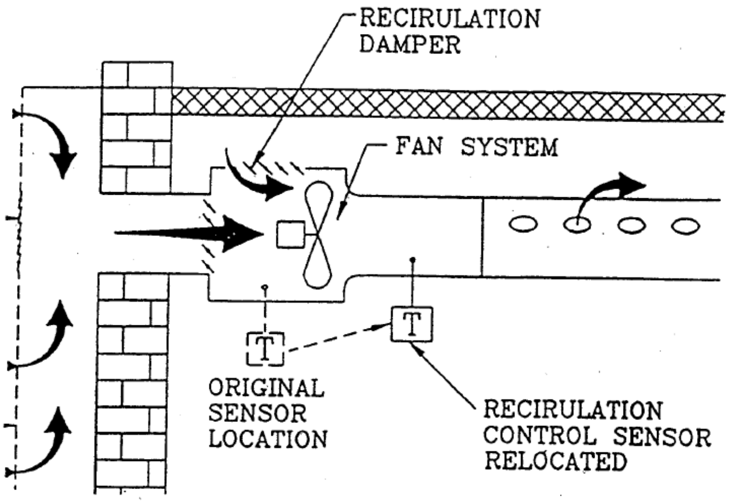


Figure 3. Air handling and control system for TSC at Ford Assembly Plant, Ontario, Canada (2).

Evaluation

The monitoring investigation focussed on 237m^2 of the TSC in 1991 and 1992. The area monitored had a consistent 2% ratio of perforations (2). It is not clear how the monitored area was chosen or whether that particular segment was considered representative. An elevation view of the monitored TSC area is shown in Figure 4.

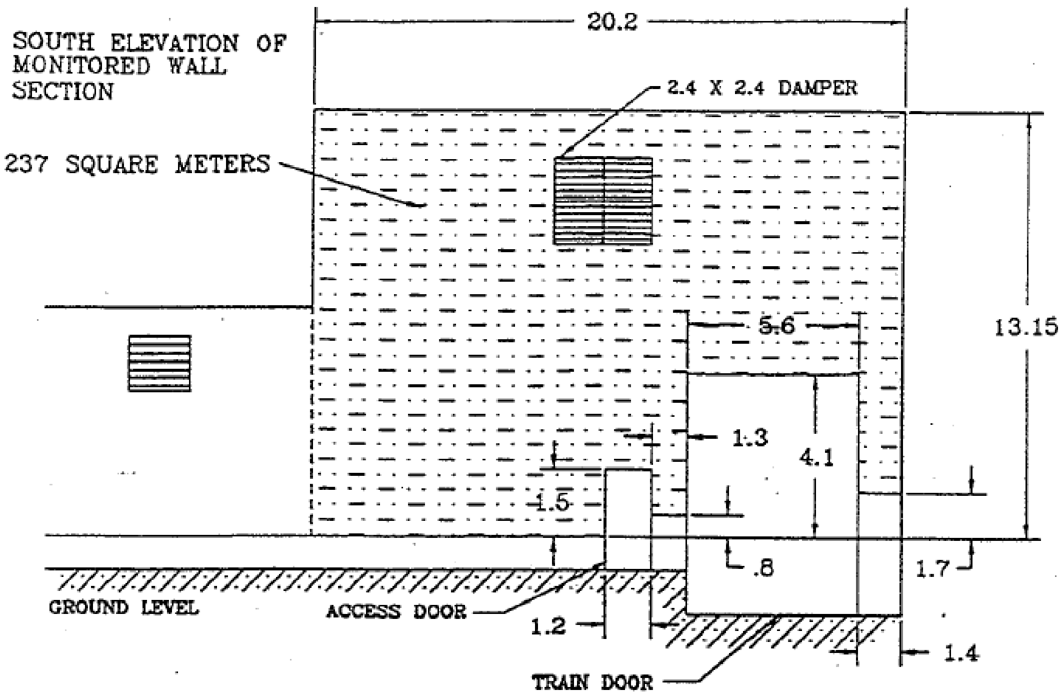


Figure 4. Elevation view of the monitored TSC area at Ford Assembly Plant, Ontario, Canada (2).

Meteorological data including vertical solar radiation (kWh/m^2/day), daytime and night-time averaged ambient temperature (°C) as well as number of days of valid data for the 9 months of monitoring are presented in Table 1. Compared to the Typical Meteorological Year (TMY) historic values for Toronto, the monitored solar radiation values were on average 12% lower, while the monitored ambient temperature values were generally higher. The criteria that were used to determine whether data was valid or not was not specified. It is noted that during the monitoring process, there were months in which there were periods of monitored weather data but without monitored performance data. This issue was alleviated through the use of data generated through simulation (in SIMAIR) and thorough data extrapolation.

Table 1. Daily average atmospheric conditions during monitored period (2).

Month	Days of valid data	Vertical solar radiation (kWh/m^2/d)	Daytime ambient temp. (°C)	Night-time ambient temp. (°C)
Mar-91	29	3.2	3.7	1.1
Apr-91	29	2.1	12.1	8.5
May-91	10	2.6	12.5	9.7
Nov-91	24	1.2	7.0	4.4
Dec-91	31	1.9	2.2	1.1
Jan-92	29	1.6	-2.2	-2.5
Feb-92	17	2.9	-1.8	-3.1
Mar-92	12	2.3	1.2	-1.0
Apr-92	21	3.0	5.2	6.2
9-month average	202 (Total)	2.3	4.2	2.5

There were a number of actions taken during the second year of monitoring in order to improve the performance of the TSC system. For example, possible air leakage through the bypass damper was minimised resulting in a more uniform airflow through the TSC by manually closing and fastening the damper. In addition, a higher maximum airflow was achieved in the TSC by tightening the fan belts and installing higher capacity fans. Besides these modifications, there were more representative days identified in the second year, which contributed to outputs of higher reliability regarding monitoring data and results. No details were provided as to how representative days were identified.

The instantaneous active solar efficiency values were plotted against collector air flow rate for monitored wind speeds reaching up to 3.5m/s. Active solar efficiencies ranging from 35.5% to 56.6% were recorded and the average value over the nine months of monitoring was 51.1%. The system reached instantaneous efficiencies over 70%. Wind effects on the perforated collector and correlations with the heat rise were assessed by monitoring wind direction and speed (included in section 3.2.4).

A range of parameters were calculated and averaged, these are presented in Table 2. Active solar heat collected was calculated (although the calculation method was not specified). Night-time heat flowing out of the walls and recaptured averaged 0.4kWh/m^2/d but was higher in the winter months. Passive solar temperature rise greater than 12°C was observed on sunny days. Destratification savings resulted from the improved homogeneity of the building's air temperature. Reduced wall heat loss was observed as the exterior fibreglass insulation, steel facing and TSC acted as heat loss barriers. Active solar efficiency averaged at 51.1% while total energy savings averaged 3.4 kWh/m^2/d. Temperature rise values of over 12°C (on sunny days) were observed. The destratification savings of 0.9kWh/m^2/d for all months relate to the ventilation's effect on the homogeneity of the building's air temperature. Reduction of the building's heat loss was observed, as the TSC acted as insulation and reduced the total south-wall's heat loss. The reduced wall heat loss occurred due to exterior fibreglass insulation and a new steel layer that was added to the building, on top of which the TSC was installed leaving a plenum in between. Energy savings associated to this amount to 0.4-1.0kWh/m^2/d, averaging 0.8kWh/m^2/d. The total energy savings were calculated at an average of 3.4kWh/m^2/d.

Table 2. Overall monitored performance analysis for days of valid data (2).

Month	Days of valid data	Active solar heat collected (kWh/m^2/d)	Night-time heat recaptured (kWh/m^2/d)	Passive solar temp rise (°C)	Destratification savings (kWh/m^2/d)	Reduced wall heat loss (kWh/m^2/d)	Active solar efficiency (%)	Total savings (kWh/m^2/d)
Mar-91	22	1.5	0.2	0.5	0.9	1.0	46.5	4.0
Apr-91	19	1.1	0.4	0.4	0.9	0.6	45.4	3.3
May-91	10	0.9	0.1	0.4	0.9	0.4	35.5	2.7
Nov-91	18	0.8	1.4	0.2	0.9	0.8	50.9	2.8
Dec-91	31	1.1	0.3	0.3	0.9	0.8	56.6	3.3
Jan-92	27	0.8	0.3	0.2	0.9	0.9	53.6	3.1
Feb-92	17	1.6	0.4	0.4	0.9	0.9	55.9	4.1
Mar-92	12	1.3	0.4	0.4	0.9	0.8	56.6	3.8
Apr-92	21	1.3	0.1	0.5	0.9	0.5	50.0	3.2
Monthly average	177 (Total)	1.1	0.4	0.3	0.9	0.8	51.1	3.4

Fan power consumption was measured and considered with respect to airflow. The fan power required was 0.22W per m^3/h airflow (or 0.79 W/l/s), This is similar to the requirements of a conventional ventilation system (approximately 0.78 kWh/m^2/day or higher). The passive solar heat gain (achieved as ambient air is heated on the surface of the collector by solar radiation before it is brought in by the TSC) was also calculated and found to be 0.3 kWh/m^2/day.

the radiant heat loss from the perforated collector (referring to a relatively constant heat loss from the absorber due to radiative exchange with the sky, ground and other surroundings) was measured to be between 15 and 25 W/m^2 in March and April 1992. The TSC met all the ventilation needs of the building while achieving total energy savings reported at 389.9 kWh/m^2 per year. Solar energy contributed 5-20% of the heating load of the ventilation (2). The cost analysis demonstrated that the initial cost[4] of the TSC including installation normalised for 2020 would be about £121.5/m^2 from which £30.4/m^2 would be installation costs. The fans and dampers' annual maintenance costs were estimated at approximately £103 in total (2).

3. General Motors (GM) Battery Plant, Canada - industrial

Design

A TSC was installed on an industrial building in the General Motors Battery Plant, Oshawa, Canada, in 1991 (2) to correct ventilation problems. It was installed during a refurbishment to correct ventilation problems. This is the first example of TSCs being incorporated on an overhanging canopy (3). As a result, the solar air heating system is a hybrid one consisting of a TSC of 365m^2 and a non-perforated vertically projected area of 55m^2 (Figure 5. TSC façade with a canopy collector in the GM Battery Plant (1). The canopy was added to regulate air flows and to capture any convective heat on the outside TSC surface. It projects 900mm beyond the TSC surface and has a cross-sectional area of 1.6 m^2.

[4] Note that costs related to a 1993 reference was converted to USD 2020 cost accounting for USD inflation using https://www.usinflationcalculator.com/ and then converted to GBP using an exchange rate of 0.81 (USD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

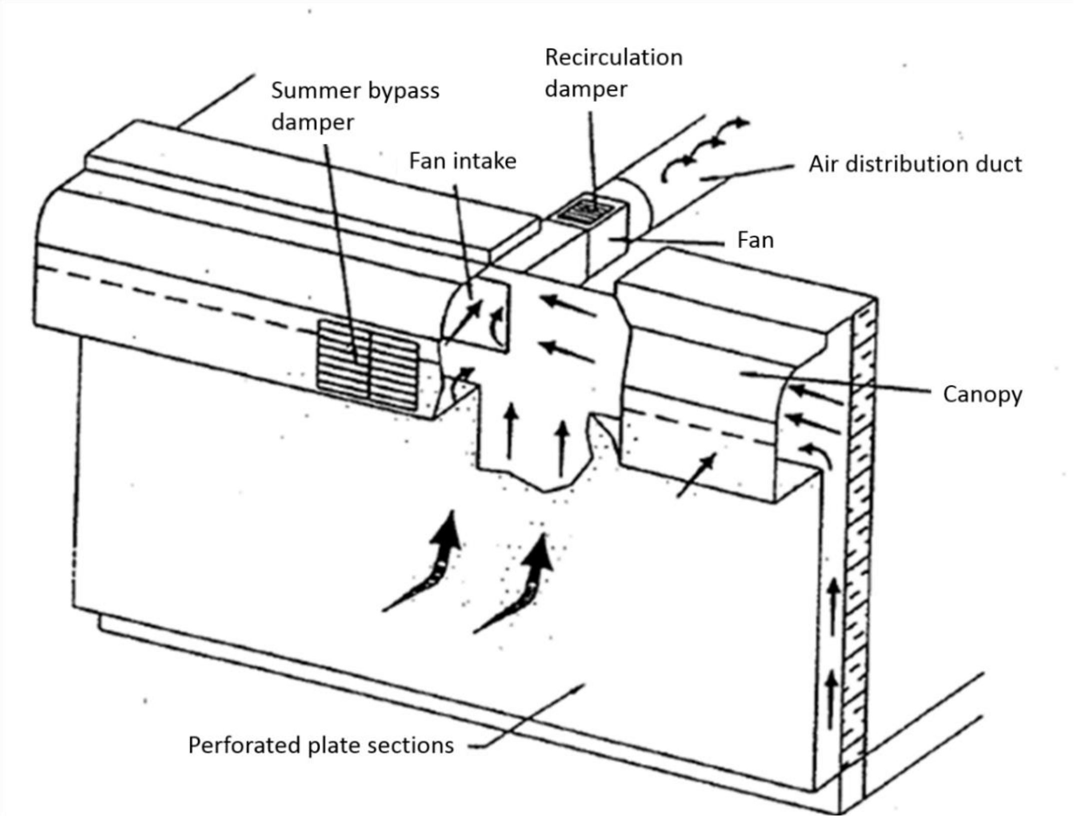


Figure 5. TSC façade with a canopy collector in the GM Battery Plant (1).

Two summer bypass dampers (of an area of 3m^2) on the face of the canopy and two constant-speed fans with recirculation dampers and air distribution ducts were used. The system was monitored during three heating seasons and some modifications were carried out during this monitoring period. After initial monitoring, modifications were made to increase airflow and decrease fan energy consumption and noise as follows. Tapered intakes were installed between the collector and the fans. The original fans and motors were replaced with vane axial fans and high efficiency motors. The original ducting was replaced with wider and upgraded fabric ducting. Fabric ducting enabled even, precise, quiet and more efficient air distribution, as it is lightweight, flexible and breathable (2, 4). Further modification included the repositioning of the temperature control on the recirculation damper and reducing the delivered air temperature setting to 13°C. The modifications resulted in the increase of the air flow rate to 162 m^3/h per m^2 of collector area (2).

Individual steam-powered unit heaters provided heat to the building independently from the solar heating system. The summer bypass dampers were triggered when the outdoor temperature reached 18°C.

Evaluation

The TSC performance after all modifications was documented during the 1993/1994 heating season (September-May). The performance was evaluated by daily averaged data collected every 15 minutes. Solar radiation was measured on the vertical surface ($kWh/m^2/d$) and was averaged for each month. Ambient temperature was also monitored and both metrics were compared against the TMY values for Toronto. It was found that the solar radiation values were very close, while the ambient temperature on the GM site was about 1°C cooler than the TMY values. Fan energy and power consumption as well as air flow were measured before and after the modifications. Based on these measurements, the energy per unit area of perforated collector ($kWh/m^2/d$) and air moving efficiency (W/l/s or W/m^3h), which is the specific air moving power per volume flow rate, were calculated (Table 3).

Table 3. Fan power and related parameters before and after modifications (2).

	Total power (kW)	Energy per unit area TSC ($kWh/m^2/d$)	Air moving efficiency ($W/m^3/h$)
Before modifications	9.2	0.53	0.19
After modifications	8.3	0.47	0.12

Heat recaptured from the building through the wall and active solar heat collected by the TSC was monitored during November 1993 and was averaged based on the time of day (Figure 6); however, no details were supplied on how this was measured and calculated.

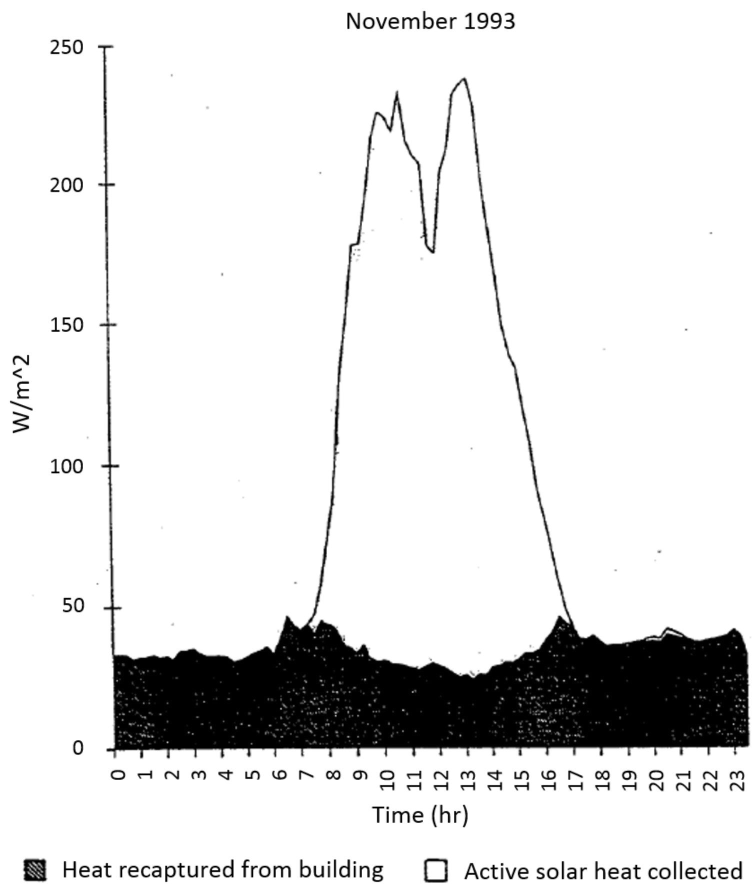


Figure 6. TSC collected heat during the day (1).

The TSC installation helped reduce the building's heat losses by sheltering the original wall from wind and by raising the air temperature in the plenum. It was envisaged that the plenum would provide some insulative function over night-time and contribute to energy savings; however, such savings were assumed to be minimal. Destratification savings were calculated by comparing monitored ceiling temperatures during the fans' operation and fan-off mode. It was shown that the TSC's operation reduced the ceiling temperature by an average of 2.2°C and the destratification savings averaged 0.49 kWh/m^2/d.

Total savings were associated with the active solar heat collected, the recaptured heat, the collector's passive insulation function and destratification mechanism. A summary of the average values for available solar radiation, collected solar heat, active solar efficiency, total savings and fan energy for each month is presented in Table 4. Efficiencies ranged between 66% (Feb) and 88% (May) and the annual average was 72% (note that efficiencies were measured when solar radiation was above 300 W/m^2). It has been claimed that the TSC system contributed to active solar heating savings of 198.7 MWh/year (473.1 kWh/m^2) and savings associated to heat loss recaptured from the wall of 76.8 MWh/year (182.9 kWh/m^2) totalling to annual savings of 275.5 MWh or 656 kWh/m^2 (3). As these values are from another source (U.S. Department of Energy Federal Energy Management Program (FEMP), NREL, U.S. (3)), they do not include destratification or other savings.

Table 4. Summary of TSC performance in GM Battery Plant (2).

Month	Solar available (kWh/m^2/d)	Solar heat collected (kWh/m^2/d)	Active solar efficiency (%)	Total savings (kWh/m^2/d)	Fan energy (kWh/m^2/d)
Sept-93	2.71	2.05	76	4.40	0.47
Oct-93	-	-	-	-	-
Nov-93	1.81	1.33	74	3.61	0.46
Dec-93	2.04	1.54	75	3.64	0.48
Jan-94	2.68	1.83	68	3.65	0.41
Feb-94	3.83	2.54	66	4.54	0.39
Mar-94	2.35	1.64	70	4.16	0.48
Apr-94	3.02	2.25	75	4.92	0.56
May-94	2.08	1.83	88	4.69	0.46
Annual average	2.54	1.86	72	4.15	0.45

The cost[5] of the TSC system was £230/m^2 of installed TSC ($159 in 1993), including the fan, motor and ducting modifications implemented soon after the commisioning of the TSC. It is argued that the cost is higher than typical installations as this system was installed at the early technology stages, before design and installation procedures had been tested and well-documented (3). A summary of the costs is shown in Table 5, where the initial and upgrade costs (after the first set of measurements and optimisation of the system) are presented. Costs are further classified into TSC costs, costs associated to the fan system and ducting as well as labour expenses.

[5] Note that costs related to a 1993 reference was converted to USD 2020 cost accounting for USD inflation using https://www.usinflationcalculator.com/ and then converted to GBP using an exchange rate of 0.81 (USD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

Table 5. Cost of the TSC in GM Battery Plant in US$/m^2. Costs are based on a 420 m^2 system and two fan systems (2).

Component	Initial cost	Upgrade cost	Total cost
Perforated plate with canopy (TSC)	56	0	56
Fan system and ducting	31	9	40
Labour	58	5	63
Total	145	14	159

The U.S. Department of Energy FEMP report (3) presented the installation costs per unit area of TSC for retrofitted applications at that time (1998), which are included in Table 6 in conjunction with more recent guidance values provided by the another TSC for 2016 (5). The two sources have significant discrepancies (it should also be taken into consideration that currency values vary over the years), so further investigation is required into clarifying the actual cost ranges currently available; however, both sources agree that the cost of the absorber (TSC) is the main contributor in this breakdown. Moreover, although the FEMP 2016 estimated that total costs are in the range of 323 US$/m^2, they mentioned that they can reach up to 431 US$/m^2 (or £358/m^2) for 2020[6].

Table 6. Installation costs in US$/m^2 of a retrofit TSC application collated from two sources: FEMP 1998 (3) and FEMP 2016 (5).

	(3) 1998 cost in US$/m^2	(5) 2016 projected cost in US$/m^2
Absorber	37.7	156.1
Supports, flashings, etc.	26.9	80.7
Installation	43	43.05
Other costs	10.8	43.05
Total	118.4	322.9

A payback time estimation was carried out in comparison to a steam system that could replace the TSC system and produce the same amount of energy. It was found that the payback time for the TSC would be 1.3 years, which could be reduced to 1 if

[6] Note that costs related to a 2016 reference was converted to USD 2020 cost accounting for USD inflation using https://www.usinflationcalculator.com/ and then converted to GBP using an exchange rate of 0.81 (USD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

the exhaust fans were located at the ceiling (as occurs in most industrial buildings – in this particular case study the exhaust fans were located at head height).

4. Göttingen Utility Co-generation Plant, Germany - industrial

Design

This was the first European installation for TSC and took place in Germany (**Error! Reference source not found.**). It was a retrofit application for the façade of an industrial building and the driver was to reduce energy consumption. The aim was to feed preheated air into boilers to serve district heating purposes and save fossil fuel, while reducing the emission of air pollutants (2). The TSC was only used as mechanism to provide extra power and pre-heat the combustion air and not for ventilation purposes.

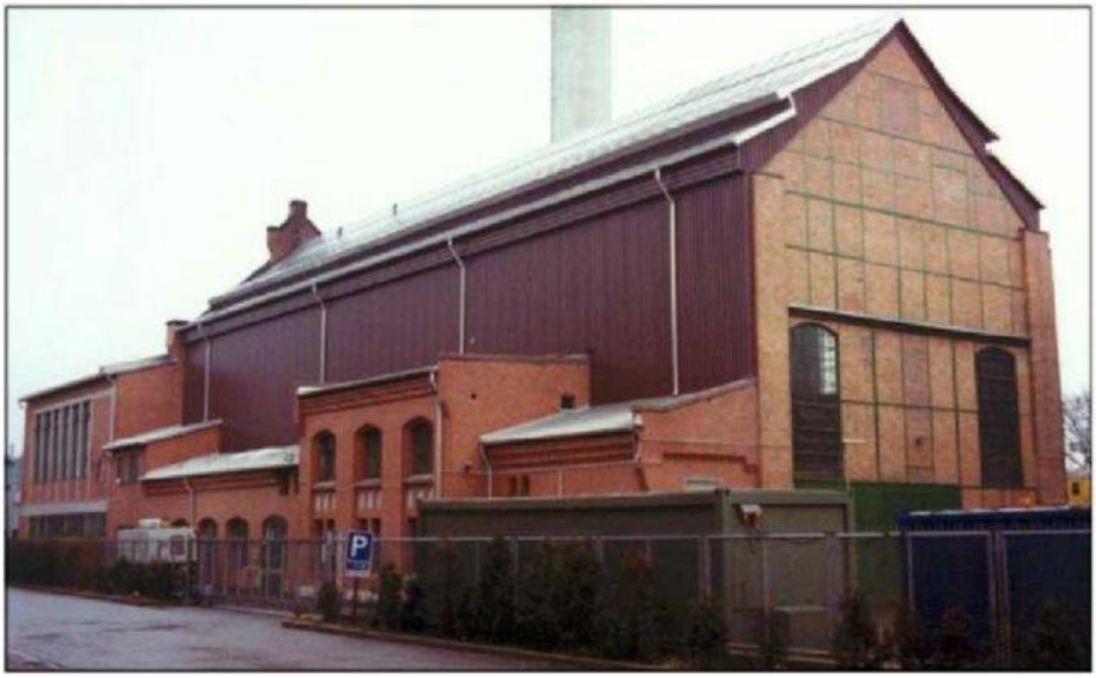


Figure 7. TSC system of the Göttingen Co-Generation Plant (Bokor and Kajtár 2018 (7)).

The installation included 343m^2 of TSC (the net absorber are being 305.6m^2 without the manifold), in dark brown colour, separated into four equal panels (2). The collector was manufactured from 0.7mm thick aluminium sheet. The back of the collector was the building's exterior wall which was a metal façade with 80 mm mineral wool insulation. A collector manifold was constructed and placed above each TSC panel section to improve flow uniformity especially at the upper corners of the panels (Figure

8). The manifold was added to the TSC system due to the relatively elongated horizontal dimensions of the wall. The average design suction air flow was 40,800 m^3/h, corresponding to 133.5 m^3/h per m^2 of TSC; however, the actual air flow in the non-heating season (heat required for hot water and industrial processes only) was measured to be about 7,500 m^3/h, corresponding to an average of 24.5 m^3/h per m^2 of TSC. This was justified by the fact that the boiler system (exhaust gas recirculation) had undergone modifications after the TSC installation and resulting in a different operating strategy.

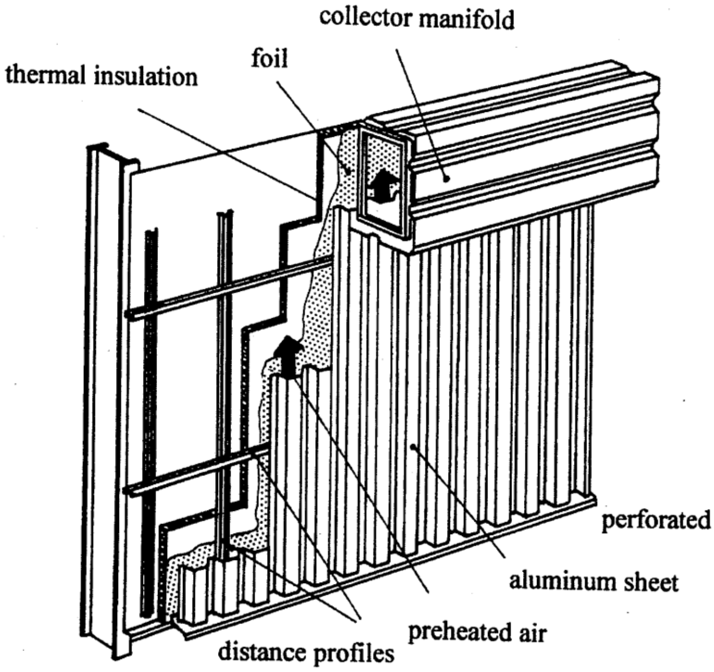


Figure 8. Construction details of the TSC wall (2).

The air through the TSC was led into three boilers through the duct system (**Error! Reference source not found.**) by the boiler fans. The air ducts were designed to capture the thermal losses from boilers and pipes. The boilers used TSC heated air during warm times and room air at other times. Each manifold was equipped with a flap, which could be manually adjusted to regulate the pressure drop in the collector. The flaps were also used to disable one or more panels during the monitoring period. In regular operation, the TSC flaps were programmed to open only if solar radiation exceeded 100 W/m^2. During the day, the flaps to the TSC are fully open and the flap to the room air junction (no. 8 in Figure 9) is closed. During night-time, the flaps to the collector field are closed and all the combustion air is drawn from the room air junction.

Additionally, the amount of air used by the boilers could be adjusted based on actual requirements[7].

[7] In the literature 2. Cali A, Kutscher CF, Dymond CS, Pfluger R, Hollick J, Kokko J, et al. Low Cost, High Performance Solar Air-Heating Systems Using Perforated Absorbers,. Washington: IEA; 1999. Report No.: SHC.T14.Air.I Contract No.: SHC.T14.Air.I. it is stated that this adjustment was possible due to boilers' blast regulator; however, no more information is given.

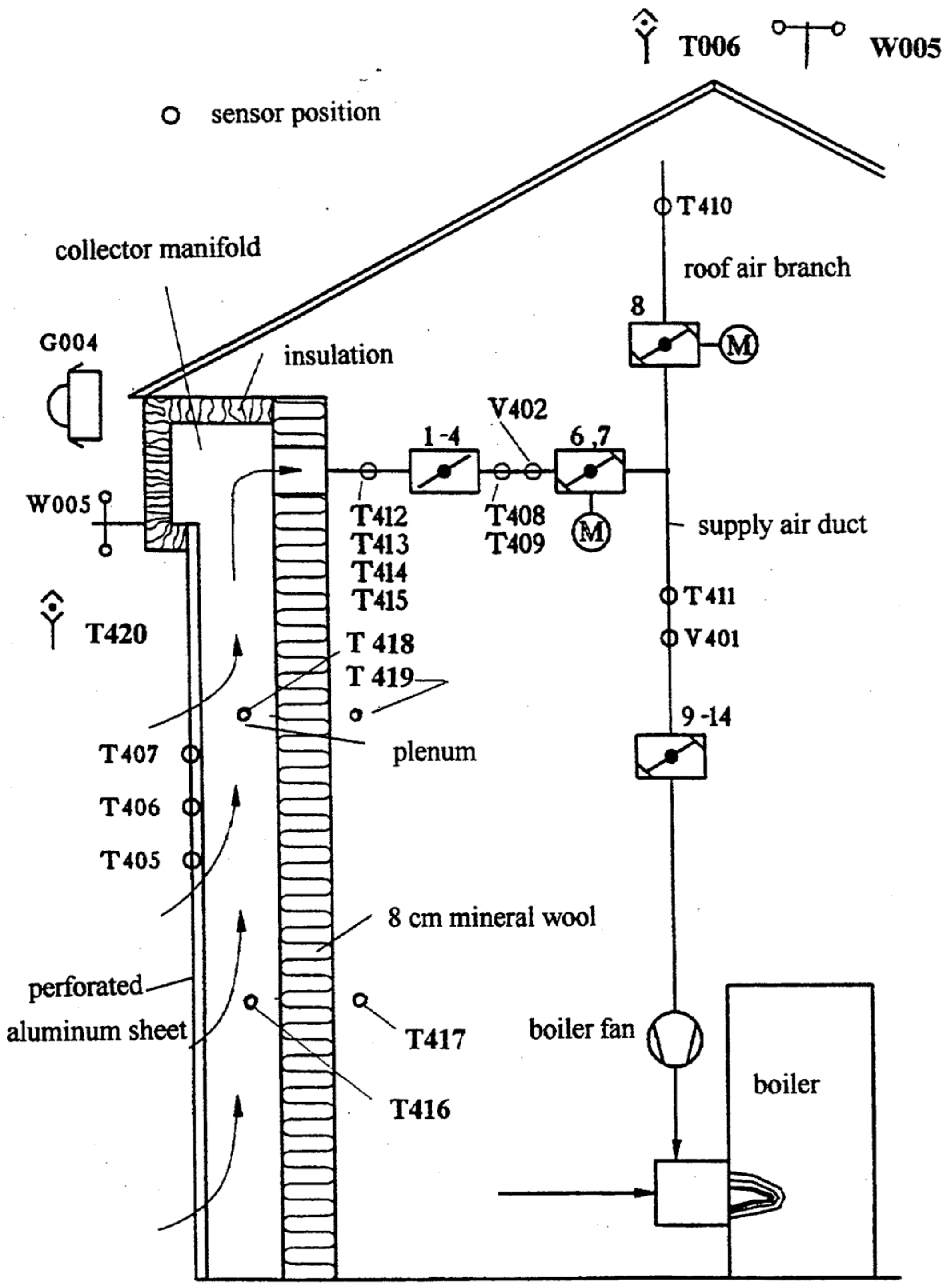


Figure 9. Vertical section of the building, showing TSC, constructions, ducting and sensor positions (2).

Evaluation

There were two monitoring periods: 10 weeks starting on August 1993 and 19 weeks starting on May 1994; this means that the monitoring occurred outside of the typical central European heating season. The sensor locations are shown in **Error! Reference source not found.** and sensor descriptions are shown in

Table 7. As shown there, measurements for delivered air flow, vertical solar radiation and wind speed as well as several temperature sensors (PT100) across the ducting were included. Vertical solar radiation (MJ/m^2/month), ambient temperature (°C) and wind speed (m/s) was captured from a meteorological station at a relevant location of Göttingen and data were presented for every month. Similar meteorological data were monitored at the site and recorded by a PC-based monitoring system. For monitoring purposes, the flaps were manually controlled for 10 weeks during the first monitoring period in order to calculate the air mass flow behaviour and study the suction air velocity. The heat collected through the TSC and from the building recirculated air for the first monitoring period is presented in Figure 10. After the 10-week period and during the second monitoring period, additional sensors were installed to investigate the heat transfer through the building in more detail, e.g., study the room temperature, plenum temperature, ambient temperature and collector temperature. Measurements were taken every 5 minutes and when there was a lack of data for less than three days, the data was interpolated.

Due to the low combustion air flow rate (non-heating season), a decision was made to use only one of the four TSC panels in the second monitoring period, reducing the flow rate from 70.8 to 27.5m^3/h per m^2 of TSC area resulting in higher temperature rise and collector surface temperatures (up to 55°C were observed).

The daytime and night-time temperature measurements were used in order to calculate the total heat that was delivered by the whole system, split into the following components:

i. The heat flux through the wall (Q_{wall})
ii. The heat transported into the plenum by air leaking from the room (Q_{leak})
iii. The solar gains (Q_{solar})
iv. The heat recovery or losses through the duct system (Q_{duct})

Table 7. Description of the sensors (2).

Parameter Measured	Sensor Location	Units	Meter Type	Accuracy + -	Label
Temperatures:					
Delivered Air	Supply Duct in Front of Fan	deg C	PT100	0.2K	T411
Roof Top Air	Roof Air Branch	deg C	PT100	0.2K	T410
Collector outlet	In front of Flap No.1 to No.4 respectively	deg C	PT100	0.2K	T412 T413 T414 T415
Branch duct					
panel 1 and 2	After Flap No. 2	deg C	PT100	0.2K	T408
panel 3 and 4	After Flap No. 3	deg C	PT100	0.2K	T409
Absorber Plate	Three Locations at Centre of Panel 2 distributed vertically	deg C deg C deg C	PT100 PT100 PT100	0.2K 0.2K 0.2K	T407 T406 T405
Free Air Ambient	At the Top of the Building roof	deg C	PT100	0.2K	T006
Southeast-side Ambient	2 Meters from Solarwall Panel 2	deg C	PT100	0.2K	T420
Plenum Air	Lower Part	deg C	PT100	0.2K	T416
	Upper Part	deg C	PT100	0.2K	T418
Building Air	Lower Part	deg C	PT100	0.2K	T417
	Upper Part	deg C	PT100	0.2K	T419
Delivered Air Flow	Supply Duct	m/s	METEO DIGIT	0.2m/s	V401
Vertical Solar	Parallel to Solarwall	W/m²	CM 11	4%	G004
Wind Speed	Top of the Roof	m/s	Anem.	3%	W004

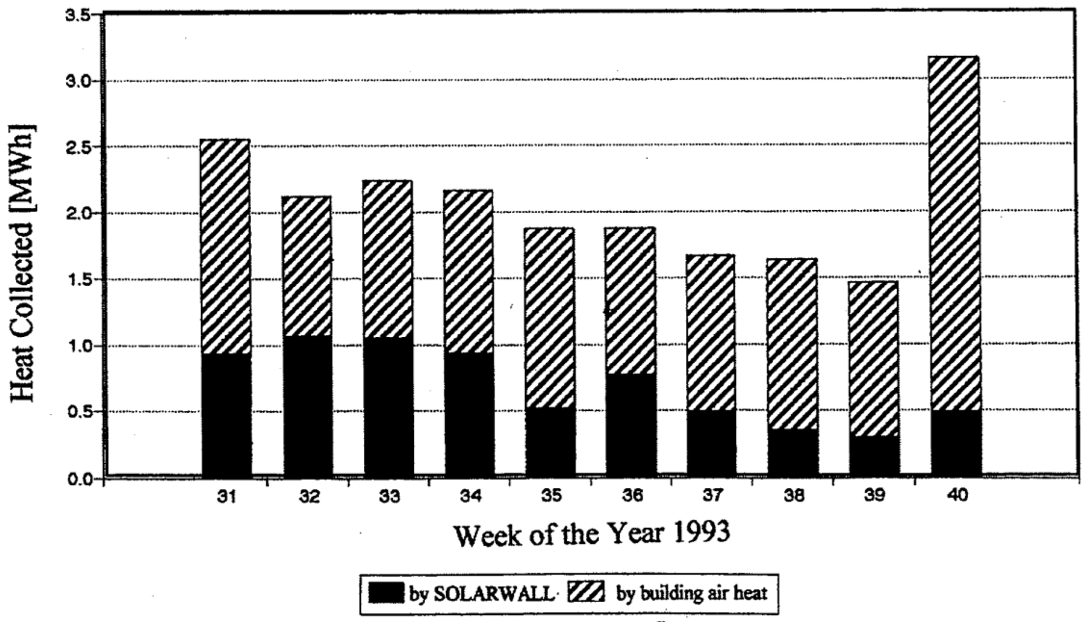


Figure 10. Solar output and heat gain from building air (2)

Daytime (Figure 11) and night-time (Figure 12) heat balance was plotted for that period (18 weeks). During daytime, while solar heat gains are as high as 0.5 MWh, losses through the walls and/or ducts are observed in weeks 25, 26, 28, 29, 30 and 31 (Q_{wall} and Q_{duct} are negative). This happens as the temperature of the preheated air is considerably higher than the room temperature. Then, during night-time, the behaviour changes: there's no solar gains, but there is some heat recovered through the walls and ducts and a contribution by a leakage air flow from the room into the cavity (Q_{wall}, Q_{duct} and Q_{leak} are all positive). The weekly total energy savings are presented in Figure 13. As it can be observed, these range from 0.45 to 0.75 MWh on a weekly basis.

Mean air temperature variations for day and night-time were observed. The collector's efficiency against suction face velocity was also studied with the results confirming higher efficiencies for higher flow rates and suction velocity as analysed in section 2.4). Due to the low air flow rate, the TSC efficiency didn't get higher than 40% during the second monitoring period (Figure 14).

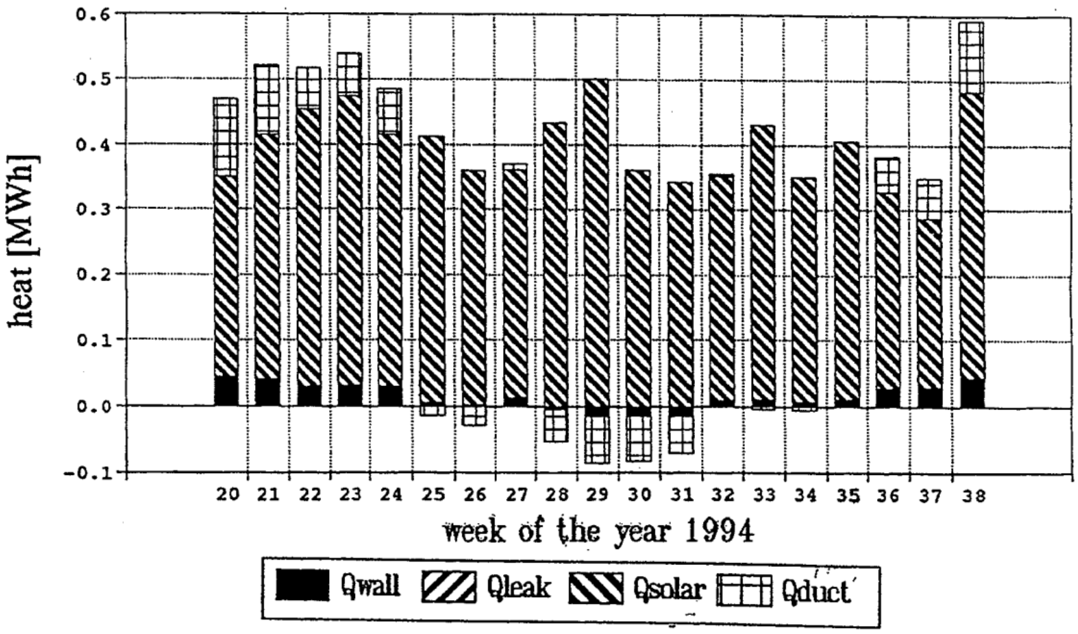


Figure 11. Weekly heat balance for the daytime hours for 1994 (2).

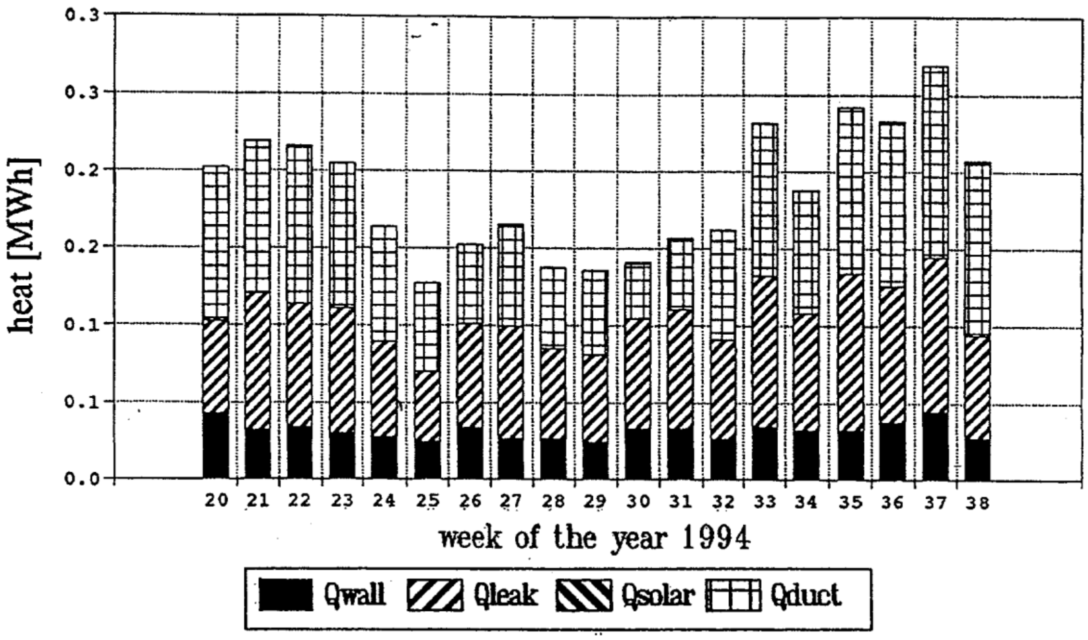


Figure 12. Weekly heat balance for the night-time hours for 1994 (2).

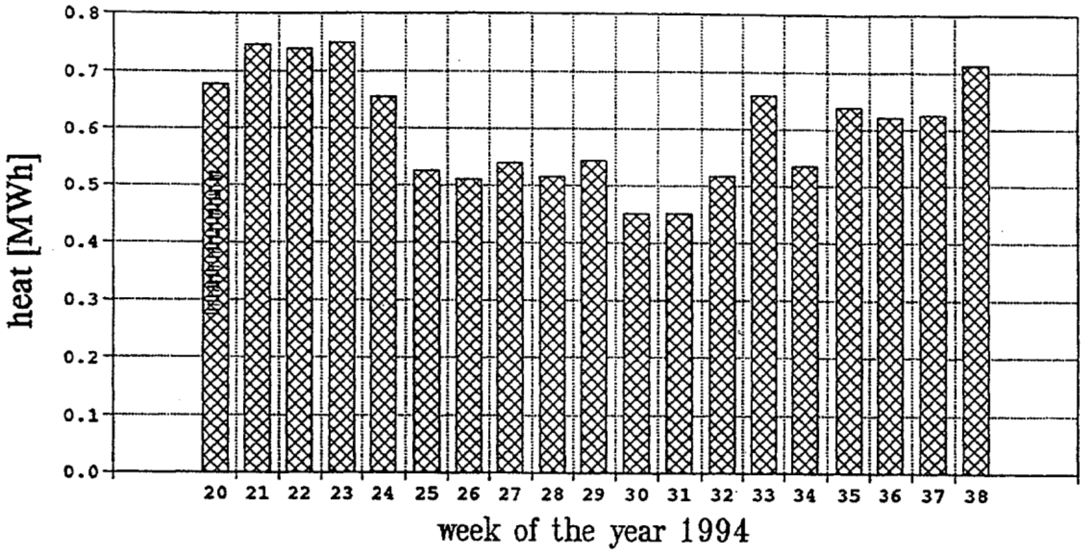


Figure 13. Weekly total energy savings for 1994 (2).

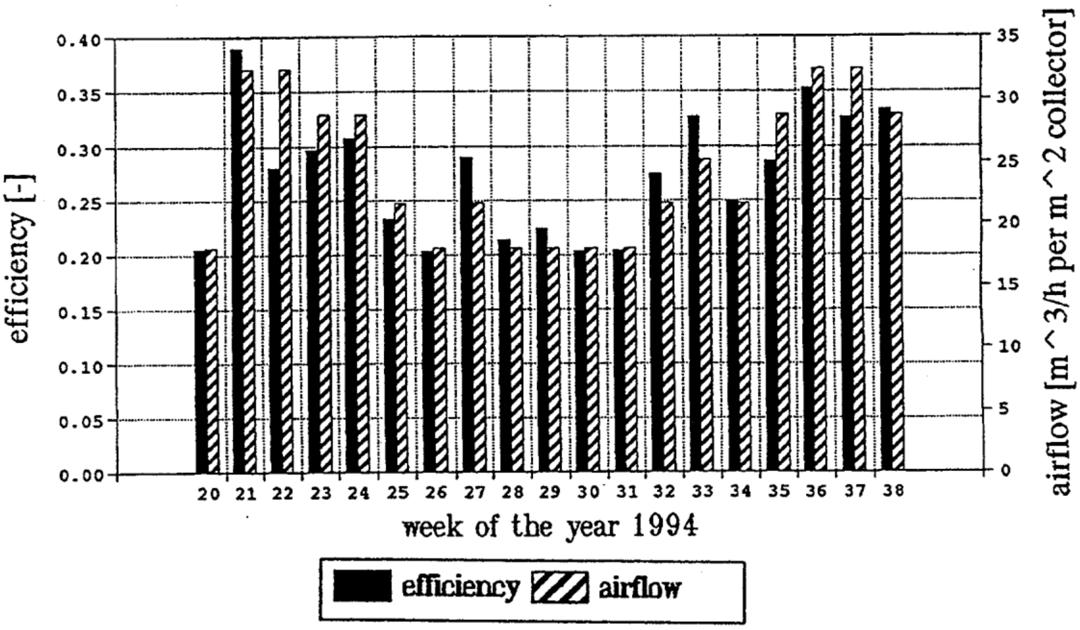


Figure 14. Weekly mean efficiency and mean air flow rate for 1994 (2).

The annual energy savings were calculated as 250 kWh/m^2 of TSC area (0.9 GJ/m^{2}yr) (2). The investment costs were estimated based on the additional cost for the TSC compared to the cost that for a conventional façade. The total investment cost[8] of the system per m^2 of TSC including VAT is £272/m^2 or £93,527 in total (2020 projected

[8] Note that costs related to a 1993 reference was converted to USD 2020 cost accounting for USD inflation using https://www.usinflationcalculator.com/ and then converted to GBP using an exchange rate of 0.81 (USD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

values). This included £142/m^2 for the TSC as an additional cost compared to a conventional façade and £98/m^2 for the air duct and control system. Other estimated costs included annual operating costs of £6.4/m^2 and annual maintenance costs of £1.2/m^2. The estimated cost/performance ratio for a lifetime of 20 years was is 1079£/(MWh/ m^{2}yr). The fan's energy demand for the TSC was not considered for the above as this was a low-pressure system and the fan's power with or without TSC would be similar. However, the extra energy cost for the TSC control was included in the calculations without a clear quantification stated in the source.

5. Bombardier Inc., Canada – industrial

Design

A TSC of 611m^2 (740m^2 in total, but the heat-absorbing surface was 611m^2) and custom olive-green colour was installed on Bombardier Inc. in Canada in 1993 (6). This technology was chosen as its cost was similar to other methods of recladding and improving ventilation. Thus, the objective of this installation was to repair the existing walls, improve the ventilation and air quality inside the building, while providing an attractive solution. The air flow rate through the TSC was 117m^3/h per m^2 of TSC, and the air was fed directly into the room (the TSC had no pre-heat function). Fans on the south wall would operate when the building was occupied in order to draw and distribute the warm air in the building through ducts at ceiling level. Dampers were used between the TSCs and the fans to regulate the temperature inside the distribution ducts so as to ensure that a minimum temperature was maintained. In the case that the outside air was too cold, the dampers would coordinate in order to mix stratified warm air near the ceiling with it to maintain the minimum set point.

Evaluation

The system was monitored for a year between March 1993 and February 1994 and the results showed that the delivered heat during this period was 431,000kWh (705kWh/m^2) and by including the destratification savings, the total energy savings were 894,000kWh (1,463 kWh/m^2).

6. US Army Hangar, Colorado, US – industrial

Design

A TSC of 725m^2 was installed in 1995, on a part of the south façade of the US Army Hangar at the Fort Carson Army Base in Colorado, U.S. (6) shown in Figure 15. The rationale behind the use of TSC was that the TSC's cost would be comparable to a conventional gas-heated ventilation system that was initially specified. The team selected a dark bronze colour for the collector and the air flow rate through the TSC varied between 50-148 m^3/h per m^2 of TSC, which had no pre-heat function. A close-up view of the collector can be seen in Figure 16. There were six fans at ceiling level behind the TSC distributing the warm air inside the building. In terms of controls, the fans were on continuously during the heating season, which is 8 months during the year. Dampers were used between the TSCs and the fans to regulate the temperature inside the distribution ducts so as to ensure that a minimum temperature is maintained. In the case that the outside air was too cold, the dampers would coordinate in order to mix stratified warm air near the ceiling with it to maintain the minimum set point.

Evaluation

No details are provided regarding monitoring; however, it is mentioned that the delivered heat was 587,400 kWh/a (810 kWh/m^{2}a) and by considering the destratification savings, the total energy savings amounted to 973,600 kWh/a (1,343 kWh/m^{2}a). These values are comparable to the monitored outputs from the Bombardier Inc. building in Canada.

Figure 15. TSC installation on the US Army Hangar, Colorado, U.S. (6).

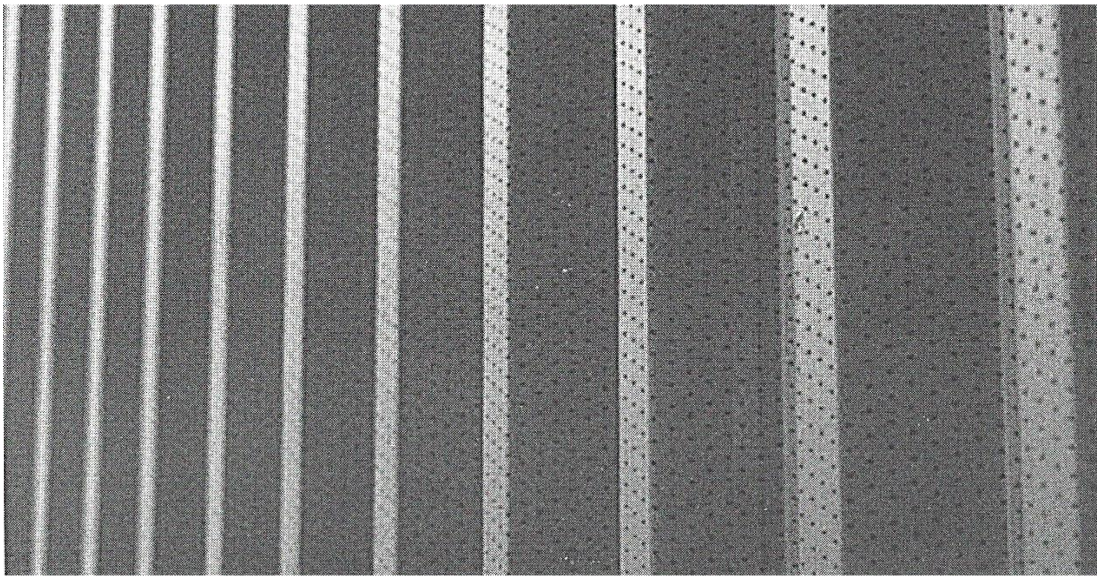


Figure 16. A close-up view of the collector (8).

7. Intek Fabrics Manufacturing Facility, North Carolina, US – industrial

Design

The objective of this study was to determine whether TSCs are appropriate for the climate in North Carolina, considering its quite short heating season (7). A black TSC of an area of 278.5m^2 was installed vertically on the south wall of the Intek Fabrics Manufacturing Facility, which is a warehouse, as shown in Figure 17. The TSC had a porosity of 0.6% and the holes had a diameter of 1.6mm. Regarding the hole spacing, the holes were 16.5mm apart horizontally and 20mm apart vertically. The plenum width was 200mm.

There was no pre-heating function associated to the TSC, so air was distributed directly into the room. There was a recirculation function though that could be used if needed. The installation did not include a summer bypass damper built into the collector. There were two 600 mm diameter fans which led the air from the TSC into four flexible ducts. Two dampers were also used; one for the TSC system which could cover the air entrance in the cavity and another one to enable recirculation. In terms of controls, the system included a Johnson Controls A350P temperature sensor and a Belimo NF24-SR US damper control. These controls operated to maintain a pre-set outlet temperature through the automated damper system. A shaft could moderate both dampers; when one was closed, the other one would open. If the warm air from the TSC was not sufficient, the system would recirculate air from the ceiling. The desired room temperature was 15.6°C (60°F); the system turn-on setting was at 10°C (50°F), so the TSC was activated if the inside temperature fell below 10°C. This control was not based on air temperature inside the plenum and this resulted in the delivery of cold air at night on many occasions. For this reason, a new controller was applied that would activate the TSC only for plenum temperatures between 18.3°C (65°F) and 23.9°C (75°F).

TRNSYS was used to build and run a simulation of a UTC system in order to extend the learning outcomes from the monitoring process. The simulation in TRNSYS was used to predict the performance of the TSC using TMY weather data in North Carolina. The energy balance of the building was modelled and the results were plotted for potential installations. Slight modifications regarding base and auxiliary heating were made to the TRNSYS model that had been earlier developed by Summers (1995) (8), in order to incorporate new correlations from the literature. However, most of the same strategies and energy balances were followed. In addition, as there was no bypass damper included in the installation, some mathematical models were applied and presented in order to simulate the effect in cooling. Results from TRNSYS were additionally used for economic evaluations and payback time estimations based on life cycle equations by Duffie and Beckman (9).

Evaluation

The intended outcomes of the monitoring process included the evaluation of the overall performance of the system components, the calculation of the actual heat delivery and the estimation of the potential monetary savings from the heat gains through the TSC system.

Figure 17. The TSC installation on the south facade of Intek Fabrics Manufacturing Facility (9).

Initial measurements were taken to optimise the flow monitoring equipment, so several air velocity measurements were taken with an Alnor Velometer in the distribution duct prior to installing a full data acquisition system. These measurements were used to determine the average velocity in the duct and estimate the average flow rate. Moreover, two Air Monitor 24” Fan-Evaluator air flow measuring stations were installed downstream from the fan outlet and coupled with two Omega PX-277 differential pressure transmitters to determine outlet air flow. Regarding other monitoring devices, a Li-Cor pyranometer was used to measure the horizontal solar radiation and a NRG Max 40 cup anemometer was installed to measure the wind speed. Furthermore, thermistors (Campbell Scientific, model T108) were used for measuring air temperature at the fan inlet from the wall, the fan inlet from the ceiling and the fan outlet. Thermocouples (T-Type) were used to measure TSC surface temperature and plenum temperature (placed approximately at the centre of the plenum). In addition, a Campbell Scientific (CSI) CR10X data logger was used with an AM 16/32 multiplexer. The system was powered by a 12 Volt DC battery charged by a Solarex 20-Watt PV module through a Sun Selector charge controller (Figure 18). Data was downloaded through a CSI DC112 modem. The Campbell Scientific software PC208W was used to build and compile a program for the data logger and also to communicate with the data logger. All sensors took measurements every thirty seconds, which were then averaged over fifteen-minute periods and the average values were recorded. Instrumentation locations and further details are shown in Table 8 and Figure 19.

Figure 18. Data acquisition system with TSC in background (9).

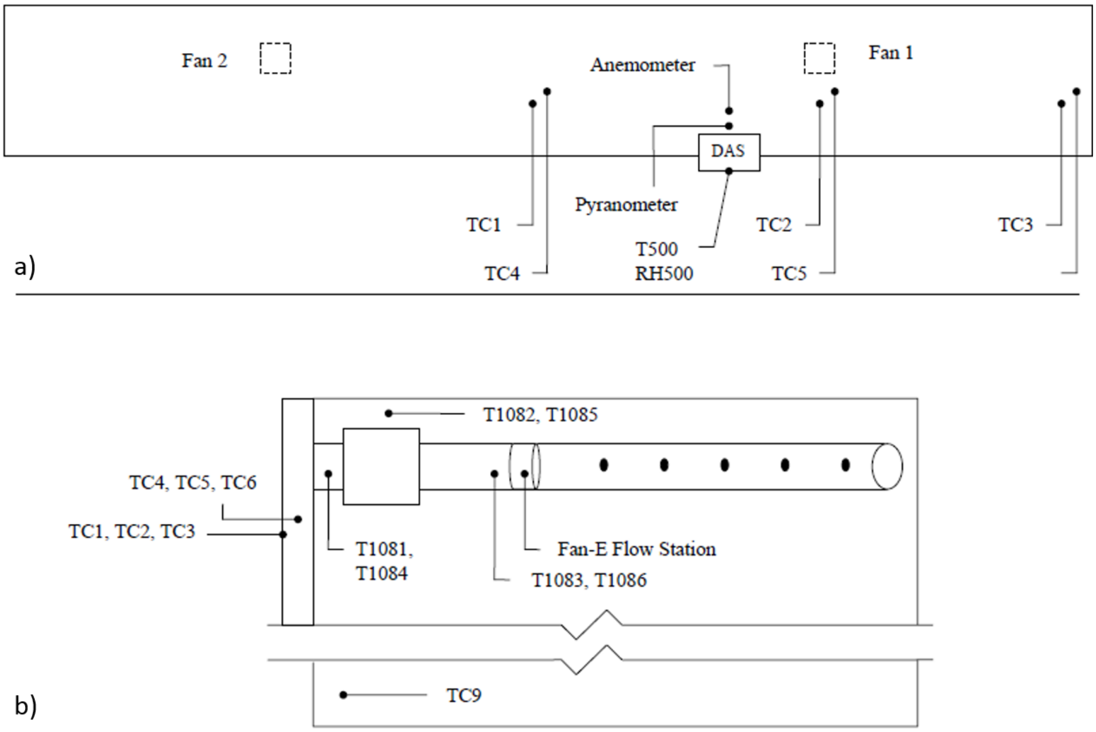


Figure 19. a) South side elevation of TSC wall and sensor placement for data acquisition system; b) Cross sectional view of sensor placement (9).

Table 8. Sensor description for data acquisition system (7).

Sensor ID	Sensor Placement Description	Manufacturer Description
T1081	Temperature sensor Fan 1 Inlet from wall	CSI T108 Thermistor
T1082	Temperature sensor Fan 1 Inlet from ceiling	CSI T108 Thermistor
T1083	Temperature sensor Fan 1 outlet	CSI T108 Thermistor
T1084	Temperature sensor Fan 2 inlet from wall	CSI T108 Thermistor
T1085	Temperature sensor fan 2 inlet from ceiling	CSI T108 Thermistor
T1086	Temperature sensor Fan 2 outlet	CSI T108 Thermistor
T107	Multiplexer Temperature Sensor	CSI T107 Thermistor
T500	Outdoor ambient temperature sensor	CSI 500 RH/Temperature Probe
RH500	Relative Humidity Sensor	CSI 500 RH/Temperature Probe
Fan-E	Outlet from Fan 1 and 2 (7 feet downstream from fan discharge)	Air Monitor Corporation 24" Round Fan-Evaluator
PX277-1	Differential pressure transmitter Fan 1	Omega PX 277 DPT
PX277-2	Differential pressure transmitter Fan 2	Omega PX 277 DPT
TC1	Thermocouple Solarwall® Surface 1 (Middle)	Omega Bolt-On Washer Type T Thermocouple
TC2	Thermocouple Solarwall® Surface 2 (Under Fan 1)	Omega Bolt-On Washer Type T Thermocouple
TC3	Thermocouple Solarwall® Surface 3 (End)	Omega Bolt-On Washer Type T Thermocouple
TC4	Thermocouple Solarwall® Plenum 1 (Middle)	Omega Type T Probe Thermocouple
TC5	Thermocouple Solarwall® Plenum 2 (Under Fan 1)	Omega Type T Probe Thermocouple
TC6	Thermocouple Solarwall® Plenum 3 (End)	Omega Type T Probe Thermocouple
TC7	Differential Thermocouple for Fan 1	Omega Type T Probe Thermocouple
TC8	Differential Thermocouple for Fan 2	Omega Type T Probe Thermocouple
TC9	Thermocouple: Ambient Indoor Temperature	Omega Type T Probe Thermocouple
Wind	Outdoor Wind Speed	NRG Max 40 Cup Anemometer
SoRad	Horizontal Solar Radiation	LI-Cor 200 Pyranometer

The fundamental base used was that the output flow power is the aggregation of the TSC flow power, the ceiling recirculation flow power and the system losses. This can be represented in Figure 20 and the $\dot{m}_{tot}T_{out\ fan} = \dot{m}_{coll}T_{out\ coll} + \dot{m}_{ceil}T_{ceil} + \dot{W}_{in}$ ***Equation 1*** and $\dot{m}_{tot} = \dot{m}_{coll} + \dot{m}_{ceil}$ ***Equation 2*** that follow the heat transfer principles analysed in section 3.2.3.

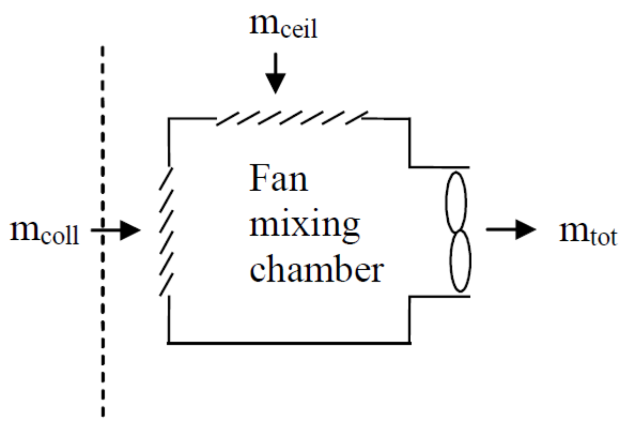


Figure 20. Mass flow balance in the fan mixing chamber (9).

$$\dot{m}_{tot}T_{out\ fan} = \dot{m}_{coll}T_{out\ coll} + \dot{m}_{ceil}T_{ceil} + \dot{W}_{in} \qquad \text{Equation 1}$$

$$\dot{m}_{tot} = \dot{m}_{coll} + \dot{m}_{ceil} \qquad \text{Equation 2}$$

Where[9]:

$\dot{W}_{in}$= work into fan that is not used to move air (heat added to system) (W or BTU/hr)

$\dot{m}_{tot}$= mass flow rate of the fan outlet (kg/s)

$\dot{m}_{coll}$= mass flow rate into the fan produced by the TSC (kg/s)

$\dot{m}_{ceil}$= mass flow rate into the fan produced by recirculation from ceiling (kg/s)

$T_{out\ fan}$= temperature of air leaving the fan and entering the room (˚F)

$T_{out\ coll}$= temperature of air leaving the collector and entering the fan (˚F)

T_{ceil}= recirculated air temperature entering the fan (˚F)

Mass flow rate is defined in $\dot{m}_{tot} = \rho_{out}\dot{Q}_{out\ fan} = \rho_{out}A_d V_{out\ fan}$

Equation 3:

$$\dot{m}_{tot} = \rho_{out}\dot{Q}_{out\ fan} = \rho_{out}A_d V_{out\ fan} \qquad \text{Equation 3}$$

Where:

ρ_{out}= density of air at outlet (kg/m3)

$\dot{Q}_{out\ fan}$= volumetric air flow from fan outlet (cfm)

A_d= cross sectional area of the duct (m^2)

$V_{out\ fan}$= fan outlet velocity (m/s)

[9] These units contain a mix of SI and Imperial units, as appeared in the literature.

Velocity can be related to the pressure using $V_{out\ fan} = \left[\frac{2gP_{abs}}{0.1922\rho_{out}}\right]^{\frac{1}{2}}$

Equation 4:

$$V_{out\ fan} = \left[\frac{2gP_{abs}}{0.1922\rho_{out}}\right]^{\frac{1}{2}} \qquad \textit{Equation 4}$$

Where:

P_{abs}= absolute velocity pressure (inches water column)

The static pressure in the duct and the total pressure at equal area cross-sections was measured through the use of the Fan Evaluator Flow Station from Air Monitor Corporation. The difference between these values gave the velocity pressure, directly related to the velocity of the air ($V_{out\ fan} = \left[\frac{2gP_{abs}}{0.1922\rho_{out}}\right]^{\frac{1}{2}}$

Equation 4).

As it was argued that measuring the solar radiation on a vertical surface instead of the horizontal one could be more accurate, the following steps were undertaken in order to calculate that:

a) Duffie and Beckman (9) equations were used for calculating solar radiation on a tilted (vertical) surface;
b) Verification on the radiation model made using Eppley Precision Spectral Pyranomenter (PSP);
c) Simultaneous radiation measurements on horizontal and vertical surface were made, which were also used to estimate the ground reflectivity.

The heat delivered to the building the TSC effectiveness and efficiency were calculated using the thermal performance indicators (as presented in section 3.1.2.). Radiative and convective heat losses were not monitored; however, through laboratory tests they could be correlated with the heat effectiveness and collector's design parameters (Duffie and Beckman (9), Kutscher (10), Kutscher et al. (11), Kutscher (12), Cali et al. (2), Van Decker et al. (13)). In this study no estimation on wall heat contribution was made. An analysis on the pressure drop through the collector and the plenum was made; however, in this field experiment there was no pressure drop data and, therefore, it was calculated by using previous studies (8).

The system was monitored for twenty-four days, after the new control system was installed. According to the measurements, the air flow rate was about 14,270 to

14,610m^3/h, which corresponds to 51.5 to 52.7m^3/h per m^2 of collector area. Compared to the design air flow rate, which was 20,390m^3/h (or 73.6m^3/h per m^2 of collector area), the measured air flow rate is lower. The measured air delivery mass flow rate was taken after the recirculation, which means that the actual TSC flow rate would, at times of mixing, be lower than the measured air flow rate.

There is a generic monitoring comment in the source on low quality measurements because of instrumentation fault positioning, high uncertainties and TSC construction and controlling mismatches.

The measured temperatures were demonstrated, and the temperature rise in the collector was related to the solar radiation. Temperature stratification was also studied and plotted against time for a 3-day period showing a difference of up to 2°C during non-sun hours between floor level and ceiling (Figure 21). The instantaneous efficiency was calculated and compared with Kutscher's and Van Decker's models for efficiency prediction. Measured and modelled efficiency was also plotted against plate and ambient temperatures showing results that agree with the analysis in section 3.2.

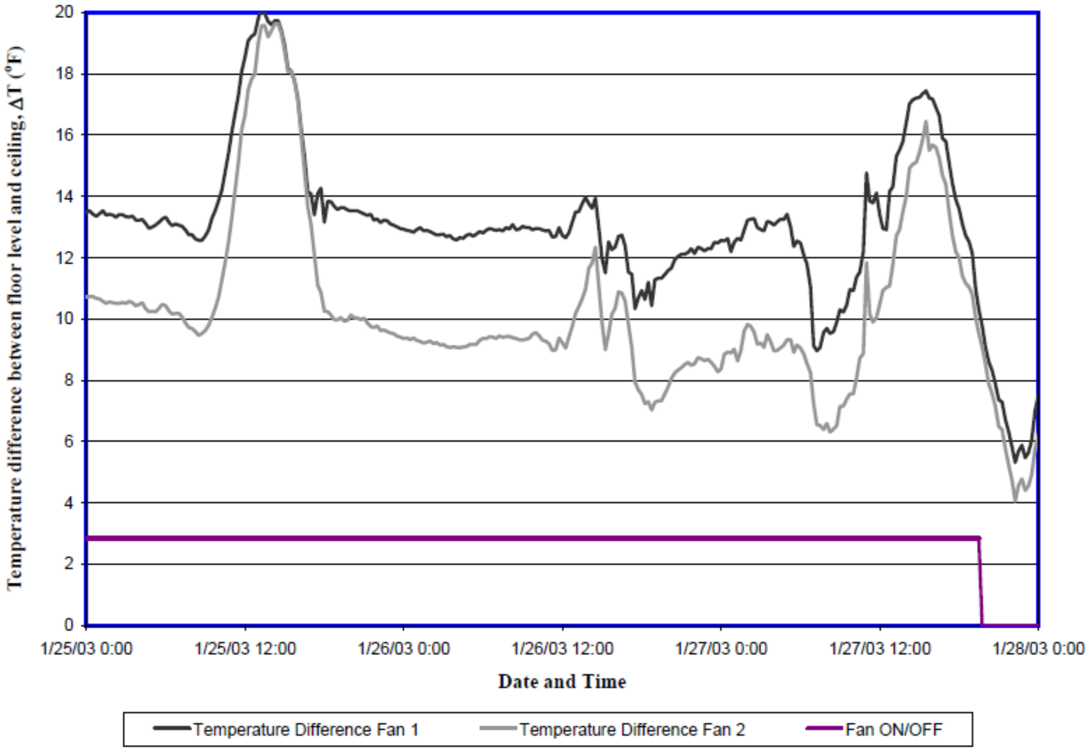


Figure 21. Air temperature difference between ceiling and floor level (9).

The delivered heat for February and March 2003 ranged from 263.8 kWh/day (0.9 MMBTU/day) to 586.1 kWh/day (2 MMBTU/day), which corresponds to about 1 kWh/m^2day to 2.1 kWh/m^2day.

The total system cost[10] for 2020 values is £66,870 and included £141 for each m^2 of the TSC collector, £2,034 shipping and miscellaneous costs and £25,692 for the cost of equipment independent of the collector. Moreover, a brief economic evaluation was performed. A three-phase power meter was used to measure the energy consumption of the fans. The energy cost was estimated and interpolated for a six-month period. The energy gain of the TSC was financially compared to a potential gas system with the same energy delivery and assuming an efficiency of 80%. The cost savings were estimated at about £216 for the 24-day period, taking into account the TSC's operation cost of about £7-10 for the same period.

8. BigHorn Home Improvement Centre, Colorado, US – warehouse

Design

The BigHorn Home Improvement Centre in Silverthorne, Colorado, US, is a new building with a floor area of about 4,000 m^2. A TSC was installed on the south façade, covering an area of 209m^2 (**Error! Reference source not found.**) and was studied b y Deru et. al. (14). The TSC delivers heat independently to the building, alongside a hydronic radiant floor system and gas-fired radiant heaters. A simulation model for the whole building was first created, run and evaluated, followed by recommendations to be taken on board during the construction phase. One of the recommendations suggested that the TSC should have as large an area as possible to minimize the load on other heating systems in the warehouse space, so the size of the TSC was informed by the available area on the south facade. Thermostatically controlled ceiling fans were also installed to prevent thermal stratification in the high ceiling areas.

[10] Note that costs related to a 2004 reference was converted to USD 2020 cost accounting for USD inflation using https://www.usinflationcalculator.com/ and then converted to GBP using an exchange rate of 0.81 (USD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

Evaluation

The building was monitored for 2.5 years after it was constructed (during 2001-2003); however, there was no individual monitoring for the TSC. Changes to the building's operation and control sequences were made during this period to improve the energy performance, but there is no specific information on these. One of the lessons learnt from this installation was that the TSC was not effective in this building (14). This was due to the fact that the warehouse always had at least one large overhead door open during business hours, so the space could not be effectively heated as most of the TSC delivery was lost through the open door. In addition, for the September 2002–August 2003 monitoring year, the TSC system operated in a limited way, as the two TSC fans ran only about one-third of the days in the heating season for 2 to 3 hours during the day. Moreover, the low temperature and low velocity warm air that was delivered through the fans near the ceiling, would not affect the occupied part of the space, so it is believed that the thermostatically controlled ceiling fans were not effective either. In addition to the above comments, the author of this work highlights multiple shading effects in a variety of solar paths (Figure 22(), caused by the driver to use the whole south elevation.

Figure 22. TSC on the south wall of the warehouse (16).

9. CA Group Roll Mill – industrial

Design

A TSC collector of an area of 410m^2 was installed on the south vertical wall of CA Roll Mill (Figure 23), which is an industrial building in Evenwood, County Durham, UK

(15). The control system included a recirculation and a bypass system including three dampers (TSC, fresh air and recirculation). Three ducts with fans drew air from the TSC at a rate of about 0.94 m^3/s each, which corresponds to about 45 m^3/h per m^2 of TSC and delivered it inside the building through perforated distribution ducts placed close to the ceiling.

In terms of the control system, three temperatures were considered: Outside temperature (T_{out}), inside temperature (room temperature) (T_{room}) and temperature in the TSC duct (T_{TSC}). The following algorithm was continuously run:

- If $T_{room} < 18°C$ and $T_{amb} < 16°C$ and $T_{TSC} > T_{room} + 2°C$ from 07:00 to 19:00, then solar heated air is delivered through the TSC.
- If $T_{room} < T_{TSC} < T_{room} + 2°C$, from 07:00 to 19:00, then solar heated air is delivered through the TSC and recirculated air.
- If $T_{room} > 18°C$ and $T_{amb} < T_{room} - 2°C$, then fresh air was delivered (using bypassing system).
- If $T_{amb} \geq 16°C$, then fresh air or recirculated air was delivered (using bypassing system).

In addition, the room temperature set point between 19:00 and 07:00 is 14°C. If there is no heat available from the TSC, heat is provided independently by a gas fired heater.

Figure 23. TSC installation in progress for the CA Roll Mill building in Durham, UK, showing the location of thermocouples (17)

Evaluation

The monitoring process followed the stages below:

a) Monitor and produce building energy performance report of the existing building.
b) Monitor the effect of TSC installation on energy costs and develop a payback period model.
c) Develop a monitoring standard procedure.

It should be noted that only about 18% of the total TSC area was monitored, which corresponds to about 75m^2, and no explanation is given on that. One of the objectives was to monitor the TSC performance and the effect of the ventilation system on the energy efficiency of the building. Therefore, BSRIA monitored this retrofitted installation for one year, from April 2006 to March 2007.

Gas consumption data was used to indicate heating energy consumption for previous years. To study the gas and electricity consumption history of the building, bills from the last five years were analysed. Only the data for the last of these five years (2005/2006) was normalised against weather changes based on historic degree days. This data served for comparison with monitored data in 2006/2007. During the monitoring period, gas and electricity consumption was derived from readings taken five times per day.

Regarding instrumentation, a total of 36 thermocouples were used for the monitoring process. An array of 32 thermocouples was installed in the TSC plenum, following a grid structure of 8 x 4 (width x height) with horizontal spacing of 1.70m and vertical spacing of 1.38m, covering the aforementioned area of 75m^2. When fixing the thermocouples to the wall using strong adhesive tape, it was ensured that their tip is 10mm away from the wall surface. Two thermocouples were placed in the delivery duct (Figure 24) to measure the delivery temperature of the TSC collector. It was installed a few meters away from the fan to avoid any mixing unbalance conditions. One thermocouple was placed in the building to measure shop-floor temperature and one outside below the TSC to measure outside temperature. A radio sensor was used to record delivery duct temperature of the TSC system.

Figure 24. Location of thermocouples within building (17).

A pyranometer was also installed on the TSC to measure solar radiation. It was calibrated in a horizontal plane having unobstructed view over a full hemisphere. It was placed on the vertical plane and it was estimated that it its uncertainty was ±7%.

In order to study the stratification, five temperature sensors with a local data logger were distributed in the room to capture the temperature gradient over the 6m height of the building. Regarding logging equipment, an Agilent 34970A data-logger plus a 20-channel multiplexer, connected to a PC in the building, was used. Data was saved every 5 minutes by the PC and was further saved to a file every night and collected every week by BSRIA.

The delivered energy (Q_{del}=$\dot{m}_{tot}C_p(T_{duct}-T_{room})$ E quation *5*) by the TSC was calculated using the heat transfer equation analysed in 3.2.3.

$$Q_{del} = \dot{m}_{tot}C_p(T_{duct} - T_{room}) \qquad \textbf{Equation 5}$$

It is important to note that the temperature difference being considered is now the difference between the room temperature and the duct temperature, whereas previously it was the difference between the ambient outdoor temperature and the temperature of air leaving the fan and entering the room. This equation is used to calculate the actual heat delivery assuming that the TSC is replacing a system that recirculates air. If recirculation is not considered, then T_{amb} should be used because the 100% of the air would be delivered from outside. Figure 25 presents the virtual display that was produced to show the important measurements and calculations.

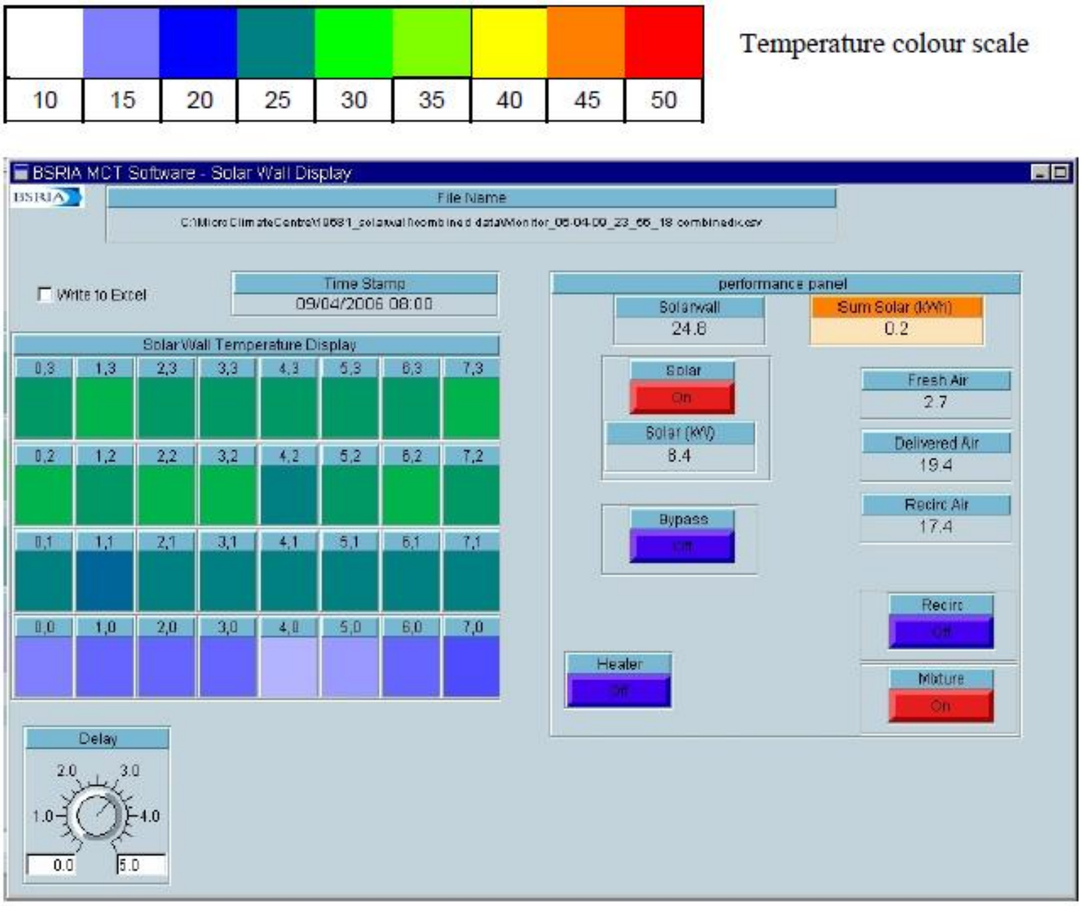


Figure 25. Overall output display (15). The temperature values of each thermocouple in the 8x4 array in the TSC plenum are depicted on the left of the picture in a similar 8x4 array. It is shown than for a day in April 2006 at the particular timestamp (08:00), the monitored TSC temperature was in the range of 12-28°C.

Table 9 presents fossil-fuel energy consumption for 2005-2006 and for 2006-2007 normalised based on degree days. The table shows the savings in kWh/dd and the energy delivered from the TSC system in kWh per month of the monitored period. As shown there, the annual savings amounted to 79,191 kWh, which corresponds to 193.1 kWh per m^2 of TSC and amounts to 21% of total heating requirement.

Table 9. Overall TSC contribution (15).

Month	2005/6 consumed (kWh)	2006/7 consumed (kWh)	2005/6 dd	2006/7 dd	2005/6 kWh/dd	2006/7 kWh/dd	Saving in kWh/dd compared to 2005/6	TSC Energy delivered (KWh)

Apr	64754	40000	223	221	290	181	38%	9396
May	41357	6709	152	147	272	46	83%	4776
Jun	6700	1023	66	58	102	18	83%	1626
Jul	0	62	38	26	0	2	0%	902
Aug	1729	85	45	37	38	2	94%	1438
Sep	9948	52	69	34	144	2	99%	2892
Oct	37541	13980	102	102	368	137	63%	7661
Nov	74563	45855	345	306	218	120	45%	25075
Dec	75316	36855	345	306	218	120	45%	25075
Jan	90721	56930	358	274	253	208	18%	4428
Feb	96076	44976	306	281	314	160	49%	2310
Mar	100751	49796	353	264	285	189	34%	9616
Total	**599456**	**295913**	**2345**	**1975**	**2545**	**1266**	**50%**	**79191**

In order to present the performance graphically, temperature variations and energy delivery was presented. The beneficial effect of TSC in destratification was also demonstrated by averaging temperatures from sensors in different heights (5 sensors at 6m range). The TSC started operating on 19th of April and the reduction in temperature variations can be observed in Figure 26. By using the TSC only when heat was available, the average stratification was reduced by 0.36°C, but when the ventilation system operated full-time, the reduction was 3.65°C.

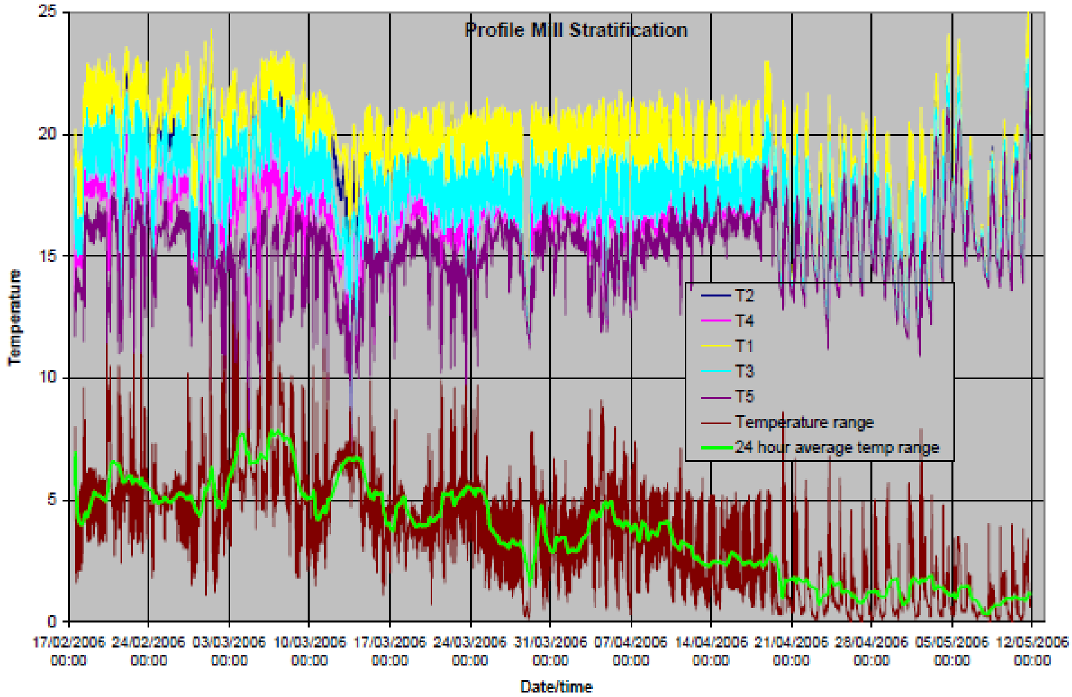


Figure 26. Graph showing air stratification from 17th February to 12th May with stratification reductions from 19th of April (15). T1, T2, T3, T4 and T5 indicate the temperature reading from the 5 sensors distributed in the building over the height of 6m to monitor destratification.

CO2 savings were calculated through the reduction in natural gas for heating (as presented in Table 9) between 2005/2006 and 2006/2007 and these amounted to 58.9 tonnes. However, these savings include additional savings to the ones associated with the TSC due to the much fewer degree days compared to 2005/2006. Based on the lessons learnt through the monitoring, some recommendations were outlined for future installations. These included the optimisation of the orientation based on the building's heating requirements, the utilisation of the high temperature air produced in summer and matching the TSC size to the fresh air and heating requirements of the building.

10. Broiler barns, Canada – industrial

Design

A vertical TSC installation on the south-east wall of two three-storey broiler barns at an angle of 50° from the south was undertaken in Canada in 2007 and studied by Cordeau 2010 (16) and Cordeau and Barrington 2010 and 2011 (17, 18). Despite the fact that the case study does not serve human heating and ventilation demand, it has a great value in analysing evaluation methods used. The TSCs had a black corrugated metal sheet with perforations covering 1% of its surface and covered an area of 73.6m2 per floor, totalling an area of 221m2 per barn. It is noted that no rationale is provided for the sizing of the TSC. Each floor of the two barns was equipped with two natural gas heaters on the two sides of each floor, adjacent to the TSC wall, at a height of 1.5m at both ends of the floors and on the TSC fresh air inlet side providing 30kW of net sensible heat each. A bypass function was also provided by opening the door at the bottom of the TSC's wooden box frame. Two or three fans with an inner cross section of 400 mm were in operation on each floor.

During the heating season and when the broilers were introduced in the barns, only two fans operated initially on each floor at a minimum speed of 55%, delivering fresh air at 0.43 m^3/s. The speed of these fans was increased automatically from 55 to 100% over a temperature increment of 1.4°C, which was informed by the indoor temperature measurements from T_1, T_2 and T_3. The temperature set-point was 32°C and dropped at a rate of 0.27°C/day until it reached 24°C. After one to three weeks, a third fan started to operate on each floor, so the three fans provided fresh air ventilation until the end of the batch. The TSC air flow rate remained between 0.83 and 1.17 m^3/s which is equivalent to 42 and 57.2 m^3/h per m^2 of TSC.

Evaluation

The TSCs were monitored over two heating seasons, that of 2007-2008 and 2008-2009 (November to March), starting when a new batch was introduced in the barns until the batch was sent for slaughter.

The temperature at all floors of both experimental barns was recorded at 5-min intervals through the use of six Smart Set Hobo sensors (Onset Computer Corporation, Pocasset, MA, USA), as shown in Figure 27. The indoor air temperature of each floor was measured at three locations at a height of 0.3 m (T_1, T_2 and T_3). The incoming fresh air temperature was measured at two locations in the TSC (T_5 and T_6) and one more temperature sensor was installed at one of the exhaust fans (400 mm interior diameter) which was in continuous operation (T_4) (Figure 28). The ventilation rate was monitored by recording the speed of one fan using an electromagnetic converter. The air flow rate was computed using a Balometer and the volumetric air displacement of all fans was measured at speeds varying from 55 to 100%. A 5V AC adapter was used to record the operating time of the natural gas heaters at 5-min intervals.

Figure 27. TSCs on the south-east wall of the two broiler barns in Canada, showing the bottom by-pass door (20).

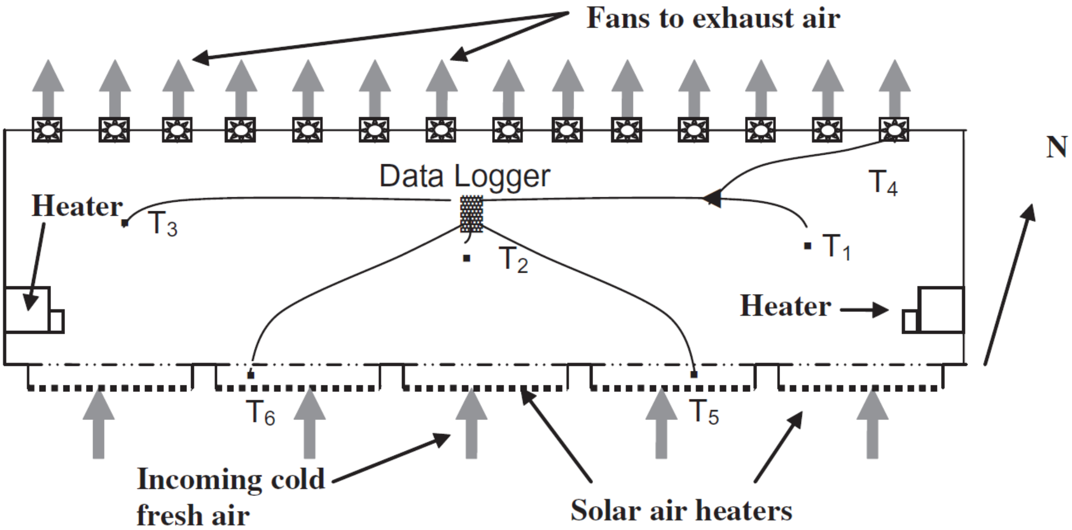


Figure 28. Experimental barn instrumentation: sensors T1, T2, T3 at 0.3m off the floor to monitor indoor temperature; T5 and T6 in TSC to monitor air inlet temperature; T4 on fan to monitor exhaust air temperature (20).

Average efficiencies reduction with wind speed increase was recorded (analysed in 3.2.4). The highest efficiency recorded at 64% whereas lower efficiency was at 35%. When in bypass mode, although there was still some heat delivery, the efficiency was lower than 20% and decreased by 4% for every 1m/s of wind speed increase. Figure 29 shows the energy contribution of 148kWh by the TSC to the heating load (labelled: “Energy recovered”) on a day in March. The total energy savings[11] derived during the two years of TSC monitoring amounted on average to 185 kWh/m^2 per year while the cost savings amounted to an average of Can$14.80/m^2. Given the annual return on investment value of 4.7% cited in the study, the initial investment cost has been calculated to be about Can$315/m^2, which is equivalent[12] to about £209/m^2 in 2020.

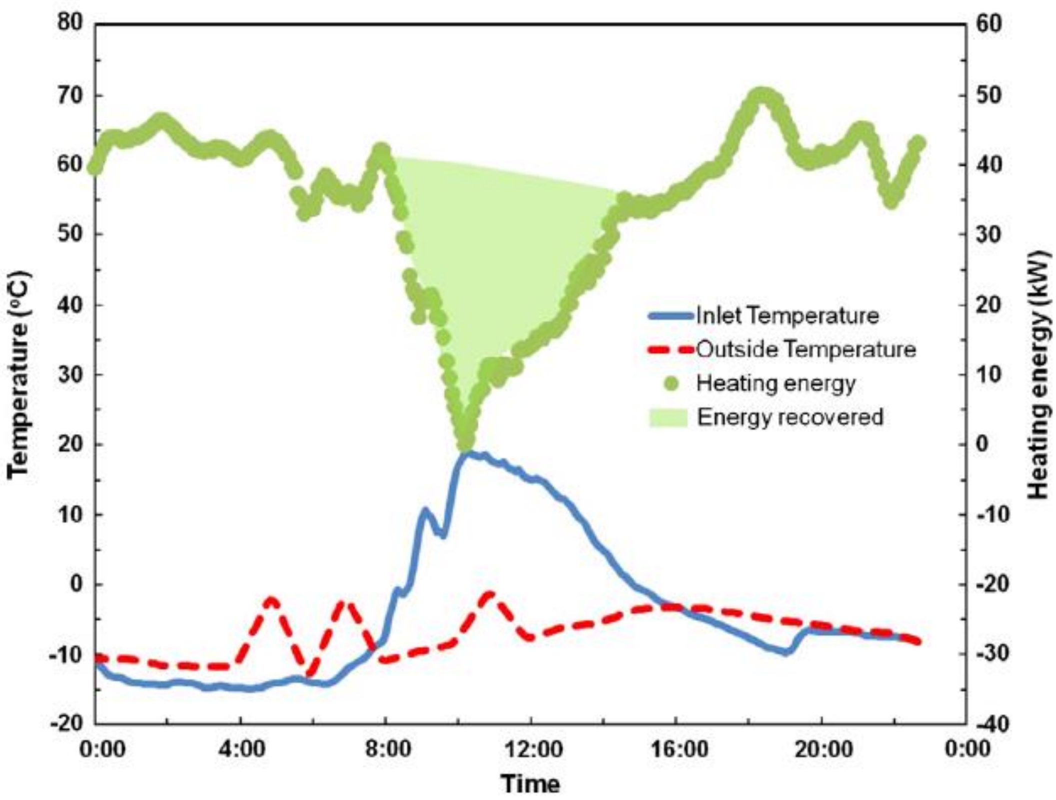


Figure 29. Heating load and inlet fresh air temperature on a representative day (4th March 2009). Total heat delivered was 148kWh (20).

[11] The total energy savings were derived by dividing the average cost savings by the energy cost per kWh mentioned in the same source, which is Can$0.08/kWh.

[12] Note that costs related to a 2011 reference was converted to CAD 2020 cost accounting for CAD inflation using https://www.bankofcanada.ca/rates/related/inflation-calculator/ and then converted to GBP using an exchange rate of 0.58 (CAD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

11. PIMSA Automotive production plant, Turkey – manufacturing/office

Design

A TSC system was installed vertically on the south façade of the multi-storey PIMSA Automotive production plant in Turkey in 2012 and analysed by Eryener and Akhan (19) (Figure 30). It covers an area of 770m2 and it has a pre-heat and recirculation function. It is connected to six air handling units (AHUs) to top-up heat when the solar resource is not sufficient. The design intent was to improve the air balance and comfort of the building, while displacing onsite auxiliary heating fuel consumption. Six fans were connected to the TSC, each of which has an air flow rate of 2.95m^3/s and is connected to one of the six AHUs. This is an equivalent air flow rate of 82.8 m^3/h per m^2 of TSC. Also 24 automatic damper controllers connected to a BMS.

Figure 30. The TSC installation on the south facade of PIMSA Automotive production plant in Turkey (22).

Evaluation

Monitoring took place during 6 months, split into two periods; the first one was between February-April 2013 and the second one was between January-March 2014. The monitoring equipment included 6 thermocouples embedded in the TSC, 6 in the delivery duct, 2 inside the building and one outside on the wall below the TSC. The authors claim that the monitoring outputs are consistent with the simulation outputs from RETScreen. The delivered energy was measured to be 113,037kWh and 246,924kWh for the three months in 2013 and 2014 respectively. This means a delivery of approximately 1.63kWh and 3.56kWh per m^2 of TSC per day respectively for the two monitoring periods in 2013 and 2014. The highest temperature rise was measured to be 45°C and up to 100% of heating energy saving was achieved during sunny days. Figure 31 shows the performance of the TSC through mapping of the TSC on the building heating power.

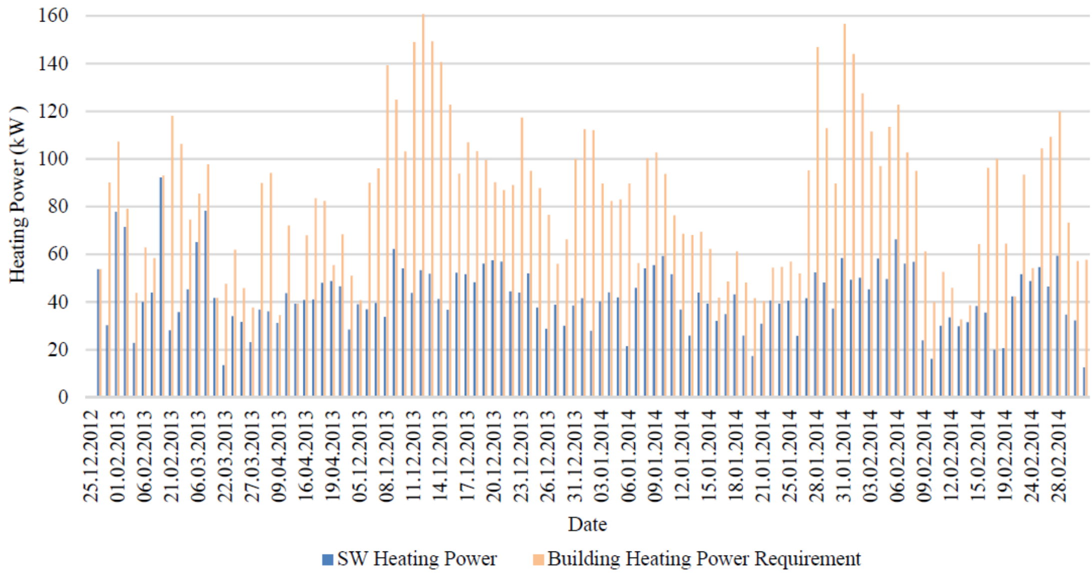


Figure 31. TSC heating power mapped on the building's heating requirement (21).

12. Wal-mart Supercenter, Colorado, US – commercial

Design

The Wal-mart store hosts a TSC on its nearly vertical south wall (Figure 32), covering an area of approximately 743m^2 and has pre-heat and recirculation functions. It was installed in 2006 and its performance was studied by Kozubal et al. in 2008 (20). The design intent behind the sizing of the collector was for it to provide both warm air for the ventilation needs of the building and space heating. However, it looks like the dual function of the TSC was an afterthought, as the literature states that the TSC was oversized for ventilation air preheating (20). Roof-top units (RTUs) attached to the TSC had a minimum and maximum air flow rate of 20,855 m^3/h and 76,941 m^3/h respectively, corresponding to normalised values from 28 to 104 m^3/h per m^2 of TSC. The TSC is also connected to 11 smaller RTUs and two large air handling units (AHUs), which distribute the air inside the building. One of the control strategies in order to employ the space heating function of the TSC includes the rapid response of the RTUs and AHUs when space heating is required. The air temperature supplied to the space can reach up to 32.2°C if needed when mixed with return air.

Figure 32. TSC installed on south wall of the Wal-mart store in Colorado (23)

Evaluation

The system was monitored for 2 months during January and February 2007 in order to evaluate its performance by measuring the delivered heat. The monitoring was performed in 15-minute intervals and the outputs are shown in Table 10. The delivered energy was on average 15 kWh/m^2 per month.

Table 10. Measured performance outputs by TSC for the monitored period (20).

	January 2007	February 2007
Incident solar energy on TSC (MWh)	123	112
Collected energy (MWh)	16.2	20.5
Delivered energy (MWh)	9.6	12.8
Delivered energy efficiency	8%	11%
Collected energy utilisation	59%	64%

It is shown that although January had higher incident solar radiation on the TSC, there was 25% less delivered energy. This happened largely because the AHUs would be forced to reduce the air flow or even shut it off when the ambient air was below freezing due to the presence of internal water coils, which constituted a design problem. This would happen even though the air delivered by the TSC could be above 0°. For a better understanding, the plot of the delivered energy versus the incident solar energy is depicted in Figure 33 . The maximum energy efficiency was 56%, which was achieved when the air flow through the TSC was close to maximum (104 m^3/h per m^2 of TSC). Moreover, as shown in Figure 33, the number of points with positive energy delivery are aggregated above 400 or 500 kWh of incident solar energy, which is attributed to programming bugs in the control system. This meant that there was a substantial amount of time during which, although solar resource was favourable, little or no air was drawn through the TSC. This resulted in a relatively low average energy efficiency of about 8% for January and 11% for February (Table 10). The low efficiency is also attributed to the low mass flow rate.

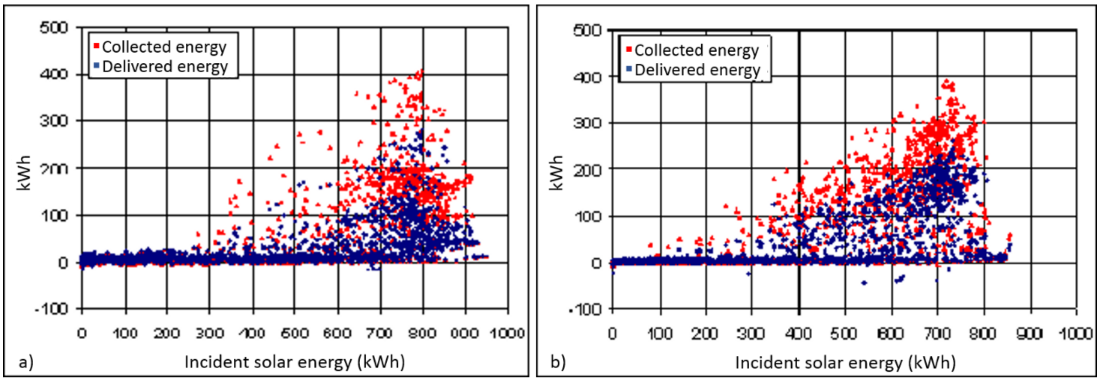


Figure 33. Delivered energy by TSC versus incident solar energy for a) January 2007 and b) February 2007 (23).

In addition, in Table 10 the collected energy is higher than the delivered energy, due to the fact that top-up energy was required to heat the incoming air to reach a temperature equal or higher than the current indoor one, which was not counted in as delivered energy. This is an important consideration, as energy collected from the TSC when the air flow rate is higher than the ventilation rate needed to be delivered above return air temperature in order to counterbalance gas use. So under the existing heat strategy, only about 60% of the collected energy was utilised during the two monitored months, which means that the system can be economically ineffective (Figure 34).

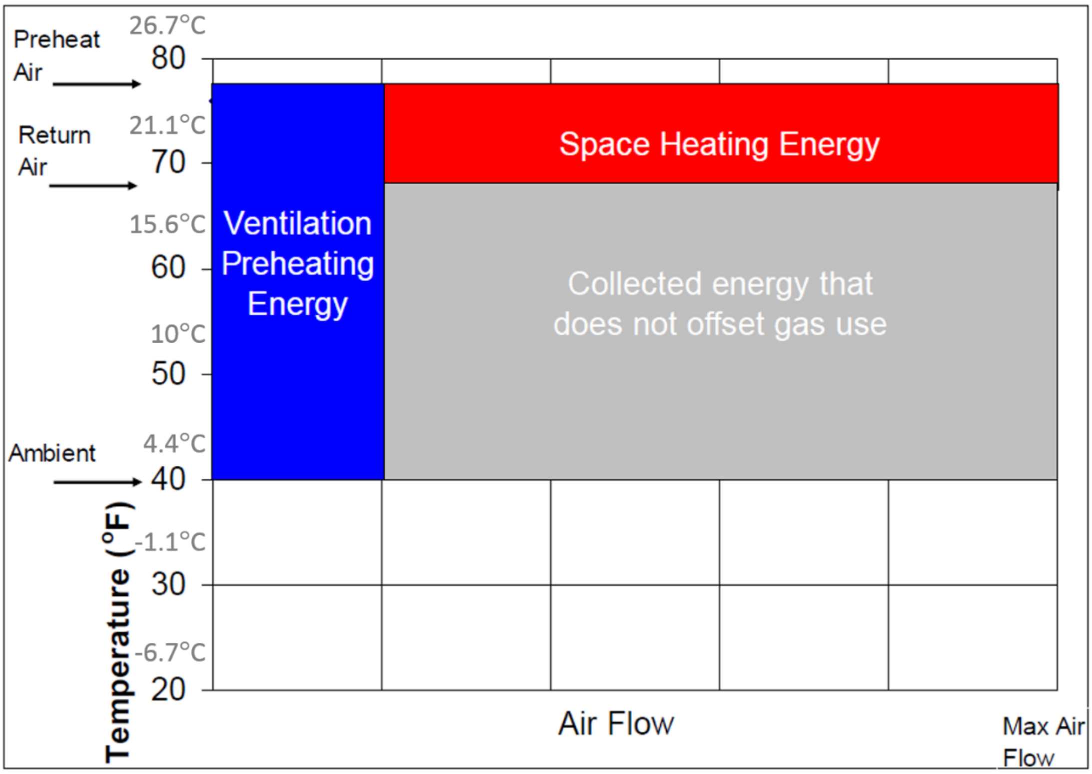


Figure 34. Example of delivered energy portion (red and blue) of total collected energy for a given preheat temperature. The rectangle areas are proportional to energy. Adapted from Kozubal et al. 2008 (20).

The findings suggest that the TSC system had been underperforming due to the non-effective utilisation of the solar resource and more specifically due to implementation and control strategy issues. By mitigating the above shortcomings, an improved system performance could be achieved. For example, the air velocity through the TSC could be raised up to 0.03m/s if the preheated air flow is maximised when solar resource is favourable. Another recommendation was related to the effective distribution of ventilation air, which could enable the immediate zone temperatures to rise higher during the day and preheat the building during the night. However, as the underlying intent of these recommendations was to modify the control strategy while continuing to use the existing infrastructure, no solution could be given to the issue with the AHUs's preheat air flow reduction during very low temperatures. With the recommended changes the system performance could be improved and based on simulations, it was estimated that it could achieve efficiencies of over 50%, as shown in Table 11. It was predicted that the delivered energy could reach on average 73.4 kWh/m^2 per month. Finally, with regard to the cost, it is argued that the installation cost target[13] would be about £136/m^2 of TSC absorber for all climates and similarly for a modular design, the cost target would be £187/m^2 in 2020 values.

Table 11. Estimated performance outputs considering recommended changes for the monitored period 2007 (20).

	January 2007	**February 2007**
Incident solar energy on TSC (MWh)	113	106
Delivered energy (MWh)	56	53
Delivered energy efficiency	50%	50%
Improvement from monitored outputs	486%	316%

13. Windsor Housing, Canada

Design

A corrugated TSC of 335m^2 and dark brown colour was installed on the south wall of the Windsor Housing building in Canada as part of a renovation project in 1994. The recladding was studied by Hollick in 1996 (21). The intent behind this installation (Figure 35) was to repair the south façade, improve the aesthetics of the building and to reduce heating costs during the 8-9 months per year that heating would be required. The diameter of the holes on the TSC is 1.5mm. The system was a pre-heat for 6 gas-fired heaters used in conjunction with the TSC. No additional fans were employed, as the existing ones were used to duct the air along the roof through the gas heaters. The air flow rate was 69m^3/h per m^2 of TSC and the system supplied 28% of the ventilation heating requirements. In addition, bypass dampers were used. when the ambient temperature was over 20°C.

Evaluation

There was no energy performance monitoring in this case study. Both Hollick (21) and Hastings (6) claimed that the annual average delivered energy was 584kWh/m^2. This figure is based on computer simulations that estimated annual energy savings of 195,700 kWh, as well as from monitoring results from another apartment building

[13] Note that costs related to a 2008 reference was converted to USD 2020 cost accounting for USD inflation using https://www.usinflationcalculator.com/ and then converted to GBP using an exchange rate of 0.81 (USD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

(6). Regarding costs, the cost[14] of the TSC system over a conventional cladding system was an additional £92/m^2 of TSC.

Figure 35. The TSC installation on the south wall of Windsor Housing Authority building (6).

[14] Note that costs related to a 1994 reference was converted to USD 2020 cost accounting for USD inflation using https://www.usinflationcalculator.com/ and then converted to GBP using an exchange rate of 0.81 (USD to GBP); https://www.xe.com/, accessed at 12/05/20 was used for the conversion.

Hollick stated that “If more wall area is available, the solar heated air could be used for both the corridors and common areas as well as the apartments adjacent to the SOLARWALL@ panels. Roof mounted panels are possible where snow is not a problem or if the roof slope is steep enough for snow to slide off.” (21).

14. House in Judgeford, New Zealand

Design

A Wellington architect designed a house utilising TSC technology in Judgeford, New Zealand in 2005. The TSC implementation was studied by Heinrich in 2007 (22). Six black aluminium TSC panels of different dimensions with a total area of 28.1m^2 and a porosity of 1% were installed vertically on the north façade of the house on walls A, B, C, D, E and F (Figure 36). The area of the panels, the maximum air flow, the duct length and the supplied rooms as well the fan’s type and power are illustrated in Table 12.

Figure 36. Elevation and location of TSC cladding (22).

Table 12. Details of TSC panels (22).

Wall	Area (m^2)	Max air flow (l/s)	Duct length (m)	Supplied room	Fan specs	Power input fan (W)
A	6.4	60	6.5	Downstairs open plan	TD-500/150	68
B	4.5	45	7	Downstairs bedroom	TD-500/150	68
C	4	50	2	Upstairs bedroom	KS 130/2E	40
D	4.6	101	5.5	Upstairs living room	TD-500/150	68
E	4.6	30	9*	Downstairs bedrooms	TD-500/150	68
F	4	43	1.5	Kitchen/dining	KS 130/2E	40

*of which 5 m have a vertical downward airflow

No preheating or recirculation function, nor bypass controls were mentioned. Separate fans and controllers were provided for each TSC and two types of fans were used as shown in Table 12. The TSCs on walls A, B, D and E were provided with variable speed fans (TD500/150 from Fantech) in order to have higher control over the heat transfer in the room, while walls C and F with on/off fans. Subsequently, depending on the fan type, different controllers were installed. The maximum air flow of the fans ranges between 30 and 101 l/s, which translates to 23.5 and 79 m^3/h per m^2 of TSC. The components of the control system, including the controller, converter, two transformers and fan speed driver module. Each controller used two temperature probes for operation; one inside the room and another one in the TSC before the fan. The control algorithm was as follows:

- If $T_{duct} > T_{in}$ and T_{duct} > set point, then activate fan;
- If T_{in} > set point, then stop fan (set point was usually set at 20°C but could be adjusted by the user).

The ability of speed variation was found unnecessary due to the large volume of the rooms and the system's high response time.

Evaluation

The TSC performance was monitored during 2007. An Agilent 34980A with 2 data cards (80 channels) was used as a data acquisition system and was placed in the house with wiring communication. Its storage capacity was 500,000 readings and when this was reached, the data needed to be downloaded using a laptop. Data were recorded every 3 minutes to capture the variable fan speed and ensure higher data accuracy, which allowed for 13 days of continuous data acquisition without downloading. Regarding temperature monitoring, type-T thermocouples were used, which were connected to the logger. An additional reference temperature sensor incorporated in Agilent was also used. In addition, 5 thermocouples (fixed to battens) were installed for each TSC (Figure 37) to observe temperature variation within the panel by measuring the temperature within the air cavity. A duct temperature sensor (thermocouple) was also placed at the centre of each duct (at least 2m away from the fan) (Figure 38). Room temperature was measured at several points in every room using thermocouples and another probe was also used to control the fan. Three thermocouples were installed around the house at unexposed places and away from direct sunlight to monitor outside temperature; however, the position of these sensors is not specified. Fan speed was measured by using the 0-10V signal from the controller and was transformed into actual airflow through the use of mathematical equations. The solar radiation was monitored using a small solar cell at each TSC panel, whereas the cell had already been calibrated by a pyranometer.

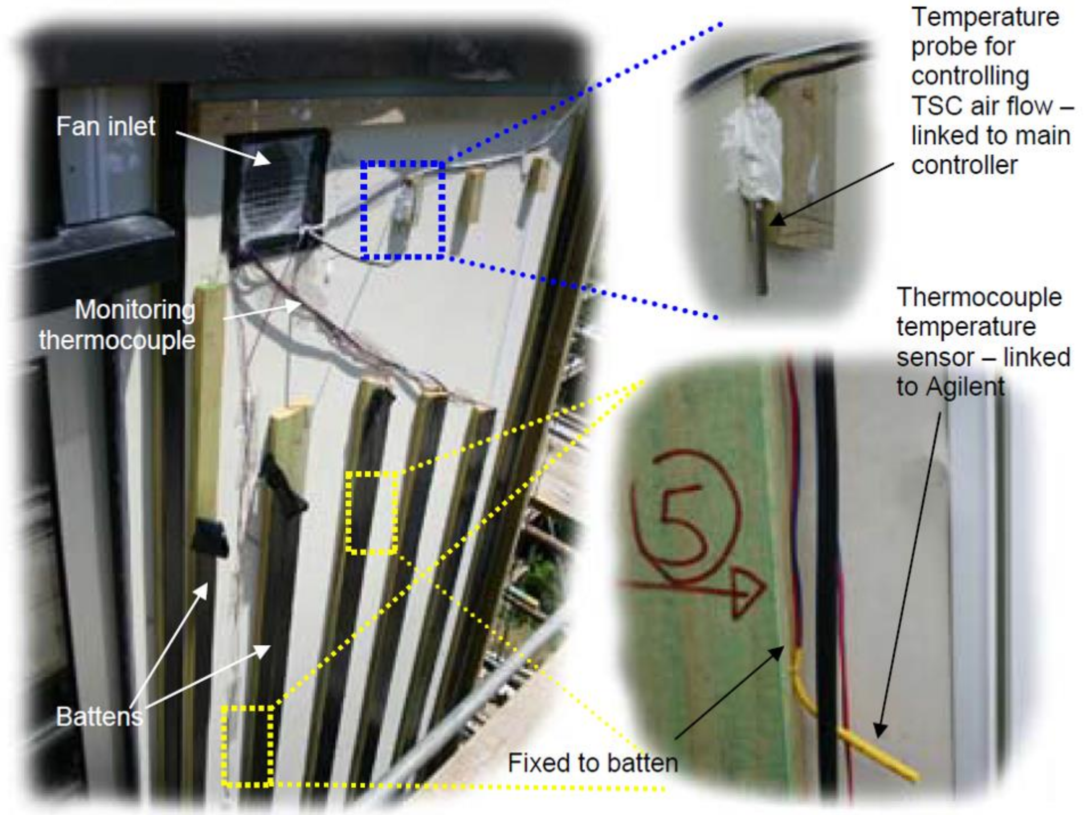


Figure 37. Monitoring and control sensors behind TSC panel (22).

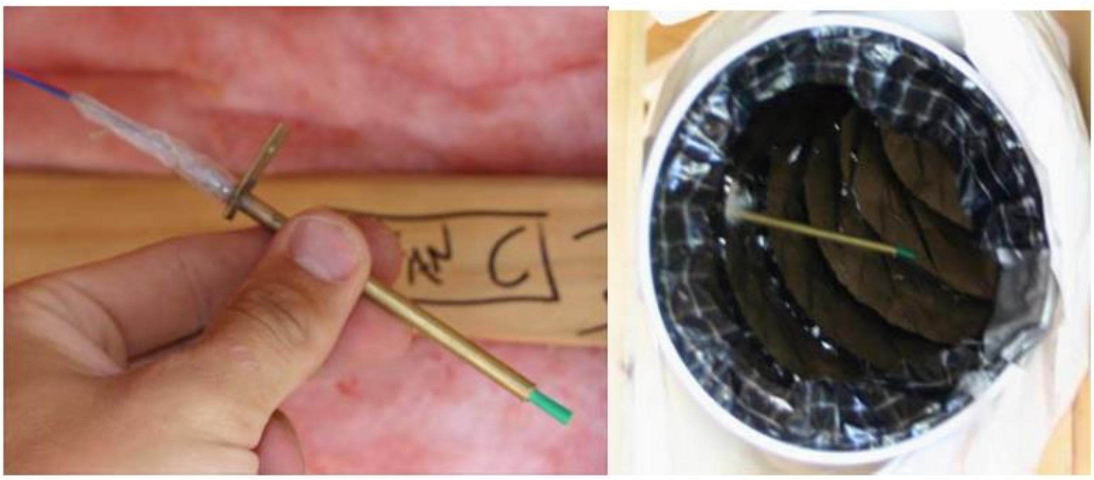


Figure 38. Temperature sensor in duct (22).

Each panel was investigated separately indicating that output temperature variations are affected by shading, flow rates and ducting length. Solar radiation against TSC power output was studied to calculate the TSC efficiency and the maximum values are presented in Table 13. The efficiencies ranged from 15 to 54% with the highest being achieved by Wall D and the lowest by Wall E. This might be seen as an odd finding, considering that the two walls are adjacent and identical; however, the ducting length and most importantly the flow rate they use differ.

Table 13. TSC efficiencies (22).

	Max power (W/m^2)		
Wall	**Output**	**Input (from graphs)**	**Efficiency (%)**
A	N/A	N/A	N/A
B	175.36	475	37
C	281.48	1000	28
D	537.21	1000	54
E	147.55	1000	15
F*	0	N/A	N/A

*After analysis was completed, wall used for cooling during the night-time (manually)

Delivered energy and maximum power are presented in Table 14; whereas fan power and consumption are shown in Table 15. Apart from the highest energy output, Wall D achieved the highest power output which is an indication of how much the mass flow rate impacts heat delivery. The average operating time of the fans was from 2 to 4.5 hours per day respectively. It was suggested that in order to reduce the consumption, the operating times of the fans could be reduced by increasing the temperature difference between the TSC wall and the room. This would result in higher temperature air drawn in a shorter period of time, thus reducing the energy required for their operation; however, this would compromise heat delivery as explained in section 2.4. The temperature distribution in each cavity wall was also studied showing a similar variation when fans were operating.

Table 14. Summary of energy and power output (22).

Wall	Area (m^2)	Capacity air flow (l/s)	Duct length (m)	Energy (kWh/day) Max	Energy (kWh/day) Average	Energy (kWh/day/ m2) Max	Energy (kWh/day/ m2) Average	Max power (W/m2)
A	6.4	60	6.5	N/A	N/A	N/A	N/A	N/A
B	4.5	45	7	1.60	0.52	0.36	0.12	175.36
C	4	50	2	3.95	0.94	0.99	0.23	281.48
D	4.6	101	5.5	11.66	1.96	2.53	0.43	537.21
E	4.6	30	9*	2.77	0.44	0.60	0.10	147.55
F	4	43	1.5	0	0	0	0	0

*of which 5 m is vertical (warm air pumped downstairs)

Table 15. Fan consumption data (22).

Wall	Fan power (kW)	Run time (hours) Max	Run time (hours) Average	Energy Consumption (kWh/day) Max	Energy Consumption (kWh/day) Average
A	0.068	-	-	-	-
B	0.068	11	4.5	0.748	0.306
C	0.04	6.9	2	0.276	0.08
D	0.068	9.5	3.5	0.646	0.238
E	0.068	9.5	3.5	0.646	0.238
F	0.04	0	0	0	0

The study concludes that there were many lessons learnt from this exploration especially on the monitoring side. Ducting and specifically its length was found to be a key factor affecting the heat delivery. Shading effects were also a crucial factor decreasing efficiencies and should be studied extensively. Moreover, it was shown that monitoring via wired communications is time-consuming and difficulties were encountered in fault detection. In addition, the data-logger was noisy because it was placed inside the house and was not capable of operating with backup batteries. Lastly, careful consideration should be given with regard to the optimal placement of the room temperature probes, so that they represent the average temperatures. Any proximity to electrical appliances that produce heat, windows, fan outlets and similar sources that could influence the measurements should be avoided.

15. Wheatley campus retrofit, 2009, Oxford Brookes University, UK

Design

A TSC application in the form of steel cassette panels took place in an unoccupied concrete-panel building at the Wheatley Campus of Oxford Brooks University. The aim was to investigate the application of TSC as over-cladding panels on existing concrete or masonry buildings, as it could potentially reduce the heating costs significantly when combined with external insulation as stated by Lawson and Hall (2010) (23) and Hall et al. (2013) (24). The building was destined for residential accommodation, though it was unoccupied during the monitoring and performance evaluation; however, there is still methodological value for this study to be included in this review.

The installation included four TSC panels and was performed on the lower two floors of the 16-storey high tower block, on the south façade, as shown in Figure 39. Two configurations for the TSC installation were used:

- Two insulated TSC panels were installed on the south façade of the first floor between the windows. The insulation was 80 mm thick and the cavity was 30 mm.
- Two un-insulated TSC panels were installed on the south façade of the second floor, with a cavity of 140 mm.

The total TSC panel area was 10.4m^2 with a porosity of 0.22%. The panels had a grey colour, were 1.2mm thick and their dimensions were typically 2.9 x 0.9m (width x height). The rest of the cladding shown in Figure 39 is non-perforated steel panels (dummy panels). The panels were sealed peripherally to prevent unwanted air ingress. Two 150 mm holes were created (one on each floor) behind the facades and two fans were placed with a maximum cumulative potential flow rate up to 120l/s, which is equivalent to 41.5 m^3/h per m^2 of TSC. The rooms were heated to simulate normal occupied conditions; however, no further information is provided on the presence of dumpers and controls.

Figure 39. Insulated, non-insulated and perforated panels on south and east façade of the building in Wheatley campus (24).

Evaluation

The monitoring process started in 2009. A weather station (DeltaT Devices WS-GP1) was placed on the roof. Data was captured every 15sec and were downloaded regularly. Thermocouples were installed to capture the temperature at specific points to investigate the impact of the materials and the air temperature change (Figure 40). Variations of temperatures during a day in March 2011 are presented in Figure 41, where the temperatures of the steel cladding, external and internal wall, incoming air and cavity are plotted. The temperature difference between the incoming and internal air was about 10°C on average. It is shown there that the steel surface reached a maximum of about 34°C; however, the average value during the heating period (11:00-16:00) was calculated to be about 25°C. The peak incoming air temperature values are about 6 to 10°C lower than the peak values of the steel surface and has and average value of about 21°C during the heating period. Outside the heating period, the steel surface temperature is 3 to 9°C lower than the internal wall surface, but the incoming air is 2 to 5°C warmer than the steel surface, indicating that heat loss through the existing façade has an impact on the TSC performance (23).

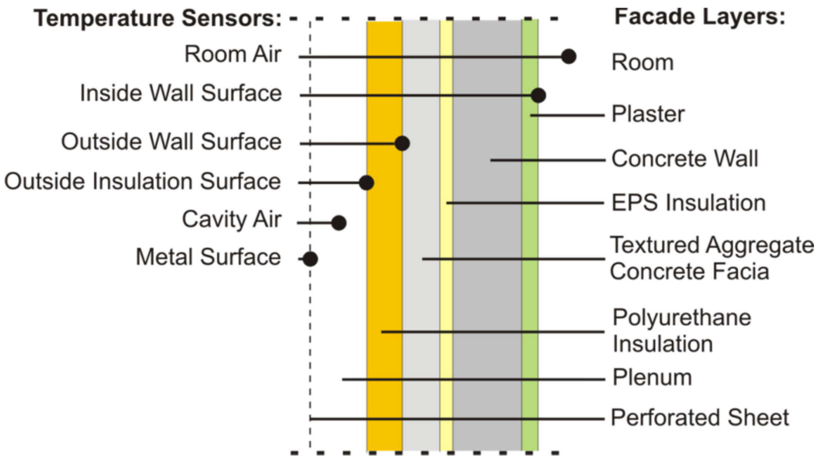


Figure 40. TSC temperature monitoring: metal surface, air cavity, before and after insulation, inside wall surface and room temperature (24).

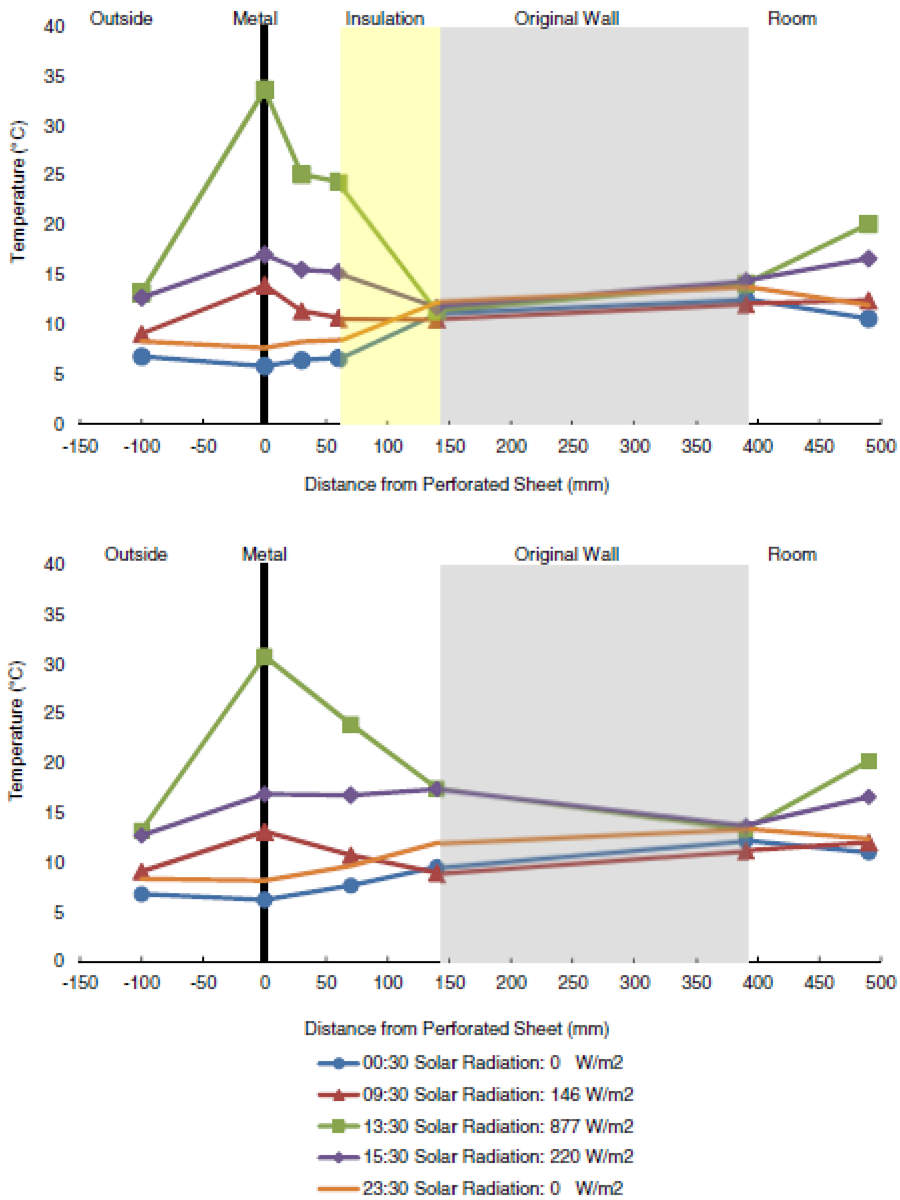


Figure 41. Temperatures of the system with or without insulation during a day in March (24).

The energy generated per hour was calculated. The flow rate was based on the fan characteristics and the temperature rise was the average rise during the aforementioned five-hour heating period. The annual produced energy was estimated by multiplying the daily heat production (calculated to be 3.6 kWh) by an assumed period of 150 days for annual yield. This provided an annual energy yield of 540 kWh (or 104 kWh/m^{2}a). However, it was not clarified how many days were analysed to obtain the average the authors based the annual yield on. Additionally, by using building dimensions of 5 x 10 m (width x length), the equivalent savings in heating energy were estimated to be 11 kWh/m^2 of floor area, which would be about 20% of the total heating demand of the building. Moreover, the fan energy consumption was calculated and was found to be about 7% of the TSC heat energy production. The assumptions for this estimation included 5 years of operation running at half the maximum flow rate (20.7m^3/h).

Lastly, the contribution of the TSC in the compensation for some heat losses, e.g. air leakage and conduction losses, was also calculated. The TSC would potentially contribute to a reduction in energy loss through air leakage during operation, through the use of $Q_{air\ leak} = lr \bullet A \bullet (T_d - T_{room})$ Equation 6:

$$Q_{air\ leak} = lr \bullet A \bullet (T_d - T_{room}) \qquad \text{Equation 6}$$

Where $Q_{air\ leak}$ is the heat loss saved by reducing air leakage (kW); l_r is the air leak rate ($m^3/m^2/s$); A is the TSC area (m^2); T_d is the temperature in the duct and in this case is the cavity temperature (°C) and T_{room} is the internal temperature inside the room (°C). By using $Q_{air\ leak} = lr \bullet A \bullet (T_d - T_{room})$ Equation 6, the authors calculated the heat loss that was saved by reducing air leakage over one panel configuration (5.3 m^2) to be 0.02 kW or 0.1kWh over a day. This represents about 3% of the heat delivered by the TSC.

Furthermore, there is a potential saving in the conductive heat loss through the façade. This can be calculated by using $Q_c = U_{ocf} \bullet A \bullet (T_d - T_{out})$ Equation 7:

$$Q_c = U_{ocf} \bullet A \bullet (T_d - T_{out}) \qquad \text{Equation 7}$$

Where U_{ocf} is the U value of the over-clad façade (W/m^2 K) and T_{out} is the outside or external temperature (°C). By using this equation and a U value of 0.25W/m^2K, the authors calculated the daily saving in conductive heat loss to be 0.07kWh. This represents about 2% of the heat delivered by the TSC and adding the savings by reducing air leakage to that, it is shown that the total reduction can amount to about 5% of the heating energy produced.

Appendix II – Chapter 3: Summary table of TSC case studies

Table 16. Summary table including TSC building-integrated case studies' characteristics (continued overleaf)

	TSCs in buildings overview						Table A Design Drivers				Table B Envelope integration							Table C Systems Integration						
	Building name	**Building use**	**Location**	**Year TSC was installed**	**Author**	**Publication year**	**Design intent**	**Ventilation demand explicitly linked to sizing/evaluation**	**Performed simulation too**	**TSC collector area in building (m2)**	**Inclination**	**Orientation**	**Surface Shape**	**Colour**	**Porosity**	**Hole diameter**	**Plenum width (mm)**	**Air flow rate (m3/h per m2 of TSC)**	**TSC integrated to HVAC auxilliary system**	**Auxiliary separate systems**	**PHV or DHV**	**Bypass Overheting**	**Recirculation**	**Controls**
1	**NREL Waste Handling Facility**	industrial	US	1990	Cali	1999	Unclear (although min ventilation req stated)	no, but mentioned in guidelines (NREL 2010)	heat transfer modelling to explore impact of back wall	27.9	vertical	south	corrugated	black	2%	N/A	N/A	183	yes Electric heater	No	PHV	yes	No	yes: electric heater based on T
2	**Ford Automotive Assembly Plant**	industrial	Canada	1990	Cali	1999	Retrofit, available south area	no	SIMAIR	1877 (237 were monitored)	vertical	southish	flat	black	1% and 2%	N/A	N/A	119	Yes to ventilation only	gas heaters	DHV	Yes at 18C	yes	yes for recircluation and byass
3	**GM Battery Plant**	industrial	Canada	1991	NREL Cali	1998 1999	Unclear/Retrofit	no	SIMAIR	365 (420 incl. non-perforated)	vertical	south	flat	black	2%	1.6mm	150	162	Yes only to ventilation	steam heaters	DHV	Yes at 18C	yes	yes for recircluation and byass
4	**Göttingen Utility Co-generation Plant**	industrial	Germany	1992	Cali	1999	Retrofit Combustion air supply	not appl. (no ventilation purpose)	N/A	305.6 (343 incl. non-absorbent area)	vertical	south-east	possibly corrugated	dark brown	1%	N/A	100	27.5-70	Not a ventilation system. Preheat for combustion air	No	PH	No	Yes when TSC would deliver at<100 W/m2	yes recirculation at<100 W/m2
5	**Bombardier**	industrial	Canada	1993	Hastings	2013	Retrofit/ ventilation with some heat	no	N/A	611	vertical	south	flat	custom dark olive-green	N/A	N/A	220	117	no new netilation only	no	DHV	N/A	Yes	yes fans driven by occupancy patterns and ricirculation driven by outside air
6	**US Army Hangar**	industrial	US	1995	Hastings	2013	Cost	no	N/A	725	vertical	south	flat	dark bronze	N/A	N/A	250	50-148	no	no	DHV	N/A	yes	yes regulator dampers would mic recirculated air driven by ext temp
7	**Intek Fabrics Manufacturing Facility**	industrial	US	1998	Mauer	2004	Unclear , is it suitabe for N. Carolina climate?	no, but mentioned that it should	TRNSYS (potential for TSC in warmer climates)	277	vertical	south	corrugated	black	0.60%	1.6mm Hole spacing: 16.5 mm apart horizontally and 20 mm apart vertically	200	51.5-52.7	no	possibly yes, implied recirculation and modelling	DHV	No	yes	yes, but no summer bypass
8	**BigHorn Home Improvement Centre**	industrial	US	2000	Deru	2005	Available area on the south façade, reduce fuel of conventional system	no, reduce heating driven	whole building energy simulation	209	vertical	south	N/A	dark bronze	N/A	N/A	N/A	N/A	no, independent system	Yes, Gas fired radiant floor system	DHV	no	no	Yes, destratification fans were also included
9	**CA Group Roll Mill**	industrial	UK	2006 (monitoring)	Pearson and Anderson	2007	Unclear	no	N/A	410	vertical	south	possibly corrugated	dark/black	N/A	N/A	N/A	45	no	gas heater	DHV	Yes	yes	yes full algorithms depending on scheduling and temp sensors
10	**Broiler barns**	industrial	Canada	2007	Cordeau and Barrington Cordeau	2011 2010	Unclear	no	CFD (to establish TSC configurations to optimize heat recovery and minimize flow reversal)	221 (for each of the two barns)	vertical	south-east	corrugated	black	1%	N/A	N/A	42-57.2	no	2 gas heaters	DHV but auxiliary was placed just after TSC outlets	Yes	no	yes for the bypass, fans and gas heaters to follow broiler tem protocol
11	**PIMSA Automotive production plant**	industrial	Turkey	2012	Eryener and Akhan	2016	Unclear	no	RETscreen	770	vertical	south	N/A	dark grey	N/A	N/A	N/A	82.8	yes to 6 AHUs	N/A	PHV	Yes	yes	yes: 24 automatic damper controllers
12	**Wal-mart**	Commercial	US	2006	Kozubal	2008	Unclear (although min ventilation req stated)	no	N/A	743	nearly vertical	south	flat	dark grey	N/A	N/A	N/A	28-104	yes RTUs & 2 AHUs	No	PHV	N/A	yes	yes
13	**Windsor Housing Authority**	residential	Canada	1994	Hollick Hastings	1996 2013	Retrofit	no	annual energy savings modelling	335	vertical	south	corrugated	dark brown	N/A	1.5mm	250	69	yes 6 gas heaters	No	PHV	Yes	N/A	yes dampers for bypass at 20C ambient
14	**House in Judgeford**	residential	New Zealand	2005 (2007 monitored)	Heinrich	2007	Unclear	no	N/A	28.1	vertical	north	corrugated (metric)	black	1%	N/A	N/A	23.5-79	no	Probably yes but no info	DHV	N/A	N/A	yes, but no recirculation/preeat/by pass mentioned
15	**Wheatley Campus Retrofit**	residential/unoccupied	UK	2009	Lawson and Hall	2010	Unclear	no	N/A	10.4	vertical	south	flat (cassette)	grey	0.22%	N/A	two: 30mm and 140mm	41.5 but 5 years extrapolation use 20.7	no	N/A	DHV	N/A	N/A	no

		Table D Evaluation									Table E Optimasation and Lessons Learnt		
	Building name	Cost (£/m2 of TSC)	Cost in 2020 (£/m2 of TSC)	Cost includes	Monitoring period (months)	Data acquisition interval	Key Performance Indicators	Supplementary Performance indicators	Heat displacement (kWh/m2a)	Savings % of total annual heating requirement	Optimisation through simulation	Optimisation in real life	Lessons learnt
1	NREL Waste Handling Facility	178	230	total: materials, installation, labour	14.5 (2 periods)	N/A	Heat delivered Heat savings %Heat savngs Cost TSC	Effecincy vs solar Effeciency vs wind Back wall impact	513	26%	no	improvements to the data acquisition system	Best sizing for ≤ 73.4m3/h per m2 of TSC 9 years payback
2	Ford Automotive Assembly Plant	70	121.5	panel supply, installation, labour	9	N/A	delivered active solar heat+ total TSC heat contribution, total energy savings, % of heat demand. Capital cost and amintenance cost	meteorological data validation,efficiency vs solar, efficiency averages, fan energy consumption, night time heat recaptured, destratification savings, radient heat loss, passive solar heat gains/losses	389.9	5-20% of fresh air heating	no	installed higher capacity fans	Destratification and back wall recaptured have major impact
3	GM Battery Plant	131	230	total incl. fans: panel supply, installation, ducts, fans, labour and upgrade	36	15 min	active solar heat collecte, delivered heat, annual energy savings, payback	efficiency, efficiency vs flow, fan energy consumption, weather data veryfication, back wall recaptured heat	656 (473.1 from active solar heat and 182.9 from recaptured heat)	N/A	no	replaced fans, motors and ducts to improve airflow	Absorber cost is less than half of the total cost
4	Göttingen Utility Co-generation Plant	153	272	total: investment costs incl. VAT, including additional cost of TSC over conventional façade, air duct and control system	7.5 (2 periods)	5 min	TSC heat delivery, room recirculation heat, annual energy savings, cost	efficiency vs suction velocity. Varation of daily temperatures. Back wall (heat flux and leak), Duct (recovery or loss). Cost/energy/m2/year	250	N/A	no	more sensors installed	There are significant night time gains
5	Bombardier	N/A	N/A	N/A	12	N/A	delivered heat, energy savings	destratifications savings	705 (additional destratification savings: 758)	N/A	no	no	Recirculation assists T rise but compromise fresh air
6	US Army Hangar	112	185	project costs - further details not specified	N/A	N/A	delivered heat, energy savings	destratifications savings	810 (additional destratification savings: 533)	N/A	no	no	Recirculation assists T rise but may compromise fresh air
7	Intek Fabrics Manufacturing Facility	187 but collector only was 100	241 but collector only was 141	total: panel, shipping and miscellaneous costs, equipment independent of the collector	0.8	15 min	Heat delivered Heat savings %Heat savngs Cost TSC	efficiency,air flow, pressure drop, eff and Trise vs solar, Stratification temp, eff vs modellng, eff vs plate and ambient temp	1 - 2.1 kWh/m2/day	N/A	no	no, but initial measurements were taken to optimise the flow monitoring equipment	Activation T sensor should be placed in the plenum Much instrumentation info
8	BigHorn Home Improvement Centre	N/A	N/A	N/A	30	N/A	whole building energy demand/consumption	N/A	N/A	N/A	yes (no specific info)	no	High-ceiling low flow heat does not heat occupancy No shading and open doors
9	CA Group Roll Mill	N/A	N/A	N/A	12	5 min	delivered heat, % heat displacement	stratification, destratification, CO2 savings, temperature variations	193.1	21%	no	proposed modifications	T rise equation is dependent on ventilation demand Lots of instrumentation info Match TSC size fresh air demand
10	Broiler barns	197	209	investment cost - further details not specified	24	5 min	delivered heat annual enerfy savings	efficiency and eff vs wind,	185	N/A	no	no	Desirable room T drives flow rate settings and T rise
11	PIMSA Automotive production plant	N/A	N/A	N/A	6	N/A	heat delivered, energy savings, cost savings	N/A	N/A	34-62% per month	no	no	Weather has a huge impact on TSC performance
12	Wal-mart	136 (target - argued)	136 (target - argued)	installation cost target	2	15 min	delivered energy	efficiency, heat del vs solar, collected energy utilisation	15kWh/m2/month on average	N/A	Simulation of improvement estimated heat delivery increase from 15 to 74 kWh/m2/month improvement from proposed modifications	proposed modifications	When air flow is higher to the ventilation needs, only delivery above room T is beneficial
13	Windsor Housing Authority	53 more to conventional cladding	92 more to conventional cladding	cost of TSC over the conventional cladding	N/A	N/A	Energy Delivered and savings prediction	N/A	584 (predicted)	28% of fresh air heating	no	no	Include TSC in initial design Potential roof implementation
14	House in Judgeford	N/A	N/A	N/A	N/A	3 min	power output, delivered energy	temperature variations, efficiency, solar	N/A	N/A	no	proposed modifications	Complex monitoring requires very detailed planning
15	Wheatley Campus Retrofit	N/A	N/A	N/A	N/A	15 sec	delivered energy, %savings	air leakage (back wall) and conduction losses, fan energy consumption, temperature variations vs solar	104 (predicted)	20% (predicted)	no	no	Back wall can contribute a total of 5% to the total heat delivery

Appendix III – Chapter 5

1 B&Q Store Cyfarthfa Retail Park

Hammerson and B&Q (clients) agreed a set of best practice sustainability targets at an early stage of development in a new store in Cyfarthfa Retail Park, Merthyr Tydfil, Wales, UK. The targets included energy efficiency, embodied carbon, recycled content, responsibly sourced timber, waste management, water consumption, biodiversity and climate change adaptation. The WSA team considered the project to have great potential for the novel application of a TSC and partnered TATA Steel to implement the TSC in the project. The TSC provider was TATA Steel who subcontracted ABS Elbrow Ltd to install the technology which comprises of two roof collectors 140m^2 each. Tata Steel subcontracted Building Technology Systems Ltd to design and install the control mechanism. The installation completed in August 2014; however, there was a 3-month testing/commissioning period to optimise the control parameters.

The initial plan proposed a façade TSC installation which would ventilate and preheat the garden centre only; however, this area was not air-tight significantly reducing the benefit from the TSC. The main store hall was a more suitable alternative; however, the installation faced structural challenges. The 280m^2 TSC (Figure 42) was designed to sit on top of the roof, in between the green roof flowerbeds and consequently it became the **first TSC roof installation in the UK**. The panel material type is *Colorcoat Renew SC®* and the profile type is *Trisobuild R32.* The southwest and southeast black collectors follow the 5^o roof inclination (Figure 42)*.* The overall concept of mimicking the corrugation of the surface and replicating it with the device seems to integrate the device in an un-obstructive way. This building won the sustainability achievement classification of the Property Awards 2015. The judges praised the collaborative and holistic approach to the project, which adopted a solar technology that was used in the UK for the first time. They added that they hoped the award would inspire more firms to enter with their cutting-edge sustainability schemes and initiatives.

Figure 42. Roof-top TSC at B&Q Store, Merthyr Tydfil, Wales, UK; WSA team

This system provides heated fresh air into the building with the aim to reduce the conventional daytime heating load. The conventional heating system uses radiators at the floor level during store opening times: weekdays 8am to 6pm, Sundays 10am to 4pm. The system is capable of carrying out a night-time purge and a recirculation routine and also provides the additional benefit of de-stratification. There is no bypass capability in the system as the building was designed for natural ventilation (Figure 43) which makes the system similar to the Intek Fabrics Manufacturing Facility (7), (see Appendix I-7).

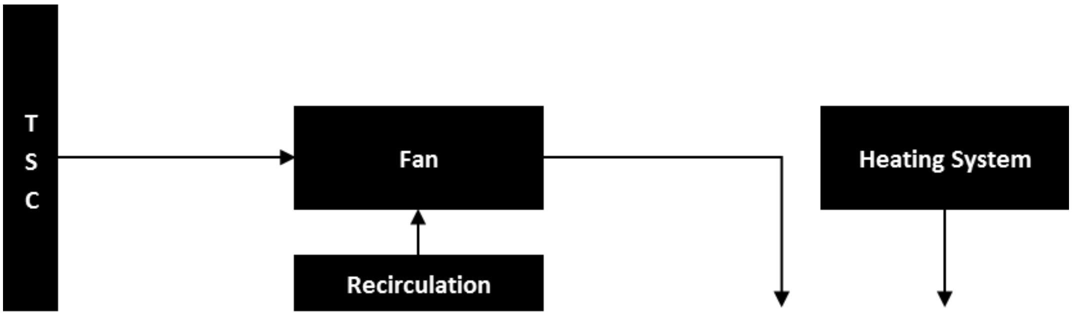


Figure 43. TSC system at B&Q store; author

2 SEDA UK Ltd. Blackwood

SEDA UK (client) is a subsidiary of SEDA International Packaging Group, a world leader in packaging for the food industry. The UK facility (Figure 44) is based in Hawtin Park, Blackwood, within the Caerphilly County Borough. This manufacturing facility employs more than 270 people and WSA was looking for an industrial partner with an existing HVAC system able to benefit from a TSC retrofitting. The building is a substantial warehouse with large open spaces in need of heating and ventilation. For the retrofit, the principal contractor was TATA Steel, the cladding contractor was

Lester Fabrications & Cladding Co. Ltd and the Control Specialist was Building Technology Systems Ltd. The installation was delivered in January 2015.

Figure 44. Roof-top TSC at SEDA UK Ltd. Blackwood, Wales, UK; author. Note: the TSC is the black panel area.

The initial proposal assumed a retrofit onto the warehouse's roof as well as the southern elevation which followed the existing lines of the façade, retaining an industrial aesthetic. The final outcome of the project was limited to the roof-based TSC as shown in Figure 44 which eased integration to the existing HVAC system. There was sufficient space on the roof to ensure functionality without compromising the appearance of the elevations. The TSC installation covers 720m^2 area of the roof while employing 635m^2 of active TSC steel panels which follow the 7° south roof inclination. The panel type used was the Colorcoat Renew SC® in grey slate colour and the profile type was the Trisobuild from TATA Steel.

This system feeds preheated air into the building's HVAC system and reduces the conventional daytime heating load of the building. After passing a motorised volume control damper, the newly installed duct work feeds into two existing gas fired space heating AHUs by connecting directly into the back of their mixing units. One feeds into the factory area and the other feeds into the warehouse area which has a 24 hour/7 days a week space heating demand. The system is capable of carrying out a night time purge, recirculation and summer bypass routine and also provides the additional benefit of de-stratification (Figure 45), similar to the PIMSA Automotive production plant case study (19) (see Appendix I-11).

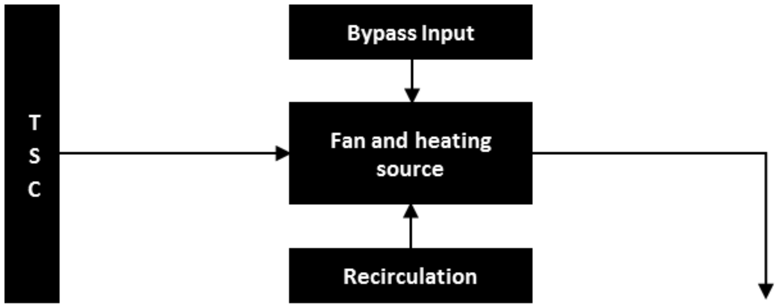


Figure 45. TSC system at SEDA UK Ltd.; author.

3 Lampeter School, Main Hall, Ceredigion

Lampeter Comprehensive School in Ceredigion was opened in 1949 and carries a strong culture in sustainability. WSA was aiming to test TSCs in schools and especially in West Wales. In contrast to the design of other buildings, this case had a different demand profile and different times of operation. The school's working hours fit better the potential sun hours which makes potential TSC heat output more responsive to the heat demand. In collaboration with TATA Steel and Ceredigion County Council (client), the WSA team ran feasibility tests and decided the south-facing roof was suitable for the TSC technology and two TSC systems were installed on site. TATA Steel was the main contractor and the Steel provider, EHS Holdings Ltd was the cladding contractor and PSA Design Ltd accompanied by Ramboll UK Ltd were the structural engineering consultants. The control was designed and delivered by Building Technology Systems Ltd. and Kimpton Building Services did the M&E works. The works finished early in 2015 and two months of testing and commissioning period followed.

The building presented retrofitting challenges due to uncertain structural durability of the roof and complex geometries. After considering sizing and aesthetics options, 215m^2 of anthracite Coloroat Renew SC®, WP40 plank TSC were installed. This was split over two areas – the main hall (described in this section) and the cloakroom (described in Section 7.2.4). 155m^2 of TSC was installed on the 24° inclined south-facing roof which feeds warm fresh air directly into the school's Main Hall when heat demand and sufficient solar radiation occurs. The overall impression of the TSC had a minimal impact on the perception of the building as the installation was roof-based and on an inclined surface (Figure 46).

Figure 46. Inclined roof TSC (left) and main hall distribution duct (right) at Lampeter School, Ceredigion, Wales, UK; author.

The operational strategy was for the TSC to deliver heated fresh air directly into the hall to reduce the conventional daytime heating load on the building (Figure 46). This system includes a recirculation damper in order to recycle part of the heat of the room's exhaust air (Figure 47). The system could be programmed to get the night purge and the distribution ducting was designed and installed to get the additional benefit of de-stratification. The system consists of fans, attenuators, filters and control dampers however it does not include a bypass damper. Conventional radiators were used to provide additional heat to the room when needed. The TSC is controlled using a set of sensors and sophisticated and alterable software that will be further analysed in the results section (Chapter 7). This TSC is controlled separately from the one delivering heating to the cloakrooms.

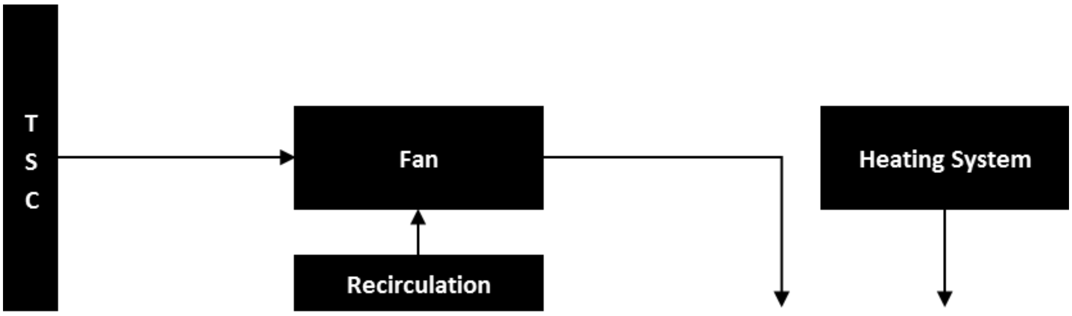


Figure 47. TSC system at Lampeter School, main hall; author.

4 Lampeter School, Cloakrooms, Ceredigion

On the same roof in Lampeter school there is another 60m^2 of matching TSC that provides warm air ventilation to two cloakrooms. The occupancy patterns are different from the main hall; however, the main operational principle is the same. This system does not include recirculation or a summer bypass feature and it is controlled independently using different sensors (Figure 48). The cloakrooms are open to the school's main corridors and are also served by wet system radiators (which were also monitored). As the main hall TSC serves a closed space and the cloakrooms TSC an open space, they have different features, use different thermostats and set points and have different occupancy patterns, they were monitored and evaluated separately.

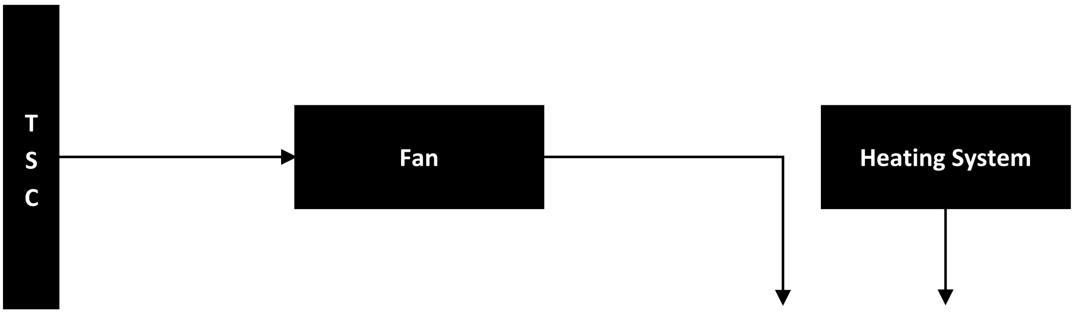


Figure 48. TSC system at Lampeter School, cloakrooms; author

5 Glan Clwyd School, Theater, St. Asaph

Glan Clwyd School has an interesting mixture of building types and usages. WSA was aiming to test TSCs in a UK school and after a thorough investigation it was decided with TATA Steel (main contractor) and the Denbinghshire Countly Council (client) to integrate TSC technology in two different solar-facing areas within the school. The cladding contractor was EHS Holdings Ltd, the control specialist was Building Technology Systems Ltd, the Structural Engineering Consultation was provided by Ramboll UK Ltd and the M&E was contracted to Kimpton Building services. The main works finished in November 2014 but the operation started three months later after a testing and commissioning period. Two installations in two separate buildings consisted of anthracite Colorcoat Renew SC® TSC panel type with a WP40 plank profile. The plank profile was promoted as it suits better the existing architecture.

The first system includes a 77m^2 TSC which sits on a 33° inclined roof and preheats the air for an HVAC system which serves the school's theatre (Figure 49) and is described in this section. The other TSC fed into the corridors and is described in Section 6.1.6. The first difficulty came from the age of the building which implied that the design of the detailing would not be straightforward. The structure of the roof was not designed to be able to support a future retrofit of a sustainable device nor was it in prime condition. Above all its geometry was a complex set of interlocking planes which made a single, rectilinear plane retrofit difficult to seamlessly integrate (Figure 49).

Figure 49. Inclined roof TSC (left) and delivery room - theatre (right) at Glan Clwyd School, St Asaph, Wales, UK; author.

The roof installation feeds the theatre's gas fired HVAC system and aims to reduce the conventional daytime heating load on the building. Additionally, the system on the roof does not include recirculation but it extracts the residue exhaust energy through a heat exchanger, which makes it the first monitored TSC feeding a heat exchanger. It includes a summer bypass and is also capable of carrying out a night purge (Figure 50). The system uses existing well-hidden ceiling distribution ductwork providing the additional benefit of de-stratification. The systems for this and the corridor TSC consist of fans, attenuators, filters and control dampers. This TSC system is controlled separately from the corridor TSC using control integrated to the HVAC system.

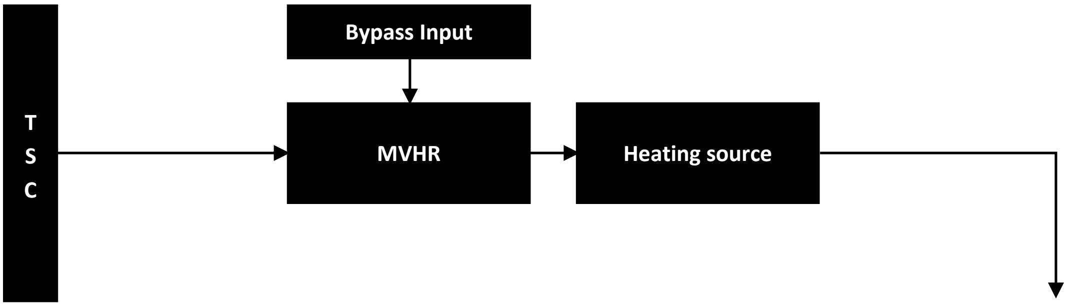


Figure 50. TSC system at Glan Clwyd school, theatre; author

6 Glan Clwyd School, Corridors, St. Asaph

On a different building a second matching installation of 34m^2 TSC was applied on a vertical south wall to feed two corridors with warm air. The system distributes the heated fresh air directly into the building via two ducts in the ground and first floor (Figure 51).

Figure 51. Vertical wall TSC (left) and delivery corridors (right) at Glan Clwyd School, St Asaph, Wales, UK; author.

The size of the vertical panel was not confined by pre-heating requirements as it was planned as a mechanical ventilation system with the benefit of delivering warm air if required. This gave the designers the opportunity to follow the lines of the elevation so as to not compromise the original intent of the architect of the building.
The system had a straightforward operational strategy without any recirculation or summer bypass function (Figure 52). Unfortunately, it was decommissioned in the summer of 2016 as the building was demolished.

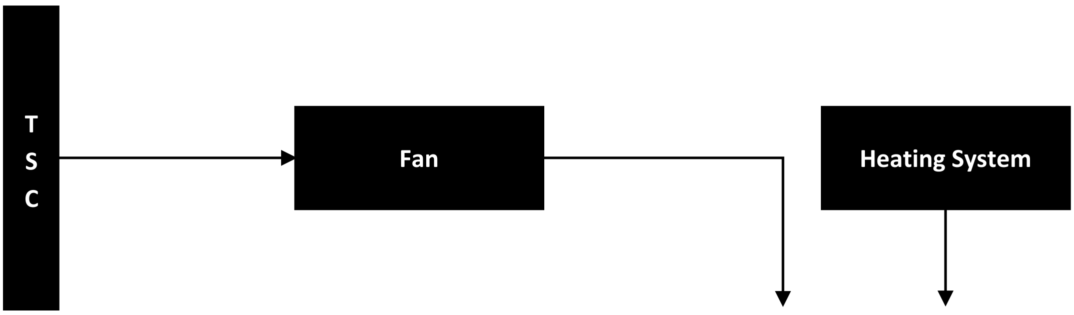


Figure 52. TSC system at Glan Clwyd school, corridors; author

7 Saxon Court residence, Ebbw Vale

This three-storey red brick building in Blaenau Gwent in Wales provides retirement/sheltered housing for its occupants and comprises of 31 flats as well as ancillary spaces including a lounge, dining room, laundry and guest facilities. The building was built in 1992 and is managed by United Welsh Housing Association (client). WSA and TATA Steel selected the site in order to demonstrate the benefits of a TSC in a multi residential building. The panel material type was the Coloroat Renew SC® anthracite and the profile type was the Trisobuild C32. The main contractor was TATA Steel, the cladding contractor was Euro Cladding Ltd and the control specialists were Building Technology Systems. The M&E consultancy delivered by SSE Contracting Ltd.

After a site investigation it was decided that the TSC would cover the whole south facing brick façade of the building feeding the three main corridors with fresh solar heated air. 108m^2 of TSC were installed on the vertical south façade of the building, however, the east façade surrounding the stairwell is clad using a dummy panel (non-active). The non-active cladding matches the TSC panel in profile and colour and to improve the architectural integration of the installation (shaded part in Figure 53). The heated fresh air is distributed directly into the stairwell by three ducting systems in the ground, first and second floor. The TSC cavity is split into three horizontal sections at each floor level and three fans supply air separately into each of the floors of the southern stairwell-corridors of the building (Figure 53).


Figure 53. Vertical wall with two TSC south facing facades and one "dummy" east facing façade (left) and one of the three delivery corridors on the 1st floor (right) at Saxon Court residence, Ebbw Vale, Wales, UK; author.

The TSC installation began on site in February 2015. The system can be described as three individual mechanical ventilation systems with the supplementary benefit of delivering warm air to reduce the conventional daytime heating load on the building. They are also capable of carrying out a night purge and they all have bypass dampers for the summer mode. The corridors were heated by a conventional wet central heating system (Figure 54). The TSC system consists of fans, attenuators, filters and control dampers. The three delivery systems are controlled separately using a set of sensors and sophisticated and alterable software.

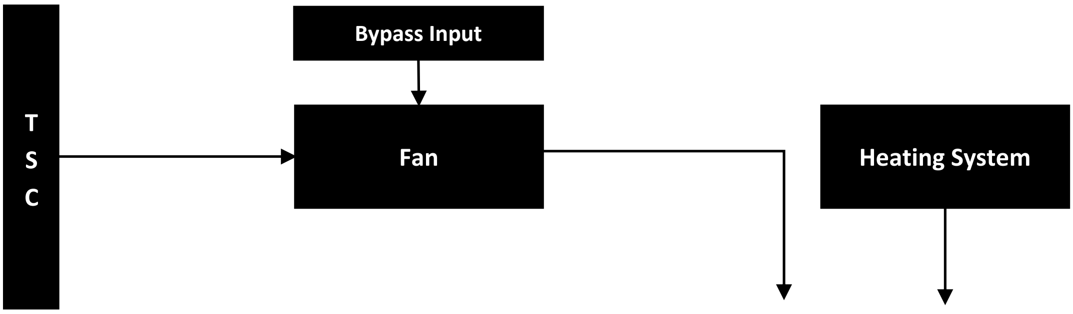


Figure 54. TSC system at Saxon Court residence, corridors; author.

8 Rhondda House (terraced)

This two-storey, mid-terrace property is located in the village of Gelli, in the Rhondda Fawr valley. This is a social housing property managed by Wales & West Housing Association (client) and occupied by two adults and one adolescent. The intention of WSA and Tata Steel was to reduce moisture in the building by introducing positive input mechanical ventilation fed by two small roof collectors of $4m^2$ total area.

Each collector of approximately $2m^2$ is placed on top of the south facing 30° pitched roof. The intention of the design is for the air collector to look similar to a small PV array or a thermal hot water system. The tiles were removed in order for the collector to integrate better onto the roof. All the internal ducting was boxed in similar to a domestic MVHR system. The attic housed all the mechanical and electrical components of the system (Figure 55).

Figure 55. Two small TSCs on an inclined roof (left) and controls and attic ducting (right) at Rhonnda terraced house, Wales, UK; author.

The system delivers heated fresh air into the building; the TSC is ducted into the loft and distributed directly down into the first-floor landing which reduces the conventional daytime heating load on this domestic building. The house had major condensation issues before the TSC installation and this was why a continuous 24/7 delivery option was provided. The system consists of an aperture through roof, ducting, axial fan, attenuator, filter, ducting and ceiling mounted supply grill. The system also includes heat recovery recirculation from the loft space as well as the ability to carry out a summer bypass procedure (Figure 56). The conventional heating system is a boiler based wet system with typical radiators. The system is controlled using multiple sensors and dampers.

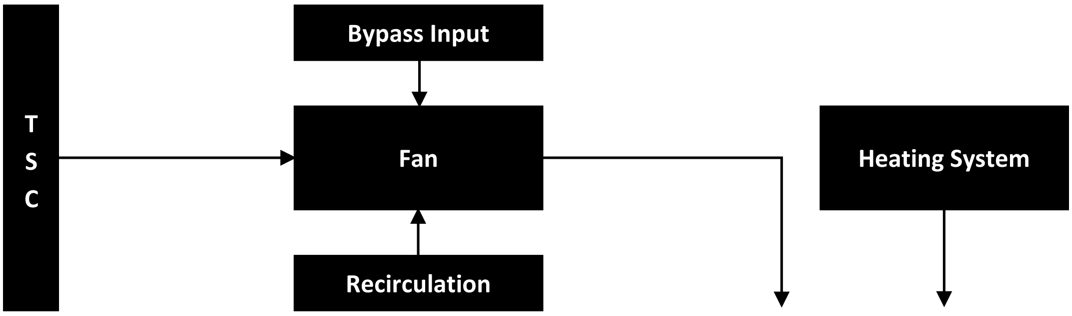


Figure 56. TSC system at Rhondda terraced house; author.

9 Solcer house

The aim of the Solcer House design was to be affordable and replicable whilst being energy positive. The house located in Bridgend has two storeys with a floor area of 50m² each, and a loft area of 34m² accessible via stairs. With one double and two single bedrooms for a family of four, the house was built as a detached property, but it was designed to be appropriate for a semi-detached or a mid-terrace property (Figure 57). The funding body conditioned the use of the building to be public use only; hence, the Solcer House is used as a demonstration facility with daily office-type user profiles, but the TSC design considered both residential and office purposes. The WSA team designed, monitored and evaluated the system. A 13.8m^2 TSC system was installed on the upper floor south façade carefully integrated to the building's envelope and adjacent to a matching colour (black) PV panel on the inclined roof.

Figure 57. South wall façade integrated TSC (left) and detail of the metal cladding and perforation (right) at Solcer house, Wales, UK; author.

The heating system included the transpired solar collector (TSC) feeding, through ducting, an MVHR integrated into an exhaust air heat pump (EAHP) which combined space heating, ventilation and hot water delivery. Air acts as the heat transfer medium, allowing the delivery of heat with the ventilation supply and avoiding the need of a wet heating system with radiators and pipework (Figure 58). Most of the ducting is integrated into the walls (risers) and the suspended ceiling. The system includes a summer bypass inlet controlled by a thermostat (independent of the heat pump).

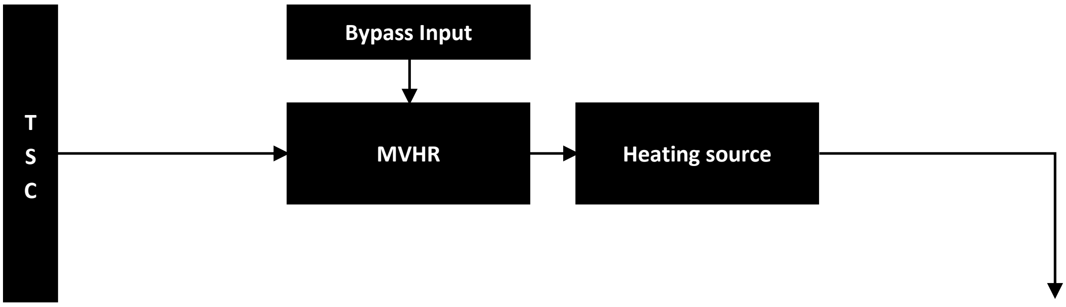


Figure 58. TSC system at Solcer house; author.

10 Rhondda House end-terrace

A typical South-Wales pre-1919 end-terrace house was selected as a representative case study of Rhondda's building stock. The house has a well-preserved south-facing wall and a west-east pitched-roof and is occupied by two adults and two children. The WSA team intended to demonstrate and investigate a wall-integrated TSC in a residential building. Wales & West Housing Association and WSA ran the project from design to commissioning and the WSA LCBE monitoring team applied a thorough monitoring and evaluation plan including optimisation strategies. A triangular 4.5m^2 TSC was installed on the south attic wall integrated to the double-pitched PV roof (Figure 59).


Figure 59. South wall façade integrated TSC (left) and detail of the ducting to the MVHR during construction phase (right) at Rhondda end-terrace house, Wales, UK; author.

The TSC feeds through ducts an MVHR unit that serves the building with three inlets and two outlets. The ducting is only partially visible in the attic as all the supply and extract ducts are boxed in. A conventional gas boiler is used to heat the water circulating through the radiators. A summer bypass was installed before the MVHR and is thermostatically controlled through sensors and dampers (Figure 60). The installation up to the MVHR unit is similar to Solcer house; however, the principal heating source here is a wet system that is independent to the TSC.

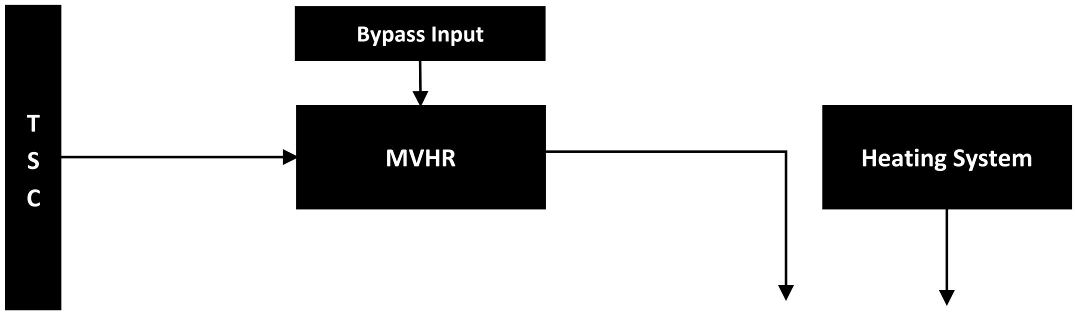


Figure 60. TSC system at Rhondda end-terrace house; author.

Appendix IV – Chapter 6

The required duration of the testing is related to the complexity of the system. A heating system monitoring period should be included for all systems; whereas a non-heating monitoring period should be included if a bypass is included in the system. For sophisticated systems that include control drivers through programming, conditions for each scenario can be created to reduce the testing time.

Ideally, the system should be monitored and evaluated for a full heating season and space heating delivery should be normalised and compared against modelling data. A high frequency monitoring interval (1min) would allow to zoom-in and observe the system's behaviour during the conditions changes to understand if errors occur. Common errors are related to the performance gap between design and reality of the system and each algorithm. System errors could involve installation faults of moving and static parts (e.g. fan real velocity etc.). Algorithm errors may be related to sensors inertia, limitations and positioning etc. or assumptions during design phase.

Appendix V – Chapter 7

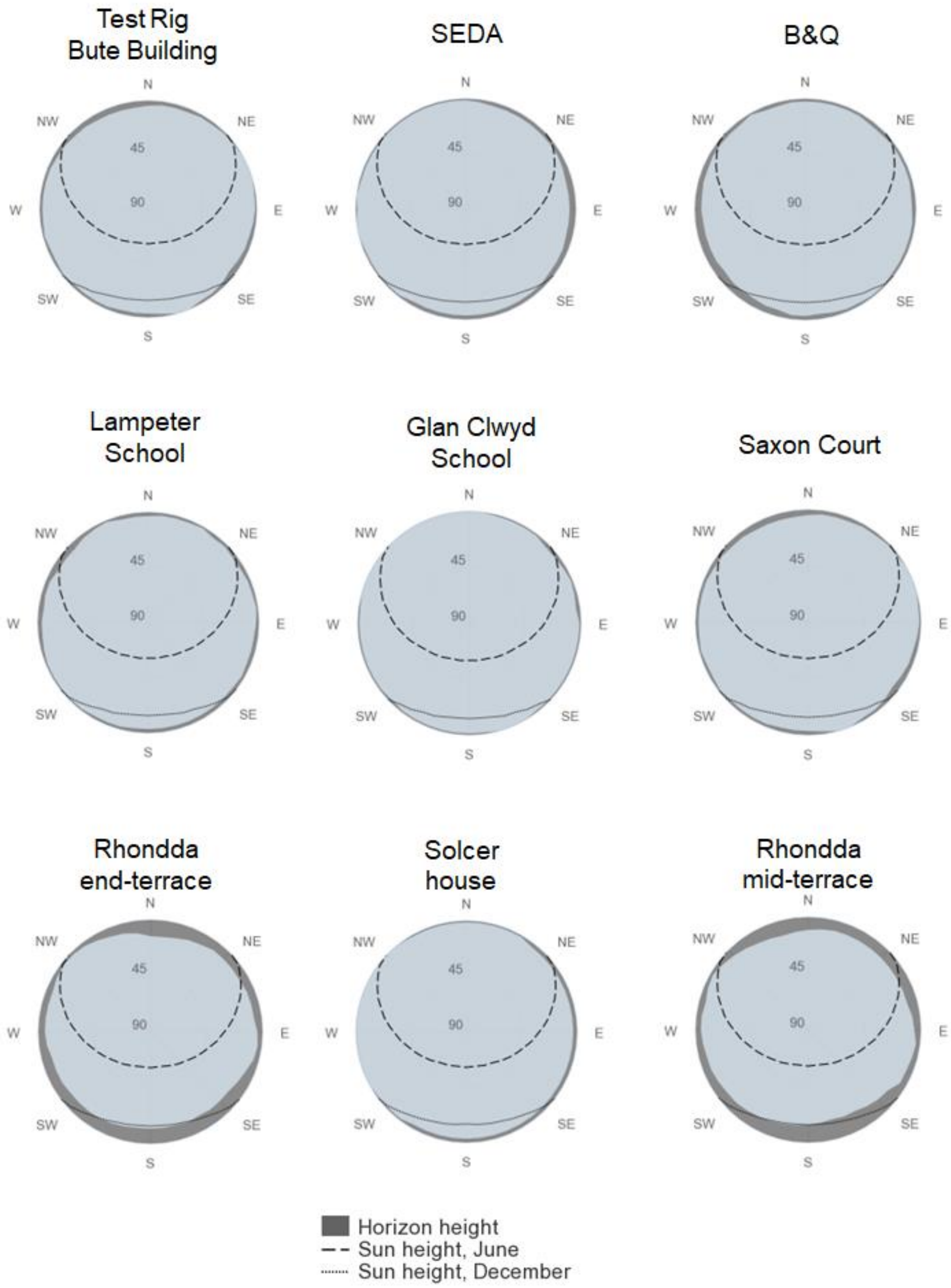


Figure 61.Outline of horizon winter sun path exposure for all the experimental case studies, using PVGIS, author.

Appendix VI – Chapter 7

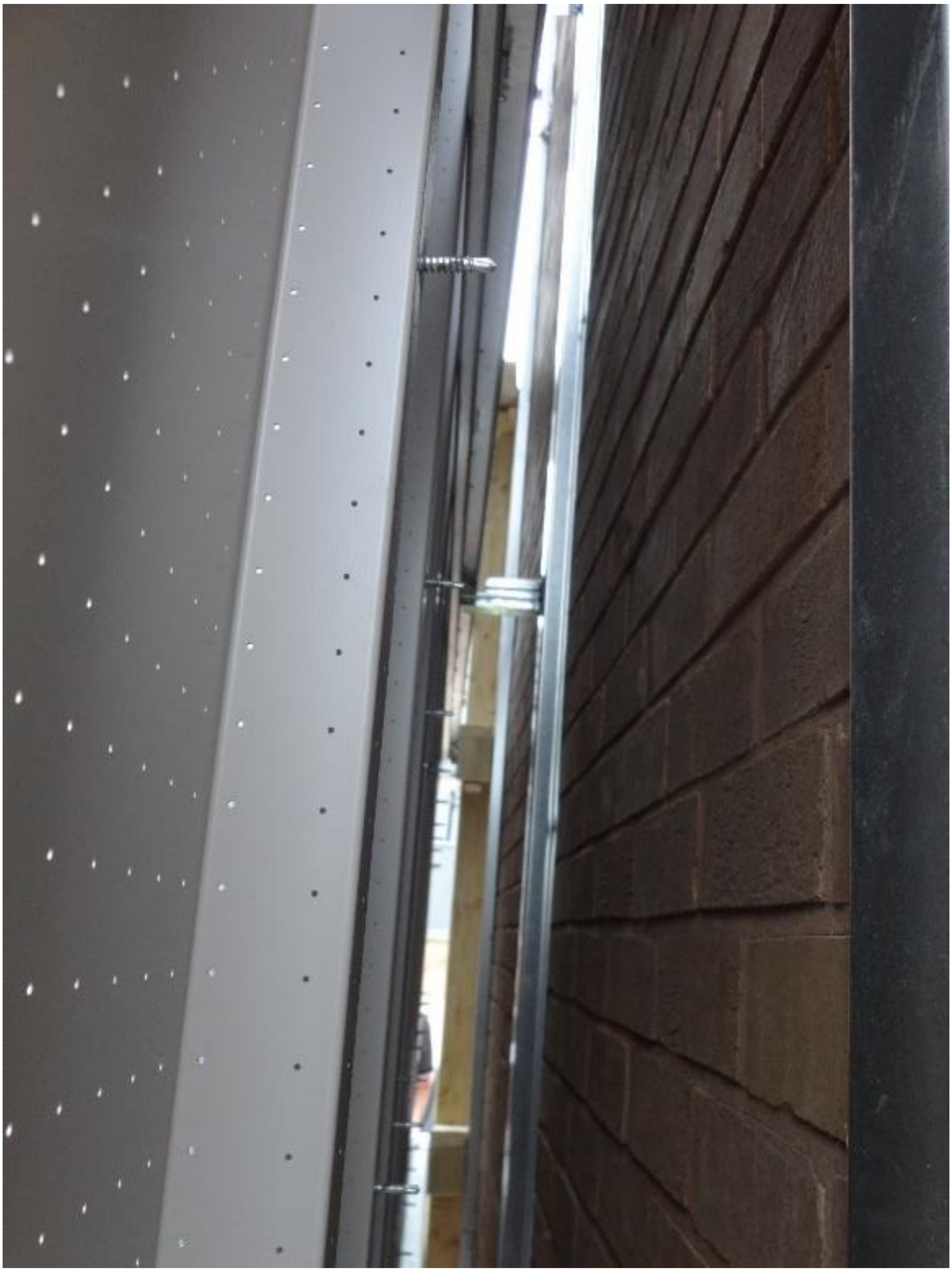


Figure 62. Spacing of the brackets behind the TSC panel on the Glan Clwyd school TSC elevation, author.

Figure 63. The finished 'Lampeter TSC' installation from up close, author.

Figure 64. The lower detail linking the TSC panel to the guttering of the B&Q roof, author.

Figure 65. The detail linking the TSC panel to the ridge of the B&Q roof, author.

Appendix VII – Chapter 7

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Low Carbon Built Environment

Amgylchedd Adeiledig Carbon Isel

@lcbe_specific

www.lcbe.uk

[redacted] Anonymised

Wales and West Housing and the Welsh School of Architecture at Cardiff University have worked together to refurbish your home to reduce your energy bills, improve your comfort and reduce impact on climate change. The work carried out will help to reduce the amount of electricity and gas that you use. Solar panels will make energy from the sun and store this energy when you are not using it.

1 EXTERNAL WALL INSULATION

Insulation has been added to the outside back and side walls of your home. This helps to keep the heat in and noise out. Please don't pierce it as it will not work properly. For example, don't use a drill to bolt anything to these walls.

2 LOFT INSULATION

Insulation has been laid in your loft. This prevents heat from inside your home escaping to your loft. This will help to keep your home warmer.

3 INTERNAL WALL INSULATION

Insulation has been added to the inside front wall of your home. This helps to keep the heat in and noise out.

4 VENTILATION

A ventilation unit has been installed in the loft space with pipework supplying fresh air to the bedrooms and living room and extracting air from the bathroom and kitchen. This will provide you and your family with good quality air and will help to reduce damp and unpleasant smells.

5 SOLAR AIR COLLECTOR

A triangular solar air collector is installed at the top of the side wall. Air within the collector is warmed by the sun before entering the ventilation unit. This helps to reduce the amount of energy needed to heat your home during the winter. In summer, this supply is automatically switched off to avoid overheating.

6 SOLAR PHOTOVOLTAIC (PV) PANELS

Solar photovoltaic (PV) panels have been installed in your roof. They use energy from the sun to make electricity. This electricity is used to power your television, washing machine and other appliances when there is enough sunlight.

7 ENERGY STORAGE BATTERY

A battery is located in your loft. Electricity produced by the solar PV panels is stored in the battery when there is more energy being made than you are using. The battery will be used when you are using a lot of electricity or there is not enough sunlight to generate new electricity.

Figure 66. Rhondda end-terraced; Home User Guide first page, LCBE team.

Frequently asked questions

How can I control the temperature of my home?

The temperature can be set on the control panel which is located by the entrance. This will activate your gas boiler. Your heating should be set at around 21^{0}C to give you a comfortable temperature.

What can I do if the house gets too cold or hot?

Your heating should be set at around 21^{0}C to give you a comfortable temperature.

If your home is too cold:
- Close windows and curtains.
- Remove clothes from radiators to allow heat out to warm up rooms.

If your home is too hot:
- Close windows and curtains when the sun is shining brightly and the outdoor temperature is high.
- Open windows during the night to let in cool air.

How does my hot water work?

Your gas boiler will heat up the water automatically when you run a hot tap.

When should I use my appliances?

It is best if you use your appliances when it is sunny as they will use energy from the solar PV panels, which is free of charge. Try to do your washing, electric cooking, hoovering and charging equipment such as mobile phones during the day. Its best to do this in the morning, if you can, as this will allow the battery to refill during the afternoon for you to use the free electricity from the battery in the evening.

Do I need to switch off/on the ventilation unit?

The ventilation unit in the attic will deliver fresh clean air to your home and will also reduce the amount of energy that you need for heating your home in the winter. It should always be ON. It costs around 10p per day to run.

When you are cooking or after a shower the amount of moisture in the air in your home will increases. The ventilation rate of the unit will increase temporarily to remove this extra moisture.

If your home feels stuffy you can use the boost button by the kitchen to temporarily increase the ventilation rate.

Can I open the windows?

You can open the windows if you want. The ventilation unit works to provide fresh air, take away moisture and keep out dust and pollen. If you do open windows during colder months extra heating will be required to keep your home warm which will cost you more.

How do the solar PV panels and the battery work together?

The solar PV panels in your roof generate electricity during the daytime when it is light. Any electricity generated will be used by your appliances if they are on. If more electricity is produced by the solar PV panels than you are using it will be stored in the battery for you to use later. The electricity stored in the battery will automatically be used by your appliances when it is dark instead of using electricity from your energy supplier.

How should the equipment be maintained?

Wales and West Housing will carry out checks and maintenance for all of the technologies in your home. If there are any problems, please contact the Customer Services CentrE.

Do I have to do anything if I leave the house for a week or more?

If you go away during the winter, set the heating thermostat to 14^{0}C. If you go away in summer, turn your heating down to minimum. Leave the ventilation system, solar PV panels and the battery ON at all times.

What are you monitoring and why?

Your home has a combination of features that will help to reduce your energy bills, improve your comfort and reduce impact on climate change. We need to measure how well these features are working.

Sensors have been placed in your home to measure temperatures, humidity and where your energy is coming from. Please do not move this equipment as it will affect our results. We may need to visit once or twice a year to collect data. You will be contacted before any visits and visitors will carry ID.

Useful contact numbers

Tenancy queries
Customer Services Centre
0800 052 [redacted]
Lines are [redacted]
E-mail:
contactus [redacted]

Repairs
Customer [redacted]
0800 052 [redacted]
Lines are [redacted]

Wales a[redacted] will carry [redacted] mainenan[redacted] nologies i[redacted] are any p[redacted] tact the [redacted] Center.

Anonymised

Funding

SPECIFIC is part-funded by the European Regional Development Fund (ERDF) through the Welsh Government, and also by InnovateUK and the Engineering and Physical Sciences Research Council (EPSRC).

Mae SPECIFIC yn cael ei ariannu'n rhannol gan Gronfa Datblygu Rhanbarthol Ewrop (ERDF) trwy Lywodraeth Cymru, a hefyd gan InnovateUK a Chyngor Ymchwil y Gwyddorau Ffisegol a Pheirianneg (EPSRC).

Led by

Funded by

Figure 67. Rhondda end-terraced; Home User Guide second page, LCBE team.

Appendix VIII – Chapter 7

MATERIALS TO BE USED

The principal items are

Titon HRV1.25Q Plus Auramode with summer bypass and summer boost.
125mm Round upvc ducting
125mm upvc ‘T’ joint
125mm upvc 90deg bend
125mm upvc 45deg bend
125mm Semi Rigid acoustic silencer
125mm upvc duct connector

125mm round to 204x60mm rectangle conversion piece
125mm dia. to 100mm dia. reducer

White steel air valves
Acrylic ducting joint sealant
12mm SDST screws
30mm No. 8 screws
20mm punched banding
2-core 0-10v signal cable

Figure 68. Rhondda end-terraced; MVHR materials to be used, Quest4 systems LTD for LCBE team.

Appendix IX – Chapter 7

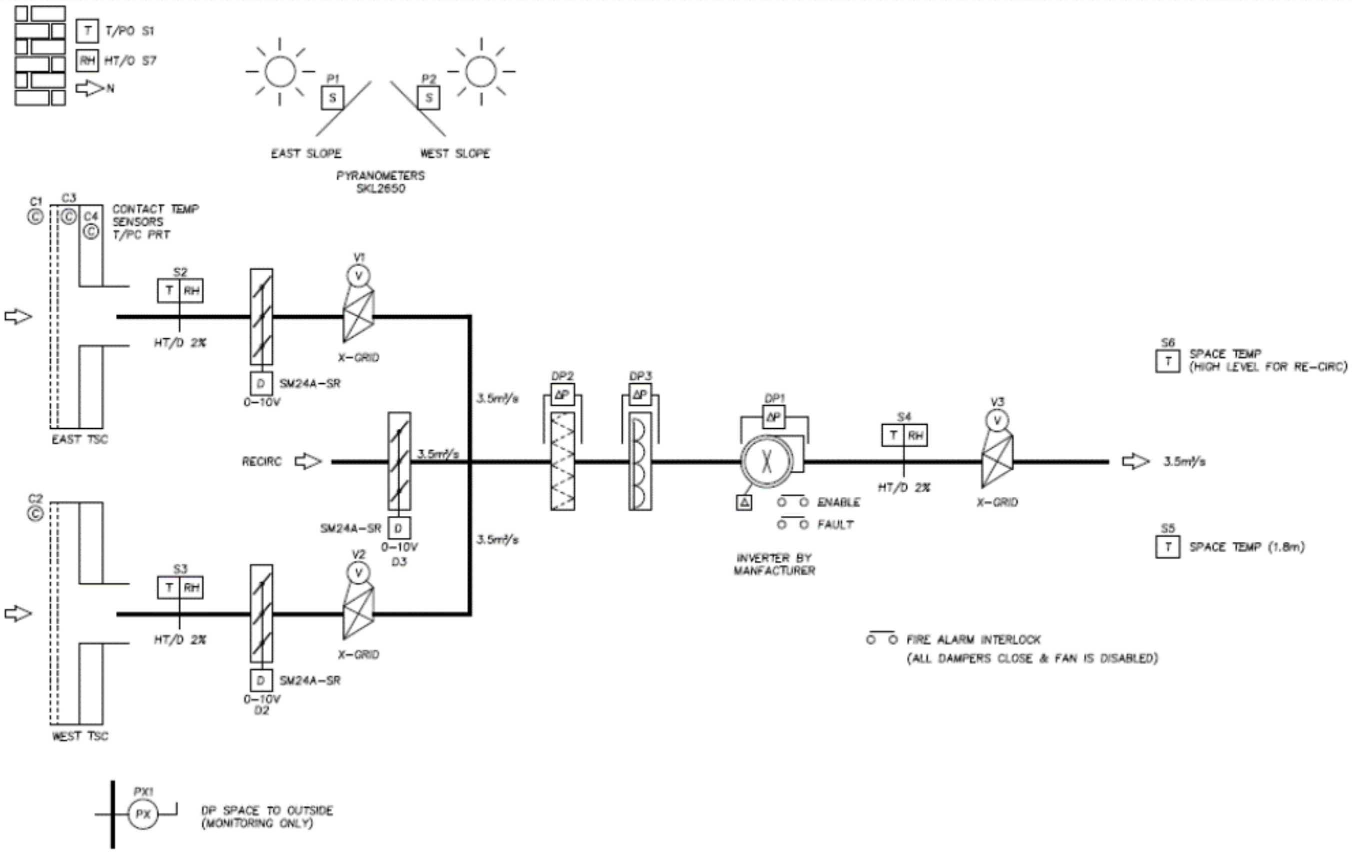


Figure 69. B&Q store; TSC system schematic, TATA steel for SBED team.

Table 17. B&Q store; Initial system settings, Tata steel for SBED team.

Vmin TSC East	1.2 m3/s
Vmin TSC West	1.2 m3/s
Space Temperature Setpoint	16 Deg. C (Fully adjustable on IQVIEW4 display)
Space Temp (Thermal Charge Boost) Setpoint	Space Setpoint +6 Deg. C (adjustable on display)
Supply Air High Limit	36 Deg. C (Fully adjustable on IQVIEW4 display)
Supply Air Low Limit	12 Deg. C (Fully adjustable on IQVIEW4 display)
Hi Ambient Threshold	18 Deg. C (Fully adjustable on IQVIEW4 display)
Duct Cross Sectional Area TSC East	1m^2 (Default). **N.B User needs to input correct value during installation on site.**
Duct Cross Sectional Area TSC West	1m^2 (Default). **N.B User needs to input correct value during installation on site.**
Controller Software Switch Positions; 1. Space Temp Driven 2. Space Temp Driven + Destrat 3. OFF	Initially set to mode 1

1.6 Demand Control

A '1.Space Temp Driven / 2.OFF' software switch on the IQVIEW 4 display dictates the demand control.

Space Temp Driven. TSC and controllers will be enabled at the dictates of the on-board time schedules (adjustable) to maintain space temp condition (see temperature control section).

Space Temp Driven + Destrat. System runs in constant recirculation mode during time schedule when no TSC renewable heat available.

Off TSC control is turned Off and both the TSC dampers D1, D2 and the Recirc Damper D2 will move to the closed position.

1.7 Temperature Control

When set to **'1. Space Temp Driven'** mode on the Trend IQVIEW4 display, the unit will operate to control the space air temperature at S5 to 16degC (adjustable). A programmable time schedule is provided outside of which TSC dampers D1, D2 and re-circ damper D3 will close.

Normal-When outside air temperature at S1 is greater than the space temperature setpoint +2degC, the space temperature setpoint shall remain the same

Boost-When outside air S1 is lower than the space setpoint +0degC, the space setpoint shall increase to space temperature setpoint +6°C to allow the building to be thermally charged using free renewable heat.

Supply Air temperature sensor at S4 will act as a high limit sensor set at 36Deg. C (adjustable). If S4 reaches 36 Deg. C then D3 will modulate open and D1, D2 close proportionately to achieve less than 36 Deg. C. If S4 exceeds 36 Deg. C at Vmin TSC then system is "off" for a delay period of 30 minutes.

1.8 System Start-Up

When the system is within the occupancy time schedule and is calling for heat input (i.e. space temperature < space temperature setpoint + boost if applicable) then the system will be permitted to start subject to the following;

If either TSC contact sensor temperature (C1, C2) is greater than current space temp + TBC Deg C then the AHU will be started and TSC dampers D1 and D2 open to their minimum flow (1.2 m3/s) so that air passes over the respective duct sensors S2 and S3.

The TSC dampers will start to modulate to 100% open if the respective duct temperatures are greater than space temperature set point. If the TSC duct temperature falls below space temperature set point then the respective TSC damper will start to modulate closed, to maintain duct temperature at space temperature set point, down to a minimum flow rate V min TSC. TSC damper will remain at Vmin TSC whilst either of the following conditions are met:

1. TSC duct temperature > TSC minimum supply temperature (12 Deg. C adj.)
2. TSC duct temperature > ambient temperature + minimum temperature lift (4 Deg. C adj.)

This recognises the net benefit of TSC air to reducing infiltration of cold ambient air.

When both TSCs are running at flow rates above the minimum then both east and west TSC's will modulate flow-rates off each TSC as measured at V1 and V2 to achieve equal TSC duct temperatures and this will vary according their individual solar gain. More flow is required from the collector with the greatest TSC duct temperature.

1.9 Volume Control

The re-circ damper D3 is modulated to maintain a volumetric flow rate as sensed on the supply air duct sensor V3of 3.5m^3/s (adj up to 4.0 m^3/s). As the TSC dampers D1& D2open to provide their heat contribution, the re-circ air damper will be proportionally closed in order to maintain the setpoint. Should the volumetric flow rate increase beyond the set-point following closure of the re-circ damper, the maximum positions of the TSC dampers will be re-scheduled in order to maintain the flow rate set-point.

1.10 Night Purge Routine

The night purge routine shall be enabled when a night cooling demand signal is received. This signal shall be initiated when the following occurs:

- The average afternoon outside air temperature at S1 > 20Deg C (adj) **and**
- The average daytime zone temperature at S5>22Deg C (adj)

The night purge routine shall run between the hours of 12PM- 5AM providing:

- The zone temperature S5 remains above the outside air temp S1 + 2Deg C (adj)
- The zone temperature > heating setpoint 16Deg C (adj)
- Outside air temp greater than 14Deg C (adj)

1.11 De-Stratification Control

During the occupancy period when there is a demand for heating (i.e. space temperature < space temperature setpoint) yet the external conditions prohibit any heat gains from either of the TSC's. The unit will run in full re-circ conditions provided that: the high level temperature at S6 is 3DegC (adjustable) > than the low level space temperature at S5; or that destrat mode is enabled (this will enable the link to the building BMS either for comms or control).

1.12 BMS General Alarms

Temperature out of limit Alarms

Recommended Clean of TSC

1.13 Fire Alarm Interface (provision)

Terminals within the panel will close the TSC and Ambient dampers on receipt of a Fire Alarm Signal (if used). This shall be a Normally Open Contact (by others) which closes on fire override. This is taken as an input to the controller which in turn closes both the TSC damper D1 and the ambient air damper D2.

1.14 BMS Control Points

Outside Air Temp	(degC)
Solar Irradiance East TSC	(W/m^2)
Solar Irradiance West TSC	(W/m^2)
TSC Skin Temp East TSC	(degC)
TSC Skin Temp West TSC	(degC)
Space Temp	(degC)
EastTSC Temp	(degC)
EastTSC RH	(%RH)
WestTSC Temp	(degC)
WestTSC RH	(%RH)
Ambient Air Temp	(degC)
Ambient RH	(%RH)
East TSC Damper Open	(%)
West TSC Damper Open	(%)
Recirc Damper Open	(%)
Velocity East TSC	(m/s)
Volumetric flow East TSC	(m^3/s) (N.B Duct Cross Sectional Area needs to be identified)
Velocity West TSC	(m/s)
Volumetric flow West TSC	(m^3/s) (N.B Duct Cross Sectional Area needs to be identified)
Supply Air Temp	(degC)
Supply Air RH	(%RH)
Unit Running Output	(IC Com)
Reznor Unit BMS Demand	(IC Com) For monitoring

Appendix X – Chapter 7

End of Life Material Disposal; Tata steel for SBED project.

R32 Profile Colorcoat Prisma® Steel Sheets - metal: widely recycled
Ashgrid galvanized light-weight steel support framework - metal: widely recycled
Unistrut and supports - metal: widely recycled
Steel Ducting - metal: widely recycled
Fans - Disposal in accordance with WEEE regulations (http://www.hse.gov.uk/waste/waste-electrical.htm)
Attenuators - Casings will be recyclable. Attenuator medium unlikely to be recyclable.
Filters - Paper filters will need to be disposed of, but due to particulates they're unlikely to be suitable for recycling.
Controls & Control Panels - as per WEEE regulations
Cabling - as per WEEE regulations
Electrical Trunking - plastic or metal: both widely recycled.
Sensors - as per WEEE regulations
Adhesives to secure sensors - not recyclable: hence to landfill
Fixings - metal: widely recycled

Appendix XI – Chapter 7

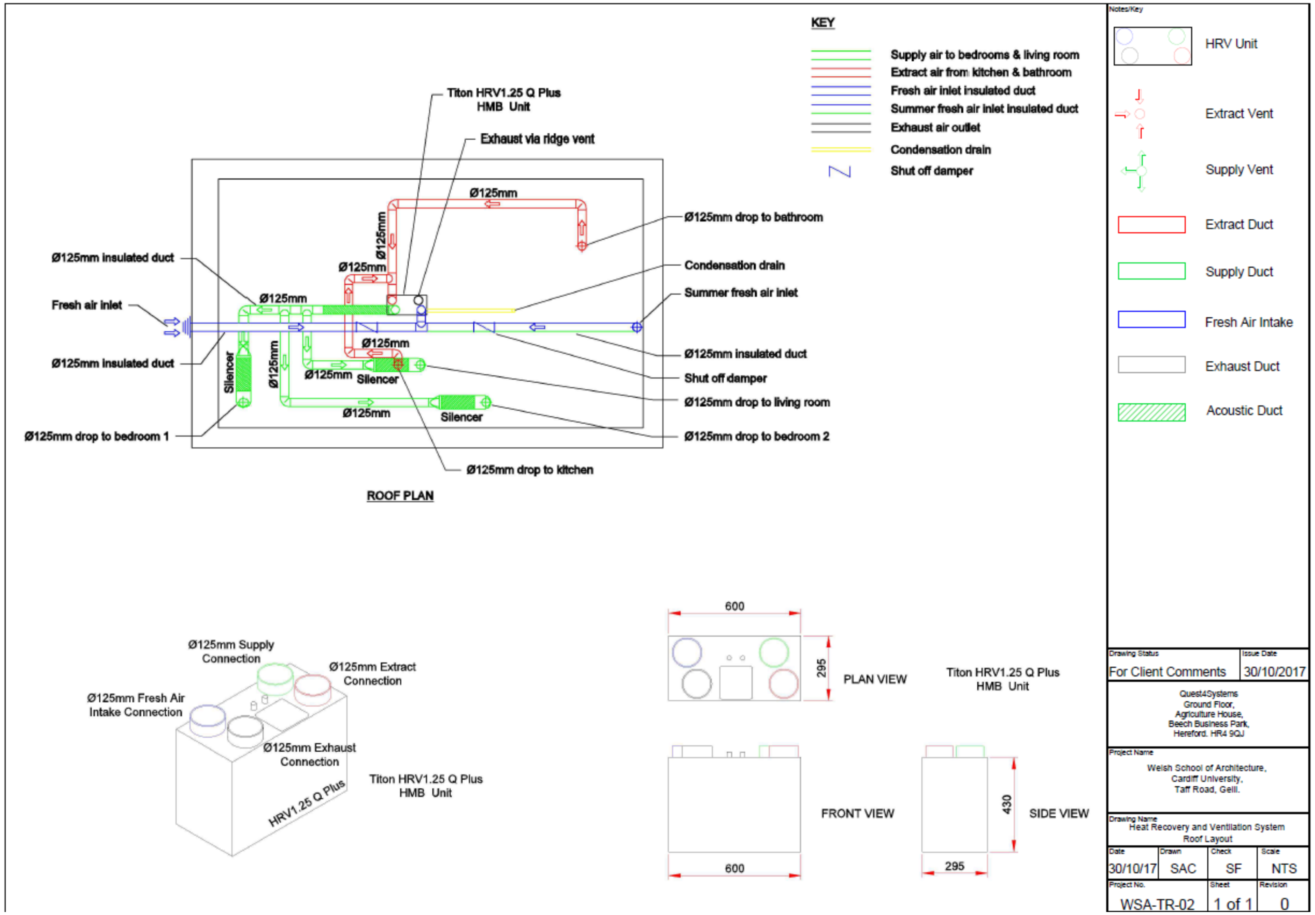


Figure 70. Rhondda end-terraced house; MVHR-TSC design prepared by Quest4 Systems LTD consulted by LCBE research project.

Appendix XII – Chapter 7

1.1 Control System Overview

This controls enclosure houses a Trend IQ3 Series DDC BMS controller which controls and monitors each Transpired Solar Collector (TSC). A door interlocked isolator is provided on the controls section. The Trend IQ3 controller can operate in a standalone capacity or can be integrated into a site wide BMS IP network. A Trend IQ VIEW 4 touch screen display panel is mounted on the control panel facia. This provides for local interrogation and operation of the TSC control system, settings and parameters (password protected).

1.2 Trend IQ3 Series Controller

The IQ3 controllers are Building Management System controllers that use Ethernet and TCP/IP networking technologies. Each controller incorporates a web server which can deliver user specific web pages to a PC or mobile device running internet browser software. If a system is set up with the correct connections, a user with the appropriate security codes can monitor or adjust the controller from any Internet access point in the world. It is also compatible with the traditional IQ system protocol.

Network TCP/IP

Additional description:

Ethernet 10 Mbps main network with TCP/IP protocol

Embedded web server

Security protected monitor/control via web browser

Compatible with existing IQ system protocol

100 to 240 Vac, or 24 Vac and 24 to 60 Vdc supply versions

Small footprint with DIN rail mounting

The IQView4 is a touch screen display which provides an interface to an IQ controller by way of its local supervisor port. It allows access to modules, graphs, alarms, and time-zones.

It has a 4.3 (109.2 mm) LCD touch screen colour display, and is housed with the electronics in a single unit suitable for rear panel mount applications. As well as a Home screen, the unit can be programmed with a number of favourite screens.

- Additional description
- Rear panel mount with front cover
- 24 Vac/dc input power supply
- Colour touch screen display
- Connects directly to IQ controller local supervisor port
- Compatible with IQ1s (v5 and above), IQ2s, IQ3s
- Key click sounder
- View of inputs, outputs, directories, logs
- Adjustment of knobs, switches, time zones, time

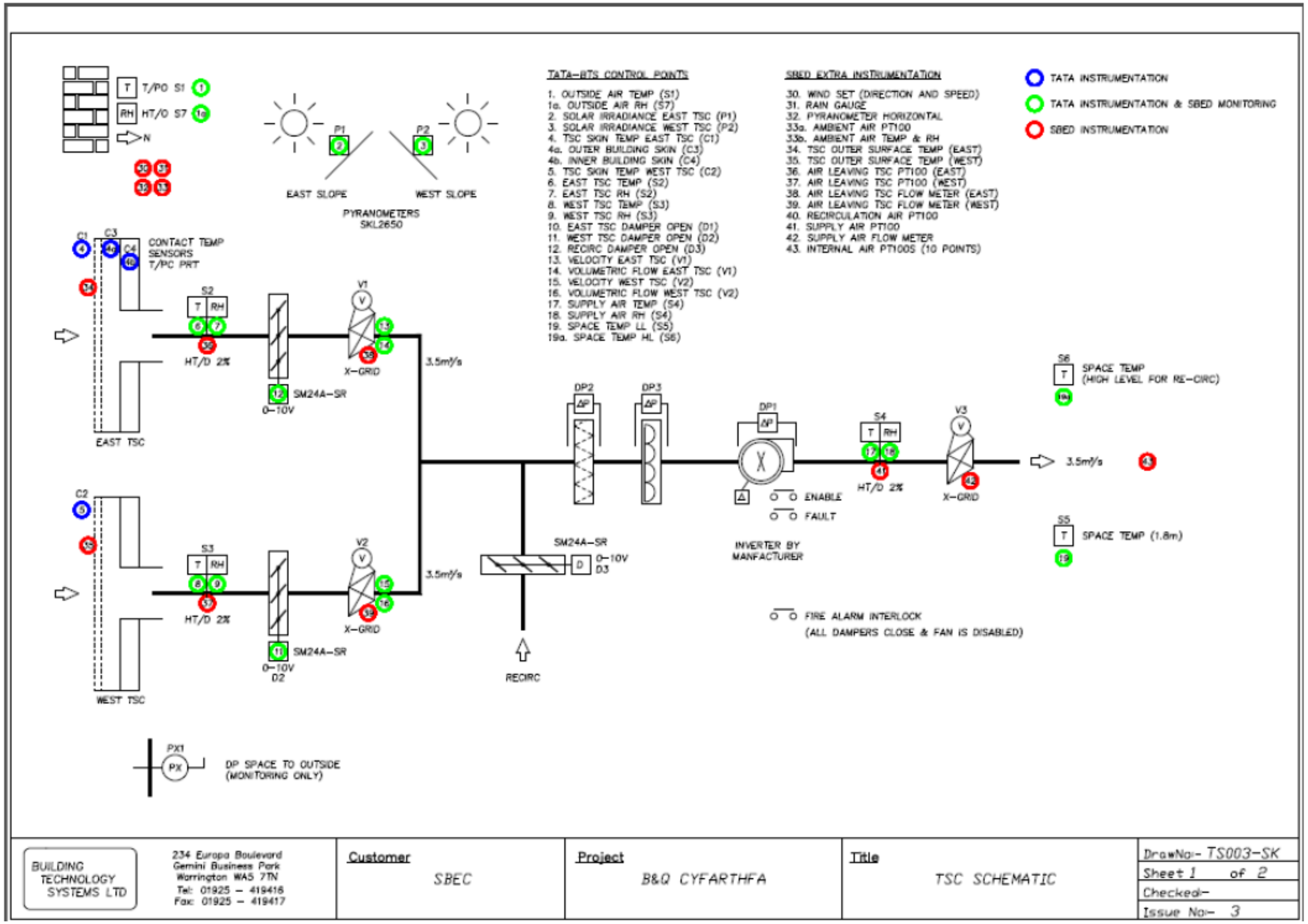


Figure 71. B&Q store; TSC system schematic including instrumentation and controls, TATA steel and SBED team.

Appendix XIII – Chapter 7

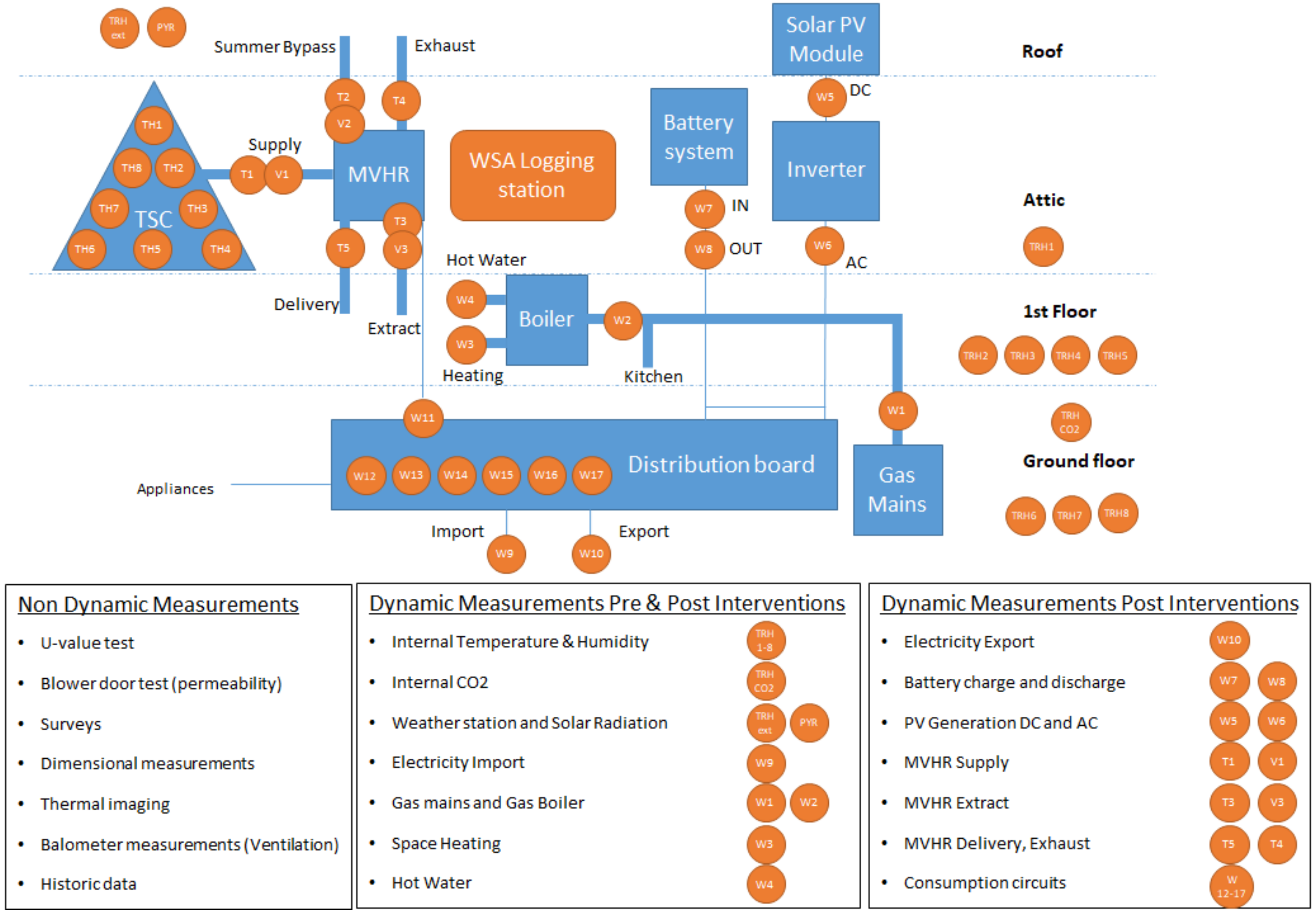


Figure 72. Rhondda end-terraced house; full monitoring plan for the whole retrofit, author.

Appendix XIV – Chapter 7

19. Please rate your overall satisfaction of the quality of the air in your house - freshness, smell, etc.:

Not satisfied 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☑ 7 ☐ Very satisfied

What rooms are particularly good or bad? What do you think is the cause?

Mornings - damp smell. - especially an Mainbedroom - worse.

20. Please rate the overall satisfaction of air movement in your house - draughts, air leaking from walls and/or windows, etc.:

Not satisfied 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☑ 7 ☐ Very satisfied

What rooms are particularly good or bad? What do you think is the cause?

Draught through front door.–

21. Is there damp / condensation problems in the following areas?

Please tick all relevant rooms

☑ Living room ☐ ~~Dining room~~ ☑ Kitchen ☑ Bedroom 1 ☑ Bedroom 2 ☑ Bathroom

☐ Other (*Please state*): ………………………… ☐ Other (*Please state*): …………………………

22. In general do you think it is too dry or damp in this house?

Too dry 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ Too damp

23. Do you feel that the house affects your health by making you feel less healthy or more healthy?

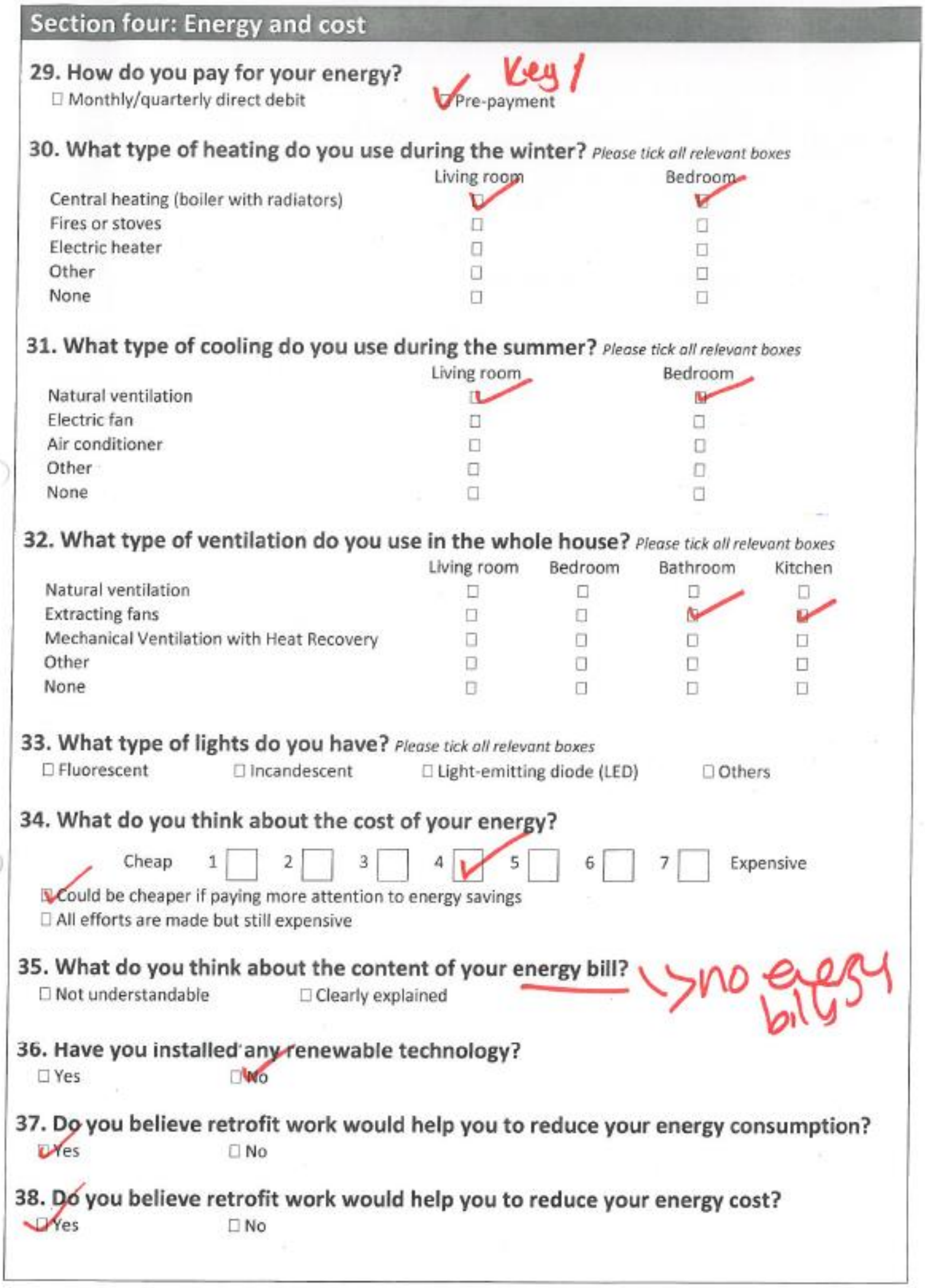
Less healthy 1 ☑ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ More healthy

Do you have any additional comments about the house's influences of your health?

- Sharons asthma has got worse - everyday.
- Coughing - all

[redacted]sthma pump.

Figure 73. Rhondda end-terraced house; part of questionnaire with responses, indicating pre-retrofit ventilation and heating issues (a), LCBE team.



Section four: Energy and cost

29. How do you pay for your energy? Key 1
☐ Monthly/quarterly direct debit ☑ Pre-payment

30. What type of heating do you use during the winter? *Please tick all relevant boxes*

	Living room	Bedroom
Central heating (boiler with radiators)	☑	☑
Fires or stoves	☐	☐
Electric heater	☐	☐
Other	☐	☐
None	☐	☐

31. What type of cooling do you use during the summer? *Please tick all relevant boxes*

	Living room	Bedroom
Natural ventilation	☑	☑
Electric fan	☐	☐
Air conditioner	☐	☐
Other	☐	☐
None	☐	☐

32. What type of ventilation do you use in the whole house? *Please tick all relevant boxes*

	Living room	Bedroom	Bathroom	Kitchen
Natural ventilation	☐	☐	☐	☐
Extracting fans	☐	☐	☑	☑
Mechanical Ventilation with Heat Recovery	☐	☐	☐	☐
Other	☐	☐	☐	☐
None	☐	☐	☐	☐

33. What type of lights do you have? *Please tick all relevant boxes*
☐ Fluorescent ☐ Incandescent ☐ Light-emitting diode (LED) ☐ Others

34. What do you think about the cost of your energy?
Cheap 1 ☐ 2 ☐ 3 ☐ 4 ☑ 5 ☐ 6 ☐ 7 ☐ Expensive
☑ Could be cheaper if paying more attention to energy savings
☐ All efforts are made but still expensive

35. What do you think about the content of your energy bill? → no energy bills
☐ Not understandable ☐ Clearly explained

36. Have you installed any renewable technology?
☐ Yes ☑ No

37. Do you believe retrofit work would help you to reduce your energy consumption?
☑ Yes ☐ No

38. Do you believe retrofit work would help you to reduce your energy cost?
☑ Yes ☐ No

Figure 74. Rhondda end-terraced house; part of questionnaire with responses, indicating pre-retrofit ventilation and heating issues (b), LCBE team.

Appendix XV – Chapter 7

Table 18. Sensors factors; non-dynamic sensor monitoring, author.

Measurement	Instrument	Important specifications
U value	Hukseflux HFP01 plates	• Range -2000 to +2000 W/m2 • Sensitivity 60 x 10-6 V/(W/m2) • Calibration uncertainty ±3%
	Type-T class 1 thermocouples	• -40°C to 125°C • ±0.5°C
	Tinytag Plus 2 TGP-4017 waterproof temperature sensors	• -40°C to +85°C • ±0.5°C from 0°C to +40°C • IP68
Permeability	Minneapolis blower door and fan Model 4 with a DG-700 flow gauge	• Up to 10,700 m3/hr • ±3% combined accuracy
Dimensional	LEICA DISTO D110 Laser distance measurer	• Up to 60m • Accuracy 1.5mm
Thermal imaging	FLIR i7 camera	• Spectral range 7.5-13μm • Resolution 120 x 120 pixels
	TESTO 405NTC anemometer	• Resolution 0.01m/s • Max velocity 10m/s • Accuracy ±5% + 0.3 m/s
Ventilation	Testo 417 vane anemometer	• Resolution 0.01m/s • Range +0.3 to +20 m/s • Accuracy ±1.5% + 0.1 m/s

Table 19. Sensors factors; dynamic sensor monitoring, author (continued overleaf).

Measurement	Instrument	Important specifications
Weather station	HC2S3 Rotronic temperature (PT100) and humidity probe	• -40ºC to + 60ºC • ±0.15ºC • <22sec • 0-100% RH • ±0.8% RH accuracy • <22s response time
	Young 05103 wind set	• 1-100m/s • ±0.3 m/s (±0.6 mph) or 1% of reading • 0 to 360° • ±3% (direction)
	CMP3 Kipp & Zonen pyranometer	• Spectral range 300 to 2800 nm • 10 to 32 µV/W/m² • < 4 % • <20s response time
Environmental	Tinytag Plus 2 TGP-4500 waterproof temperature and humidity sensors	• -35ºC to +85ºC • ±0.5ºC from 0ºC to +40ºC • 0-100% RH • ±3% RH accuracy • IP68
	Type-T class 1 thermocouples	• -40ºC to 125ºC • ±0.5ºC
	PT100 class A 4wire temperature sensors	• -50ºC to +260ºC • ±0.15ºC +0.002ºC x t • <2s response time
	Flamefast CO_2, T, RH sensor	• CO_2 range 0-10,000ppm • ±40ppm +3% • Temperature range 0-50ºC • ±0.5ºC • RH range 0-100% • ±2% @ 20 - 80%
Energy	Itron G4 Secondary gas meters	• 6m3/h max flow • 1pulse=0.01m3
	Sontex Supercal 539 Heat meters	• 2.5m3/h max flow • 1pulse=0.01m3 • PT1000 accuracy
	DDS 353 50A DIN rail electricity meter	• 45A max current • 1pulse = 1Wh

Measurement	Instrument	Important specifications
Flow	Low differential pressure sensor (TPAVT8/10) and multi point velocity probes (TPVPMP) from Titan	• 0-100Pa • 0-10m/s, • Accuracy ±3% • 0.5s response time

Appendix XVI – Chapter 7

CR1000 WS	Project Name:	Saxon Court	Date revised:	17/03/2015

	1			2			3			4										POWER IN	
	1	2	⏚	3	4	⏚	5	6	⏚	7	8	⏚		⏚		⏚		⏚			
	H	L		H	L		H	L		H	L		VX1		P1		P2			G	12V DC
NAME	SE PYR01	SE PYR02	SE PYR03	SE PYR04	SE PYR05	SE PYR06	LA WD01		LA WD03	LA WD01		LA WD03	GC WD02	GC WD04	LGCWS01	GC WS02	LGCWS01	GC WS02	GROUND LUG	Power Supply	
WIRING							3 black		4 black	3 black		4 black	3 blue	4 blue	5 black	5 blue	9 black	9 blue			
DESTINATION	SE Pyranometer horizontal			SE Pyranometer inclined			LA Wind Direction			LA Wind Direction			LA Wind Direction		LA Wind Speed		LA Rain Gage		⏚	Battery or 240AC/12DC Transformer	
COMMENT	check cable colours			check cable colours			check 24 core cable colours			check 24 core cable colours			check 24 core colour		check 24 core colour		check 24 core colour			Check + & - wiring	

CAMPBELL SCIENTIFIC

	5			6			7			8						RS-232
	9	10	⏚	11	12	⏚	13	14	⏚	15	16	⏚		⏚		
	H	L		H	L		H	L		H	L		VX2		VX3	
NAME													GC WD02	GC WD04		
WIRING													3 blue	4 blue		
DESTINATION													LA Wind Direction			
COMMENT													check 24 core colour			

	POWER OUT								COM1		COM2			COM3		COM4			CS I/O	PERIPHERAL PORT
									Tx	Rx	Tx	Rx		Tx	Rx	Tx	Rx			
	G	5V	G	SW12V	G	12V	12V	G	C1	C2	C3	C4	G	C5	C6	C7	C8	G		
NAME							LA TRH03	LA TRH02								GC TRH04		GC TRH01		
WIRING							7 black	7 blue								6 blue		6 black		
DESTINATION							Weth. St. TRH									W.S. TRH		W.S. TRH		
COMMENT							check 24 core colour									24 core		24 core		

CR1000 TSC	Project Name:	Saxon Court	Date revised:	17/03/2015

	1			2			3			4										POWER IN	
	1	2	⏚	3	4	⏚	5	6	⏚	7	8	⏚		⏚		⏚		⏚			
	H	L		H	L		H	L		H	L		VX1		P1		P2			G	12V DC
NAME	4WB100 module			AM16 PTs			AM32 Volt a						4WB100						GROUND LUG	Power Supply	
WIRING																					
DESTINATION		ODD H	ODD L	EVEN H	EVEN L		ODD H	ODD L	ODD H				1 H						⏚	Battery or 240AC/12DC Transformer	
COMMENT	check the 8 core wire colour codes						check 4 or 8 wire colour						PT100 ex							Check + & - wiring	

CAMPBELL SCIENTIFIC

	5			6			7			8						RS-232
	9	10	⏚	11	12	⏚	13	14	⏚	15	16	⏚		⏚		
	H	L		H	L		H	L		H	L		VX2		VX3	
NAME	SCVM01			SCVM02			SCVM03									
WIRING			ground			ground			ground							
DESTINATION	Air del Flow Ground fl			Air del Flow First fl			Air del Flow First fl									
COMMENT	check instrument wiring			check instrument wiring			check instrument wiring									

	POWER OUT								COM1		COM2			COM3		COM4			CS I/O	PERIPHERAL PORT
									Tx	Rx	Tx	Rx		Tx	Rx	Tx	Rx			
	G	5V	G	SW12V	G	12V	12V	G	C1	C2	C3	C4	G	C5	C6	C7	C8	G		
NAME					AM32 Volt a		AM16 PTs		AM16 PTs		AM32 Volt a									
WIRING																				
DESTINATION					G	12V	12V	G	CLK	RES	CLK	RES								
COMMENT					check wire colour		check the 8 core wire colour codes				check wire colour									

Figure 75. Saxon court residence; logging terminals wiring diagram (a), author.

AM16 PTs	Project Name:	Saxon Court	Date revised:	17/03/2015		
	1	**2**	**3**	**4**	**5**	**6**
	1 (H, L), ⏚, 2 (H, L), ⏚	3 (H, L), ⏚, 4 (H, L), ⏚	5 (H, L), ⏚, 6 (H, L), ⏚	7 (H, L), ⏚, 8 (H, L), ⏚	9 (H, L), ⏚, 10 (H, L), ⏚	11 (H, L), ⏚, 12 (H, L), ⏚
NAME	SCPT02	SCPT03	SCPT04	SCPT05	SCPT06	SCPT07
WIRING						
DESTINATION	U2-Air delivery T Ground floor	U3-Internal space T South Ground floor	U3N-Internal space T North Ground floor	U5-Air delivery T 1st floor	U6-Internal space T South 1st floor	U2N-Internal space T North 1st floor
COMMENT	check the 24 core weather station wire colour codes	check the extension wire colour code	check the extension wire colour code	check the extension wire colour code	check the extension wire colour code	check the extension wire colour code
	Connection	**COM**	**7**	**8**	**9**	**10**
	RES, CLK, ⏚, 12V	ODD (H, L), ⏚, EVEN (H, L), ⏚	13 (H, L), ⏚, 14 (H, L), ⏚	15 (H, L), ⏚, 16 (H, L), ⏚	17 (H, L), ⏚, 18 (H, L), ⏚	19 (H, L), ⏚, 20 (H, L), ⏚
NAME	Connection to CR1000 power & trigger; 4x16	Connection to the CR1000 ports	SCPT08	SCPT09	SCPT10	
WIRING	2x32	ground; ground				
DESTINATION	Rx C2; Tx C1; G; 12V	4WB L Ch.1; 4WB G Ch.1; ground; Ch. 2 H; Ch.2 L; ground	U8-Air delivery T 2nd floor	U9-Internal space T South 2nd floor	U1N-Internal space T North 2nd floor	
COMMENT	check the 8 core wire colour codes		check the extension wire colour code	check the extension wire colour code	check the extension wire colour code	
	11	**12**	**13**	**14**	**15**	**16**
	21 (H, L), ⏚, 22 (H, L), ⏚	23 (H, L), ⏚, 24 (H, L), ⏚	25 (H, L), ⏚, 26 (H, L), ⏚	27 (H, L), ⏚, 28 (H, L), ⏚	29 (H, L), ⏚, 30 (H, L), ⏚	31 (H, L), ⏚, 32 (H, L), ⏚
NAME						
WIRING						
DESTINATION						
COMMENT						

AM32 Vs a	Project Name:	Saxon Court	Date revised:	17/03/2015		
	1	**2**	**3**	**4**	**5**	**6**
	1 (H, L), ⏚ / 2 (H, L), ⏚	3 (H, L), ⏚ / 4 (H, L), ⏚	5 (H, L), ⏚ / 6 (H, L), ⏚	7 (H, L), ⏚ / 8 (H, L), ⏚	9 (H, L), ⏚ / 10 (H, L), ⏚	11 (H, L), ⏚ / 12 (H, L), ⏚
NAME	P1 / C1a	C1b / C1c	C2a / C2b	C2c / S1	S2 / D1a	D2a / Va
WIRING	ground / ground	ground / ground	ground / ground	ground / ground	ground / ground	ground / ground
DESTINATION	Shared Pyranometer / TSC1 outer surface ground fl	TSC1 outer surface 1st fl / TSC1 outer surface 2nd fl	TSC2 outer surface ground fl / TSC2 outer surface 1st fl	TSC2 outer surface 2nd fl / Shared Ambient T	Shared Ambient RH / Bypass Damper Ground fl	Delivery Damper Ground fl / Shared Delivery V ground fl
COMMENT	Check colour code / Check colour code	Check colour code / Check colour code	Check colour code / Check colour code	Check colour code / Check colour code	Check colour code / 2:1 H, 2:1 L, 2:1 G	2:1 H, 2:1 L, 2:1 G / Check colour code
		COM	**7**	**8**	**9**	**10**
	RES, CLK, ⏚, 12V	ODD (H, L), ⏚, EVEN (H, L), ⏚	13 (H, L), ⏚ / 14 (H, L), ⏚	15 (H, L), ⏚ / 16 (H, L), ⏚	17 (H, L), ⏚ / 18 (H, L), ⏚	19 (H, L), ⏚ / 20 (H, L), ⏚
NAME	Connection to CR1000 power & trigger; 4x16	Connection to the CR1000 ports	S3a / S4a	D1b / D2b	Vb / S3b	S4b / D1c
WIRING			ground / ground	ground / ground	ground / ground	ground / ground
DESTINATION	Rx C4; Tx C3; G; 12V; 2x32	Ch. 5 H; Ch. 5 L; Ch. 5 G	delivery Temp Ground fl / delivery RH Ground fl	Bypass Damper 1st fl / Delivery Damper 1st fl	Shared Delivery V 1st fl / delivery Temp 1st fl	delivery RH 1st fl / Bypass Damper 2nd fl
COMMENT	check 4 or 8 wire colour	check 4 or 8 wire colour	Check colour code / Check colour code	2:1 H, 2:1 L, 2:1 G / 2:1 H, 2:1 L, 2:1 G	Check colour code / Check colour code	Check colour code / 2:1 H, 2:1 L, 2:1 G
	11	**12**	**13**	**14**	**15**	**16**
	21 (H, L), ⏚ / 22 (H, L), ⏚	23 (H, L), ⏚ / 24 (H, L), ⏚	25 (H, L), ⏚ / 26 (H, L), ⏚	27 (H, L), ⏚ / 28 (H, L), ⏚	29 (H, L), ⏚ / 30 (H, L), ⏚	31 (H, L), ⏚ / 32 (H, L), ⏚
NAME	D2c / Vc	S3c / S4c	S5aS / S5aN	S5bS / S5bN	S5cS / S5cN	
WIRING	ground / ground	ground / ground	ground / ground	ground / ground	ground / ground	
DESTINATION	Delivery Damper 2nd fl / Shared Delivery V 2nd fl	delivery Temp 2nd fl / delivery RH 2nd fl	Internal Ground fl South / Internal Ground fl North	Internal 1st fl South / Internal 1st fl North	Internal 2nd fl South / Internal 2nd fl North	
COMMENT	2:1 H, 2:1 L, 2:1 G / Check colour code	Check colour code / Check colour code	Check colour code / Check colour code	Check colour code / Check colour code	Check colour code / Check colour code	

Figure 76. Saxon court residence; logging terminals wiring diagram (b), author.

Appendix XVII – Chapter 7

```
'CR1000 Saxon Court
'Declare Variables and Units
'   6 x 2:1   Voltage  Dividers  Required
Dim LCount_3
Dim LCount_4
Dim LCount_6
Dim HalfBR(9)
Public BattV
Public PT100(9)
Public SEVolt(30)
Public SolinckW
Public TpRH(2)
Public Rain_mm
Public FanPower

Alias TpRH(1)=AirTp
Alias TpRH(2)=RH
Alias PT100(1) = PT_Del_Gndfl
Alias PT100(2) = PT_IntS_Gndfl
Alias PT100(3) = PT_IntN_Gndfl
Alias PT100(4) = PT_Del_1stfl
Alias PT100(5) = PT_IntS_1stfl
Alias PT100(6) = PT_IntN_1stfl
Alias PT100(7) = PT_Del_2ndfl
Alias PT100(8) = PT_IntS_2ndfl
Alias PT100(9) = PT_IntN_2ndfl

Alias SEVolt(1) = v1_Pyran
Alias SEVolt(2) = v2_TSC1skin_Gndfl
Alias SEVolt(3) = v3_TSC1skin_1stfl
Alias SEVolt(4) = v4_TSC1skin_2ndfl
Alias SEVolt(5) = v5_TSC2skin_Gndfl
Alias SEVolt(6) = v6_TSC2skin_1stfl
```

```
Alias SEVolt(7) = v7_TSC2skin_2ndfl
Alias SEVolt(8) = v8_AmbT
Alias SEVolt(9) = v9_AmbRH
Alias SEVolt(10) = v10_Dmp_Byp_Gndfl          'Requires 2:1 Divider
Alias SEVolt(11) = v11_Dmp_Del_Gndfl          'Requires 2:1 Divider
Alias SEVolt(12) = v12_Flow_Del_Gndfl
Alias SEVolt(13) = v13_Temp_Del_Gndfl
Alias SEVolt(14) = v14_RH_Del_Gndfl
Alias SEVolt(15) = v15_Dmp_Byp_1stfl          'Requires 2:1 Divider
Alias SEVolt(16) = v16_Dmp_Del_1stfl          'Requires 2:1 Divider
Alias SEVolt(17) = v17_Flow_Del_1stfl
Alias SEVolt(18) = v18_Temp_Del_1stfl
Alias SEVolt(19) = v19_RH_Del_1stfl
Alias SEVolt(20) = v20_Dmp_Byp_2ndfl          'Requires 2:1 Divider
Alias SEVolt(21) = v21_Dmp_Del_2ndfl          'Requires 2:1 Divider
Alias SEVolt(22) = v22_Flow_Del_2ndfl
Alias SEVolt(23) = v23_Temp_Del_2ndfl
Alias SEVolt(24) = v24_RH_Del_2ndfl
Alias SEVolt(25) = v25_IntS_Gndfl
Alias SEVolt(26) = v26_IntN_Gndfl
Alias SEVolt(27) = v27_IntS_1stfl
Alias SEVolt(28) = v28_IntN_1stfl
Alias SEVolt(29) = v29_IntS_2ndfl
Alias SEVolt(30) = v30_IntN_2ndfl

Units SolinckW=kW/m^2
Units Rain_mm=mm

'Define Data Tables
DataTable(Table2,True,-1)
	DataInterval(0,1440,Min,10)
	Minimum(1,BattV,FP2,False,False)
EndTable
DataTable(PrinSt_Met,True,-1)
	DataInterval(0,60,Sec,10)
	Sample(1,SolinckW,FP2)
	Sample(1,AirTp,FP2)
```

```
    Sample(1,RH,FP2)
 Sample(1,PTAmbi_1, FP2)
    Totalize(1,Rain_mm,FP2,False)
EndTable

DataTable(PT100s,True,-1)
    DataInterval(0,60,Sec,10)

Sample(1,PT_Del_Gndfl, FP2)
Sample(1,PT_IntS_Gndfl, FP2)
Sample(1,PT_IntN_Gndfl, FP2)
Sample(1,PT_Del_1stfl, FP2)
Sample(1,PT_IntS_1stfl, FP2)
Sample(1,PT_IntN_1stfl, FP2)
Sample(1,PT_Del_2ndfl, FP2)
Sample(1,PT_IntS_2ndfl, FP2)
Sample(1,PT_IntN_2ndfl, FP2)
EndTable

DataTable(SEVolts,True,-1)
    DataInterval(0,60,Sec,10)

Sample(1,v1_Pyran, FP2)
Sample(1,v2_TSC1skin_Gndfl, FP2)
Sample(1,v3_TSC1skin_1stfl, FP2)
Sample(1,v4_TSC1skin_2ndfl, FP2)
Sample(1,v5_TSC2skin_Gndfl, FP2)
Sample(1,v6_TSC2skin_1stfl, FP2)
Sample(1,v7_TSC2skin_2ndfl, FP2)
Sample(1,v8_AmbT, FP2)
Sample(1,v9_AmbRH, FP2)
Sample(1,v10_Dmp_Byp_Gndfl, FP2)
Sample(1,v11_Dmp_Del_Gndfl, FP2)
Sample(1,v12_Flow_Del_Gndfl, FP2)
Sample(1,v13_Temp_Del_Gndfl, FP2)
Sample(1,v14_RH_Del_Gndfl, FP2)
Sample(1,v15_Dmp_Byp_1stfl, FP2)
```

```
Sample(1,v16_Dmp_Del_1stfl, FP2)
Sample(1,v17_Flow_Del_1stfl, FP2)
Sample(1,v18_Temp_Del_1stfl, FP2)
Sample(1,v19_RH_Del_1stfl, FP2)
Sample(1,v20_Dmp_Byp_2ndfl, FP2)
Sample(1,v21_Dmp_Del_2ndfl, FP2)
Sample(1,v22_Flow_Del_2ndfl, FP2)
Sample(1,v23_Temp_Del_2ndfl, FP2)
Sample(1,v24_RH_Del_2ndfl, FP2)
Sample(1,v25_IntS_Gndfl, FP2)
Sample(1,v26_IntN_Gndfl, FP2)
Sample(1,v27_IntS_1stfl, FP2)
Sample(1,v28_IntN_1stfl, FP2)
Sample(1,v29_IntS_2ndfl, FP2)
Sample(1,v30_IntN_2ndfl, FP2)

EndTable

'Main Program
BeginProg
        Scan(60,Sec,1,0)
                'Default Datalogger Battery Voltage measurement BattV
                Battery(BattV)
                'CM6B & CM11 Pyranometer (CSL) measurements SlrkJ and SlrkW
                        VoltDiff(SolinckW,1,mV25,1,True,0,_60Hz,1,0)
                If SolinckW<0 Then SolinckW=0
'               SolinckJ=SolinckW*3.333333
                SolinckW=SolinckW*0.1111111 'change
                'CS215 Temperature & Relative Humidity Sensor measurements
AirTp and RH
'''     SDI12Recorder(TpRH(),1,"??,"M!",1,0)
        '52202/52203 Rain Gage (CSL) measurement Rain_mm
'''     PulseCount(Rain_mm,1,2,2,0,0.1,0)
                'Fan Power - find pulse rate!
'''             PulseCount(FanPower,1,1,2,1,??,0)
```

```
'_______________________________________________________________________
_____________________________
'                     Turn AM16/32 Multiplexer On         P T 1 0 0
   PortSet(2,1)
                  Delay(0,150,mSec)
                  LCount_4=1
                  SubScan(0,uSec,10)
                           'Switch to next AM16/32 Multiplexer channel
                           PulsePort(1,10000)
    'PT100 PRT Temperature Probe (4WPB100) (CSL) measurements on the
AM16/32 Multiplexer
    BrHalf4W(HalfBR(LCount_4),1,mV25,mV25,4,1,1,2035,True,True,0,_50Hz,1,0)
    PRTCalc (PT100(LCount_4),1,HalfBR(LCount_4),1,1.0,0)
                           LCount_4=LCount_4+1
                  NextSubScan
                  'Turn AM16/32 Multiplexer Off
                  PortSet(2,0)
                  Delay(0,150,mSec)

'_______________________________________________________________________
_____________________________
'                     Turn AM16/32 Multiplexer On      S E V o l t s
                  PortSet(4,1)
                  Delay(0,150,mSec)
                  LCount_6=1
                  SubScan(0,uSec,30)
                           'Switch to next AM16/32 Multiplexer channel
                           PulsePort(3,10000)
                           'Generic Single Ended Voltage measurements on the AM16/32
Multiplexer:
                           VoltDiff(SEVolt(LCount_6),1,mV5000,5,True,0,_60Hz,1,0)
                           LCount_6=LCount_6+1
                  NextSubScan
                  'Turn AM16/32 Multiplexer Off
                  PortSet(4,0)
                  Delay(0,150,mSec)
'____________________________________________________________________
```

```
v1_Pyran= v1_Pyran/5
v2_TSC1skin_Gndfl=(v2_TSC1skin_Gndfl-960)/76.8-10
v3_TSC1skin_1stfl=(v3_TSC1skin_1stfl-960)/76.8-10
v4_TSC1skin_2ndfl=(v4_TSC1skin_2ndfl-960)/76.8-10
v5_TSC2skin_Gndfl=(v5_TSC2skin_Gndfl-960)/76.8-10
v6_TSC2skin_1stfl=(v6_TSC2skin_1stfl-960)/76.8-10
v7_TSC2skin_2ndfl=(v7_TSC2skin_2ndfl-960)/76.8-10
v8_AmbT= (v8_AmbT-960)/42.6666-40
v9_AmbRH= (v9_AmbRH-960)/38.4
'v10_Dmp_Byp_Gndfl
'v11_Dmp_Del_Gndfl
v12_Flow_Del_Gndfl= (v12_Flow_Del_Gndfl-960)/384
v13_Temp_Del_Gndfl= (v13_Temp_Del_Gndfl-960)/96
v14_RH_Del_Gndfl= (v14_RH_Del_Gndfl-960)/38.4
'v15_Dmp_Byp_1stfl
'v16_Dmp_Del_1stfl
v17_Flow_Del_1stfl= (v17_Flow_Del_1stfl-960)/384
v18_Temp_Del_1stfl= (v18_Temp_Del_1stfl-960)/96
v19_RH_Del_1stfl= (v19_RH_Del_1stfl-960)/38.4
'v20_Dmp_Byp_2ndfl
'v21_Dmp_Del_2ndfl
v22_Flow_Del_2ndfl= (v22_Flow_Del_2ndfl-960)/384
v23_Temp_Del_2ndfl= (v23_Temp_Del_2ndfl -960)/96
v24_RH_Del_2ndfl= (v24_RH_Del_2ndfl-960)/38.4
v25_IntS_Gndfl= (v25_IntS_Gndfl-960)/76.8-10
v26_IntN_Gndfl= (v26_IntN_Gndfl-960)/76.8-10
v27_IntS_1stfl= (v27_IntS_1stfl-960)/76.8-10
v28_IntN_1stfl= (v28_IntN_1stfl-960)/76.8-10
v29_IntS_2ndfl= (v29_IntS_2ndfl-960)/76.8-10
v30_IntN_2ndfl= (v30_IntN_2ndfl-960)/76.8-10


'_______________________________________________________________________

          'Call Data Tables and Store Data
          CallTable(PT100s)
```

```
        CallTable(SEVolts)
        CallTable(PrinSt_Met)
        CallTable(Table2)
    NextScan
EndProg
```

Appendix XVIII – Chapter 8

Key performance indicators

- Total heat savings (11)
- Heat delivered (11)
- TSC cost (6)
- % of heat supply (5)
- TSC cost and payback (2)
- Whole building energy demand/consumption (1)
- Cost savings (1)
- Power output (1)

Supplementary performance indicators

- Efficiency (5)
- Efficiency vs incident solar (2)
- Efficiency vs wind speed (2)
- Efficiency averages (1)
- Efficiency vs air flow (1)
- Efficiency vs suction velocity (1)
- Efficiency and Trise vs solar (1)
- Efficiency vs modelled efficiency (1)
- Efficiency vs plate and ambient T (1)
- Temperature variations (3)
- Temperature variations vs solar (1)
- Stratification T variations (1)
- Destratification savings (3)
- Destratification (1)
- Stratification (1)
- Back wall impact (1)
- Back wall recaptured heat (1)
- Air leakage and conduction losses of back wall (1)
- Heat losses and gains of back wall (1)
- Fan energy consumption (3)
- Collected energy utilisation (1)

- Meteorological data validation (2)
- Solar (1)
- Active solar heat collected (2)
- Heat delivered vs incident solar (1)
- Room recirculation heat (1)
- Radiant heat loss (1)
- Night-time recaptured heat (1)
- Passive solar heat and T gains
- Heat losses and gains of ducts (1)
- Air flow (1)
- TSC cost / kWh/m2a (1)
- Pressure drop (1)
- CO2 savings (1)

Literature seasonality of analysis [annually/seasonally/monthly/hourly]

- (NREL) Daily, but it was suggested that the evaluation of the TSC efficiency is performed weekly or over longer periods of time
- (Ford) averaged daily data per month.
- (GM) averaged daily data per month and hourly air flow.
- (Gottingen) weekly.
- (Bombardier) annual.
- (US army Hangar) annual.
- (Intek) unclear depth – possibly due to low quality measurements. 15-min interval, hourly flow rate.
- (BigHorn) no analysis
- (CA Group) monthly normalised based on degree days. Annual savings presented too
- (Broiler Barns) unclear – one-day brief analysis presented and total annual value presented
- (PIMSA) 3-month and almost daily (unclear from the graph).
- (Wal-mart) monthly – for 2 months when monitoring took place.
- (Windsor) no analysis, but estimation of annual average delivered energy through simulations and from monitoring results from another apartment building.

- (Judgeford) daily (max and average energy, max power/m2, fan consumption)
- (Wheatley) “The energy generated per hour was calculated.” Estimation of annual produced energy. Some daily analysis too.

Comparisons

- (NREL) comparison of efficiencies on consecutive days. Also the heat transfer to/from the concrete back wall was also considered through modelling and the impact was observed in monitoring data.
- (Ford) monthly comparisons of averaged daily data. Monitored meteorological data (vertical solar radiation, daytime and night-time averaged ambient temperature) compared against TMY values for Toronto.
- (GM) monthly comparisons of averaged daily data. Monitored solar radiation ambient temperature compared against the TMY values for Toronto. Compared fans’ daily energy consumption and hourly air flow before and after modifications. Compared monitored ceiling temperatures during the fans’ operation and on fan-off mode to calculate destratification savings.
- (Gottingen) implied that monitored meteorological data (vertical solar radiation, ambient temp and wind speed) were compared against data captured from a meteorological station.
- (Bombardier), (US army Hangar), (BigHorn), (Broiler Barns) no comparisons
- (Intek) compared measured air flow rate to designed air flow rate. The instantaneous efficiency was calculated and compared with Kutscher’s and Van Decker’s models for efficiency prediction. Cost: energy gain of the TSC was financially compared to a potential gas system.
- (CA Group) Data from energy consumption bills served for comparison with monitored data. Monthly comparisons are possible.
- (PIMSA) monitoring outputs compared with simulation outputs from RETScreen. Compared delivered energy between two 3-month periods of monitoring.
- (Wal-mart) month with another month (Jan and Feb)

    - (Windsor) cost: compared TSC system cost against conventional cladding system.
    - (Judgeford) comparisons among the different panels
    - (Wheatley) comparison with or without insulation

Visualisation

- (NREL) collector radiation and ambient temperatures daily
- (Ford) no graph visualisation – only two tables with monthly data averaged per day. Though they mention that instantaneous active solar efficiency values were plotted against collector air flow rate for monitored wind speeds reaching up to 3.5m/s. Wind effects on the perforated collector and correlations with the heat rise were assessed by monitoring wind direction and speed.
- (GM) Heat recaptured from the building through the wall VS active solar heat collected by the TSC. Used tables for comparisons.
- (Gottingen) various stacked column graphs as described below:
    - heat collected through the TSC and heat from the building recirculated air per week.
    - Weekly daytime and night-time heat balance including Qwall, Qleak, Qsolar, Qduct.
    - Weekly total heat savings.
    - Weekly mean efficiency and mean air flow rate
- (Bombardier), (US army Hangar), (BigHorn), (Windsor) no visualisation.
- (Intek) 15-min interval air temperature difference between ceiling and floor level for a 3-day period. No further graphs, but mentioned that measured and modelled efficiency was also plotted against plate and ambient temperatures.
- (CA Group) Table with TSC contribution normalised based on dd. Graph showing air temperature stratification/temperature variations prob 5-min int over 2 months.
- (Broiler Barns) Heating load and inlet fresh air temperature on a representative day
- (PIMSA) column graph with TSC heating power mapped on the building's heating requirement.

- (Wal-mart) plot of the delivered energy versus the incident solar energy for each month (Jan and Feb). Graph plotting air flow against temperature with rectangle areas showing delivered energy portion of total collected energy for a given preheat temperature.
- (Judgeford) no graphs – only tables with daily data (max and average energy, max power/m2, fan consumption)
- (Wheatley) Graph - variations of temperatures during a day in March 2011 were presented, where the temperatures of the steel cladding, external and internal wall, incoming air and cavity are plotted

Appendix XIX – Chapter 8

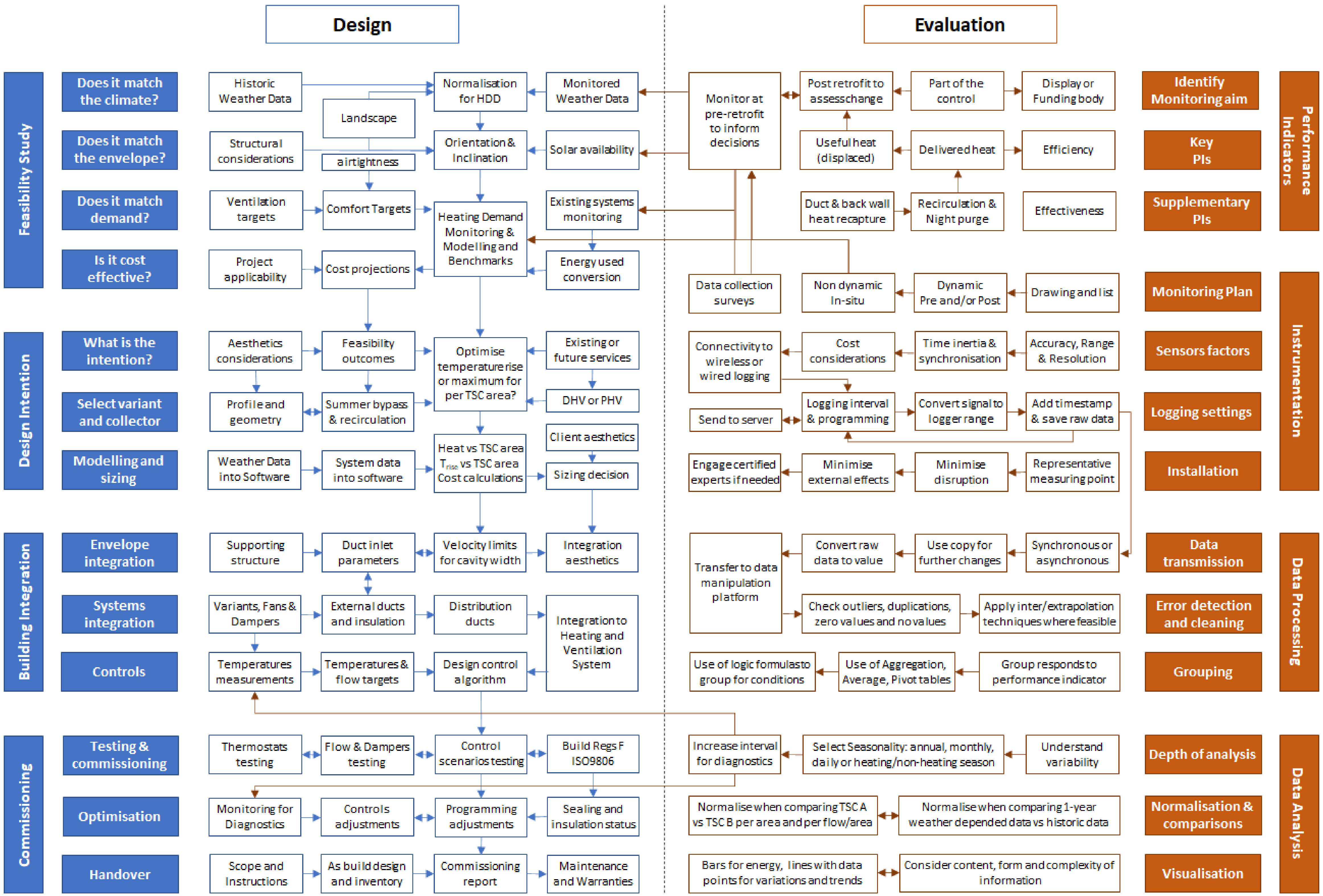


Figure 77. TSC Design and Evaluation Framework summary flow chart, author.

Appendices References

1. U.S. Department of Energy - Energy Efficiency & Renewable Energy. Transpired solar collector at NREL's waste handling facility uses solar energy to heat ventilation air. Federal Energy Management Program; 2010.
2. Cali A, Kutscher CF, Dymond CS, Pfluger R, Hollick J, Kokko J, et al. Low Cost, High Performance Solar Air-Heating Systems Using Perforated Absorbers,. Washington: IEA; 1999. Report No.: SHC.T14.Air.I Contract No.: SHC.T14.Air.I.
3. FEMP. Transpired Collectors (Solar Preheaters for Outdoor Ventilation Air). The U.S. Department of Energy; 1998.
4. DuctSOX. Fabric vs Metal: Six ways fabric air dispersion systems reduce lifetime ownership costs. 2018.
5. Whole Building Design Guide: U.S. Department of Energy Federal Energy Management Program (FEMP). Solar Ventilation Air Preheating: National Institute of Building Sciences; 2016 [Available from: https://www.wbdg.org/resources/solar-ventilation-air-preheating.
6. Hastings R. Solar air systems: a design handbook: Routledge; 2013.
7. Maurer CC. Field study and modelling of an Unglazed Transpired Solar Collector System. Raleigh: North Carolina State University; 2004.
8. Summers DN. Thermal simulation and economic assessment of unglazed transpired collector systems: University of Wisconsin-Madison; 1995.
9. Duffie J, Beckman W. Solar Engineering of Thermal Processes, New York: John Wiley& Sons. Inc; 1991.
10. Kutscher CF. An investigation of heat transfer for air flow through low porosity perforated plates: University of Colorado; 1992.
11. Kutscher CF, Christensen CB, Barker GM. Unglazed transpired solar collectors: heat loss theory. Journal of Solar Energy Engineering. 1993;115(3):182-8.
12. Kutscher C. Heat exchange effectiveness and pressure drop for air flow through perforated plates with and without crosswind. Journal of Heat Transfer. 1994;116(2):391-9.
13. Van Decker G, Hollands K, Brunger A. Heat-exchange relations for unglazed transpired solar collectors with circular holes on a square or triangular pitch. Solar Energy. 2001;71(1):33-45.
14. Deru M, Pless SD, Torcellini PA, editors. BigHorn home improvement center energy performance2006; Quebec City, QC.
15. Pearson C. SolarWall™ monitoring CA Roll Mill. County Durham: BSRIA Ltd carried out for CA Group Ltd; 2007.
16. Cordeau S, editor The performance of a solar air pre-heater system for the ventilation of two commercial poultry barns. Masters Abstracts International; 2010.
17. Cordeau S, Barrington S. Heat balance for two commercial broiler barns with solar preheated ventilation air. Biosystems engineering. 2010;107(3):232-41.
18. Cordeau S, Barrington S. Performance of unglazed solar ventilation air pre-heaters for broiler barns. Solar Energy. 2011;85(7):1418-29.
19. Eryener D, Akhan H. The performance of first transpired solar collector installation in Turkey. Energy Procedia. 2016;91:442-9.
20. Kozubal E, Deru M, Slayzak S, Norton P, Barker G, McClendon J. Evaluating the performance and economics of transpired solar collectors for commercial applications. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2008.
21. Hollick J. World's largest and tallest solar recladding. Renewable energy. 1996;9(1-4):703-7.
22. Heinrich M. Transpired Solar Collectors - Results of a Field Trial. Judgeford, New Zealand: BRANZ Ltd; 2007. Contract No.: SR 167.
23. Lawson M, Hall R. Field trials on a Transpired Solar Collector renovation system. SCI Steel Knowledge; 2010.

24. Hall R, Kendrick C, Lawson RM. Development of a cassette-panel transpired solar collector. Proceedings of the ICE-Energy. 2013;167(1):32-41.