Steady State and Dynamic Modelling of Residential Transpired Solar Collectors Performance

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Abstract

This paper introduces a methodology for the integration of the Transpired Solar Collector (TSC) technology into the Standard Assessment Procedure (SAP). The challenges addressed by this work include the demonstration of the integration of a dynamic low-energy device into an inflexible steady state calculation method. Two innovative techniques are introduced and their use depend on how the TSC is connected to the buildings' mechanical ventilation with heat recovery (MVHR) system. A case study demonstrates the effectiveness of the methodology as the model's results are compared against extensive monitoring data and other data-adjusted dynamic modelling. The results indicate that the application of the TSC to a UK detached house reduces the heat demand by 1000kWh in a heating season. Moreover, when connected to a heat recovery unit the benefit is not cumulative, yet it still reduces the heat demand by approximately 300kWh.

Introduction

Installation of innovative technologies in the domestic sector is a challenging process as there are great expectations from an immature market. In addition to reliable installation, warranties, maintenance and robust commissioning protocols, the market is expected to provide credible prediction tools. Also, the Governmental supporting mechanisms demand evidence and evaluation tools to adopt and enhance new technologies. For these reasons, continuous commissioning is a vital process in order to fill the performance gap, educate modelling tools and feedback to both market and occupants (Jradi et al., 2018).

What is a TSC

Transpired Solar Collectors (TSCs) have been used to help reduce building energy consumption for over 30 years (Brown et al., 2014, Shukla et al., 2012). TSCs consist of perforated cladding panels which are installed on the southerly façade or roof of a building, separated from the building envelope by a cavity. As the collector absorbs solar radiation, its surface becomes warmed and a fan draws the surface air into the cavity through the perforations. The heated air can then be directly distributed into a building through a mechanical ventilation system or ducted into an air heating system such as a heat pump.

Domestic TSCs limitations and opportunities

Previous research in the UK has found that TSCs can contribute approximately 20% of the building's heating demand with a payback of 2 to 10 years (Hall et al., 2011). The National Renewable Energy Laboratory in US indicates lifespan of 30+ years and claims an installation cost of approximately £50/m^2 for new construction and £100/m^2 for retrofit applications (NREL, 2000). Data collection from UK commercial sites support market claims stating that the system can deliver from 200 to 300kWh/m^2/year for a volume flow rate between 50 and 150m^3/hr/m^{2}TSC (TATA steel, 2017, Pearson, 2007, Brewster, 2010). TSC Installation in residential buildings or individual dwellings have been relatively uncommon due to the rarity of domestic mechanical ventilation systems and the mismatch between the heat demand and TSC solar based generation. However, there is an increased demand for air tight houses and improved air quality which has led to controlled 24/7 fresh air requirement (Maier et al., 2009, Zero Carbon HUB, 2013). Mechanical ventilation is becoming well-accepted in the residential construction market (Evola et al., 2017); however, there are still challenges to be addressed such as noise, supply-delivery balance, drafts, increased heat demand and cost (Gupta et al., 2015). Heat exchangers reduce the additional heating demand caused by the fresh air delivery of the mechanical ventilation systems. Furthermore, small aesthetically pleasing TSCs can preheat the required fresh air and reduce the house heat demand still further. However, the TSC delivers a proportion of the heat that would be provided by the heat exchanger of the MVHR, which is a drawback of combining the systems. This paper attempts to explore and quantify this impact.

Monitoring – Evaluation of TSCs

The performance of a TSC depends on a wide variety of parameters such as climatic conditions, size, absorptivity, building aspect, perforation pattern and air flow rates (Shukla et al., 2012). The design of the TSC panel, the spacing of the holes and size of the cavity is well understood and optimised by using the TSC efficiency equation which indicates the percentage of solar radiation transformed into heat. In this study, commercial optimised "anthracite" coloured TSC panels were used in a UK house and the fundamental performance indicator is the heat delivery.

Abbreviations – Nomenclature

HE	Heat exchanger (commonly in an MVHR)
LCRI	Low Carbon Research Institute
MVHR	Mechanical Ventilation with Heat Recovery
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
SBET	Sustainable Building Estimation Tool
SOLCER	Smart Operation for Low Carbon Energy Region
TSC	Transpired Solar Collector
UK	United Kingdom
WEFO	Welsh European Funding Office
C_p	Specific heat of air (1.007 to 1.048 kJ/kg.K at 1 atm)
$\dot{m}$	Air mass flow rate (kg/s)
η_{HE} or η	Heat exchanger – recovery efficiency in SAP
η_{TSC}	TSC efficiency
η'	Combined TSC+HE efficiency
T_{amb}	Air temperature external – ambient (K or °C)
T_{del}	Air temperature delivered after the HE (K or °C)
T_{exh}	Air temperature exhaust from the HE (K or °C)
T_{ext}	Air temperature from extract ducts (K or °C)
T_{rise}	Air temperature rise (K or °C)
T_{TSC}	Air temperature after the collector – delivery (K or °C)
T'_{del}	Air temperature delivered after the TSC+HE (K or °C)
T'_{exh}	Air temperature exhaust from the TSC+HE (K or °C)
Q_{delHE}	Heat exchanger heat delivery (W)
$Q_{delHE'}$	Heat exchanger heat delivery affected by the TSC (W)
Q_{delTSC}	TSC heat delivery (W)
$Q_{delTSC+HE'}$	Total Heat delivery by the TSC and the heat exchanger (W)

In the case study, the supply from the TSC is connected by ductwork to a Heat Exchanger (HE). The heat transfer across the heat exchanger was monitored and the impact of the TSC preheat on the performance of the MVHR's heat exchanger was investigated and integrated into the SAP (Standard Assessment Procedure) model.

TSC Simulations and SAP

Swift, developed by Enermodal Engineering, is a simulation tool specialised in TSC performance prediction, based on empirical models (Natural Resourses Canada, 2017). 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 (Canadian Government) and SBET (Sustainable Building Estimation Tool for TATA steel).

HTB2 is a dynamic simulation tool for the energy and environmental performance of buildings from Cardiff University (Sat and Yik, 2003). It is not a TSC performance evaluation tool, however it can simulate the collector as a heat gain from an external wall by using heat transfer parameters.

SAP (Standard Assessment Procedure) is the UK government approved system for assessing the energy rating of dwellings. It is a steady state national calculation method for dwellings, however it was developed as a fast energy rating tool and not a building performance tool. This simplification in building's physics raises a seiries of uncertainties and errors discussed in both industrial and institutional level (Martin and Sheldrick, 2015, Kelly et al., 2012). There is little research in the integration of solar thermal technologies into SAP and it is limited to hot water technologies (Murphy et al., 2011, O'Hegarty et al., 2014). SAP is not a sizing tool and it does not include a full spectrum of building integrated renewables such as TSCs. The UK national calulation method for non-domestic buildings, SBEM (Simplified Building Energy Model), includes TSC calulations in non-domestic buildings (IES, 2014), however it does not study TSCs in conjuction to an MVHR.

This study demostrates the development of two simple approaches for integrating the TSC into the national calculation model. The first method is similar to the HTB2 model for TSC integration into SAP, and the second is an innovative approach for HE+TSC modelling in SAP by introducing a new combined efficiency. In addition, this paper validates the SAP TSC results by using HTB2, SWIFT and monitoring data.

Experiment

TSC Monitoring as a system response indicator and modelling validator

The extensive monitoring used in this study was an essential instrument in order to understand the performance of the collector and its ductwork in response to the weather and demand profiles. Also, monitoring enabled the interaction between the TSC and MVHR systems to be quantified. Furthermore, the dynamic modelling tool (HTB2) was informed by monitored local weather, real-life demand data and most importantly by variable mass flow rates and temperature rises in response to the heat transfer equation (1). Averaged monitoring parameters informed and optimised the steady state modelling tools (SAP and Swift) and their prediction (heat delivery) was then compared against calculated heat delivery from monitored data.

The effectiveness of the TSC is determined by the ventilation and heat demand of the case study, as well as environmental conditions, size, inclination and orientation. The heat delivery (Q_{delTSC}) of the TSC is calculated using the fundamental equation for fluid heat transfer.

$$Q_{delTSC} = \dot{m}\ C_p\ T_{rise} = \dot{m}\ C_p\ (T_{TSC}\text{-}T_{amb}) \qquad (1)$$

where $\dot{m}$ is the air mass flow rate, C_p is the specific heat of air and T_{rise} is the temperature difference between the ambient (T_{amb}) and the duct air after the collector (T_{TSC}). The monitoring methodology at the demonstration house was based on the Perisoglou and Dixon study on TSCs (Perisoglou and Dixon, 2015).

High accuracy temperature sensors (4 wires, PT 100 class A) measured the ambient outside and supply air temperature. Also, multipoint, high accuracy, low differential pressure probes were placed in the delivery and exhaust duct to calculate the mass flow rate. The data collection time interval was set to 5 minutes to record transient conditions.

Case study – TSC in Solcer house

The SOLCER House demonstrator was built as part of the Cardiff University-led Low Carbon Research Institute project (LCRI) and funded by the European Regional Development Fund through WEFO to enable Wales and its industry partners to lead the way in research to cut carbon emissions. A condition of the funding body was that the building could not be for domestic use; consequently the SOLCER House was occupied as a test facility with daily office-type user profiles (see figure 1 left). To minimise heating energy demand, a fabric approach was used with very high levels of insulation in walls, roofs and floors, and very high-performance windows.

A south-facing 13.8m² vertical TSC has been installed as a preheater for a combined exhaust air to air space heating and hot water heat pump. Before the heat pump the incoming air passes through a balanced MVHR system with a heat exchanger between the outgoing and incoming air. In this study, only the TSC and MVHR are studied as a preheating stage to the heat pump.

Figure 1: Solcer House, Bridgend, Wales (latit. 51.5º). Left: TSC located across the façade of the upper floor. Right: Detail of the metal cladding/ perforation.

Experimental Methodology and Results

The heat demand of the house and the heat contribution of the TSC and the MVHR were modelled using different tools and also measured for a duration of one year (July ’16 to June ’17). The dynamic modelling tool used was HTB2 informed by hourly monitored occupancy patterns and monthly averaged flow rates and weather data. SAP and SWIFT were also informed by monthly averaged monitored weather data and annually averaged monitored flow rates. All models used the same weather file informed by monitoring data collected by a weather station on site. The building parameters were verified or corrected by in-situ testing. Fundamental parameter inputs can be found in the following table (Table 1).

Table 1: Solcer house fabric and system parameters.

Main Parameters	Values	Units
Floor area -Ground Floor	51.8	m^2
Floor area - First floor	51.8	m^2
External wall area - Gross	148.4	m^2
External wall area - Openings	15.4	m^2
External wall - U value	0.12	W/m^2K
Roof - U value	0.15	W/m^2K
Floor - U value	0.15	W/m^2K
Pressure test	3.0	$m^3/h.m^2$@50Pa
Summer Bypass	25	ºC
TSC area	13.8	m^2
TSC Cavity depth	0.3	m
Aver. TSC annual supply flow rate	165	m^3/h
Heat recovery rate (η_{HE}), manufacturer PHPP certificate	76	%

As SAP is not able to directly calculate the impact of a TSC, the first approach proposed in this study is to simulate the TSC as an external wall with heat gains similar to the heat delivery from a TSC. This method requires TSC efficiency (η_{TSC}) and area input as well as a weather file with solar radiation corresponding to the inclination and orientation of the collector. The η_{TSC} and the vertical solar radiation falling to the collector were calculated using monitoring data and were fed into the SAP model.

When the house is equipped with an MVHR, this method is insufficient as there is an interaction between the TSC and the MVHR's heat exchanger which is investigated and quantified below. For SAP modelling of HE+TSC system, this paper suggests that the TSC could be treated as a preheat to the MVHR and for this reason it introduces a second method by using a new combined efficiency for the HE+TSC system (η') in order to replace the HE efficiency in SAP (η). This method is described below:

i. SAP models the impact of the MVHR to the heat demand of a building by including the Specific Fan Power (SFP), the heat exchanger efficiency and ducting information to the calculations (BRE, 2011). The heat exchanger's efficiency (η), also used by manufacturers, could be calculated by using measured temperature data (2).

$$\eta = \frac{T_{del}-T_{amb}}{T_{ext}-T_{amb}} \tag{2}$$

where T_{del} is the temperature delivered to the building after the heat exchanger. T_{amb} is the input temperature coming from the ambient fresh air. T_{ext} is the resultant air temperature from all of the dwelling's extract ducts (Figure 2).

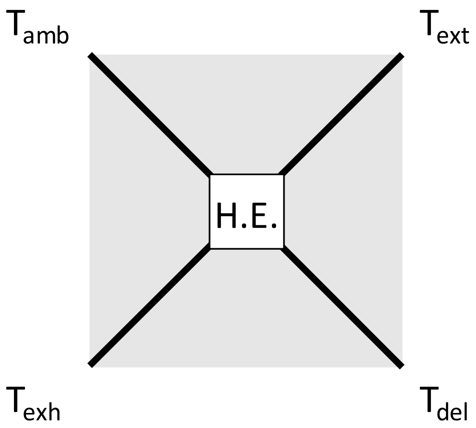

Figure 2: Heat Exchanger of the MVHR.

ii. Heat transfer equation also applies for the heat exchanger which delivers heat:

$$Q_{delHE} = \dot{m}\ Cp\ (T_{del}-T_{amb}) \tag{3}$$

iii. When a TSC is added, the heat exchanger will get a new input temperature (T_{TSC}) which will change the HE delivered temperature (T'_{del}) and the exhaust temperature (T'_{exh}) as shown in figure 3A. The TSC can be represented as an additional preheating device to the heat exchanger. The new system (HE+TSC system) will, in combination, deliver heat according to the equation for fluid heat transfer:

$$Q_{delTSC+HE'} = Q_{delTSC} + Q_{delHE'} = \dot{m}\ Cp\ (T'_{del}-T_{amb}) = \dot{m}\ Cp\ (T_{TSC}-T_{amb}) + \dot{m}\ Cp\ (T'_{del}-T_{TSC}) \tag{4}$$

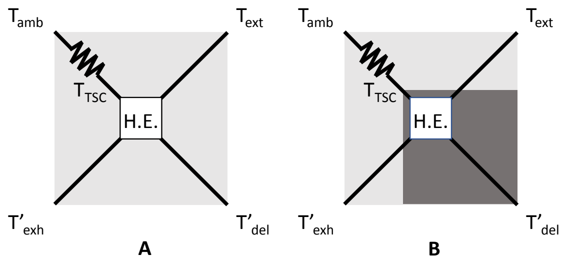

Figure 3: Heat Exchanger with the TSC as a system. Combined view 3A and Heat exchanger focus 3B.

iv. The SAP model cannot adopt heat delivery equations; however, it allows for the user to adjust the heat exchanger efficiency which can now be called system's efficiency (η') for combined HE+TSC.

$$\eta' = \frac{T'_{del}-T_{amb}}{T_{ext}-T_{amb}} \tag{5}$$

v. Meanwhile, the heat exchanger efficiency (η) equation still describes the physics of the dark grey box in figure 3B where the new delivery temperature (T'del) is affected by the new TSC delivered temperature (T_{TSC}):

$$\eta = \frac{T_{del}-T_{amb}}{T_{ext}-T_{amb}} = \frac{T'_{del}-T_{TSC}}{T_{ext}-T_{TSC}} \tag{6}$$

$$\begin{aligned} T'_{del} &= \eta(T_{ext}-T_{TSC}) + T_{TSC} \\ &= \eta T_{ext} + (1-\eta)T_{TSC} \end{aligned} \tag{7}$$

vi. Which means that equation (5) can be transformed to:

$$\eta' = \frac{\eta T_{ext}+(1-\eta)T_{TSC}-T_{amb}}{T_{ext}-T_{amb}} \tag{8}$$

This last equation shows that the new HE+TSC efficiency (η') is only depended on the exchanger's efficiency (η), the input temperature (T_{amb}) and the TSC delivered temperature (T_{ext}) which is subject to the TSC characteristics and weather conditions.

The following diagram (Figure 4) summarises the methodology followed in order to calculate or model the heat delivery of the HE, the TSC and the combined HE+TSC. SWIFT methodology is not included as it was only used to model the TSC gains.

The MVHR's heat exchanger's efficiency (η) and the HE+TSC efficiency (η') were calculated by using monitored data in equations (5) and (6). The efficiency (η) was calculated at 75.5% which is very close to the manufacturers HE η at 76% stated in PHPP certificate (table 1). The new HE+TSC efficiency (η') was calculated at 92.2% which shows the benefit of the TSC.

By knowing the heat exchanger stand-alone efficiency (η) in equation (2), the hypothetical MVHR delivered temperature (T_{del}) was calculated and used in equation (3) in order to calculate the heat delivery from the MVHR as

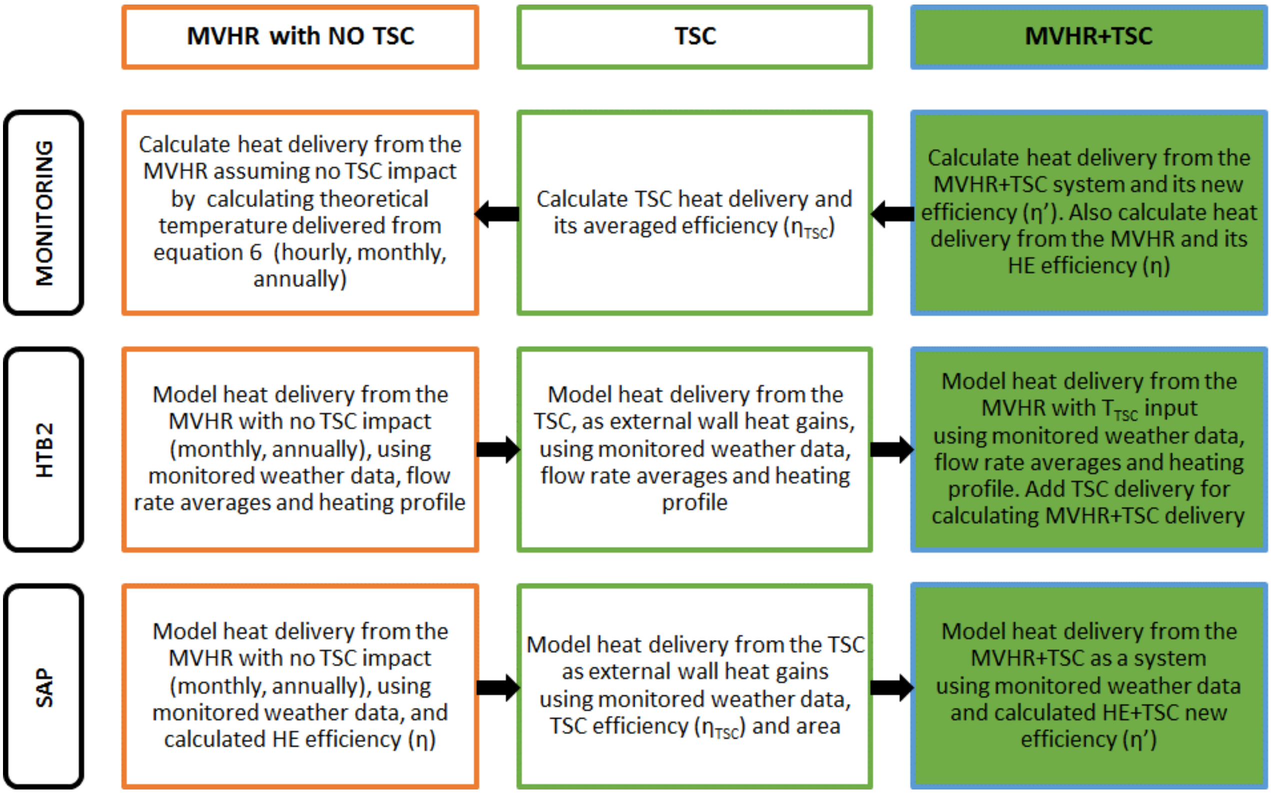

Figure 4: Modelling and monitoring methodology used to calculate the heat delivery of the MVHR assuming no TSC, TSC and MVHR+TSC.

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if there were no TSC. The heat delivery equation was also used with monitored data to calculate TSC delivery and MVHR delivery.

SAP model was informed by the new efficiencies and used to model the heat delivery from the MVHR alone, the TSC alone, and the MVHR+TSC system.

HTB2 modelled the MVHR heat delivery alone, the TSC heat delivery alone, and the MVHR+TSC combined heat delivery. All the modelling and the monitoring-based calculations are shown in figure 5 below.

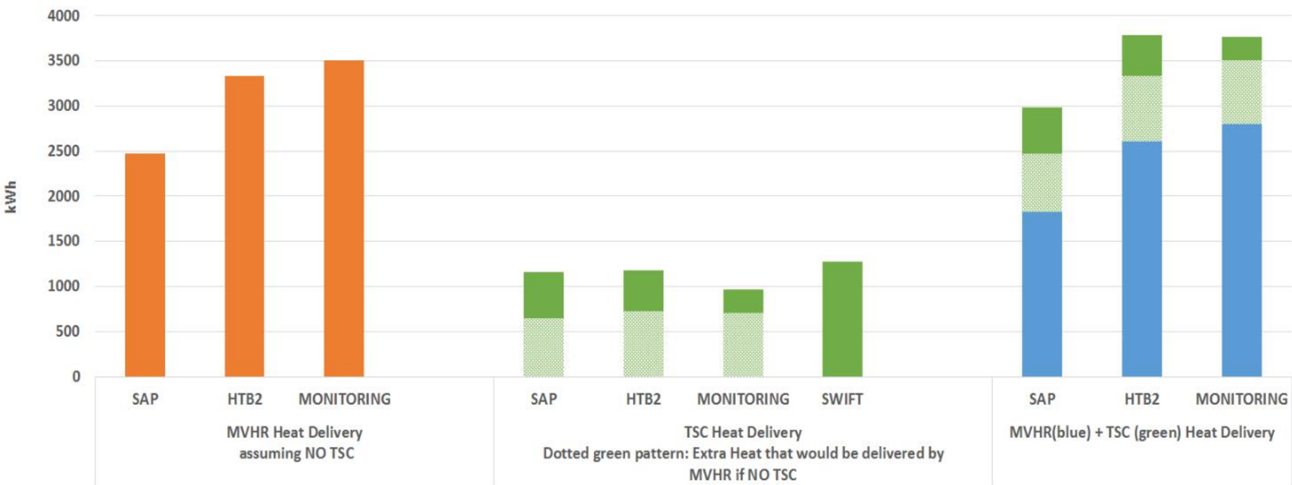

Figure 5: Graphical representation of SAP, HTB2 and Monitoring-based calculations for heat delivery of the MVHR assuming no TSC (orange), TSC heat delivery (green) and MVHR+TSC heat delivery (blue and green). Bars in dotted green pattern indicate the part of the TSC delivery that would be delivered by a standalone MVHR and is compromised because of the TSC. SWIFT modelling results was used as a reference in TSC Heat Delivery comparisons. The delivery refers to a full heating season (Oct-May).

Discussion

The two models and the monitoring-based calculations were compared in figure 5. SAP's MVHR heat delivery is relatively low as the mass flow rate measured and used by HTB2 is higher than the one suggested by SAP. The reason is the usage of non-dynamic SAP flow rates and internal temperatures.

The TSC connected to the MV or MVHR delivers the same amount of heat. In the case study it delivered 971kWh of heat for the heating season as shown in figure 5 (green monitoring bar). TSC delivery models slightly overestimated the heat delivery (10 to 20%). This could be for several reasons, such as the dynamic mass flow rate, the shape of the panel, the heat loss recirculation, or low flow turbulence effects and further investigations are needed.

When the TSC is connected to an MV, the final heat delivery is not affected by the MV; however, when it is connected to an MVHR, the benefit of the MVHR+TSC is not cumulative. The presence of the TSC benefits the system's heat delivery (MVHR+TSC); however, it compromises the heat exchanger's potential. This means that a stand-alone MVHR would deliver approximately an additional 2/3 of the TSC delivery in the TSC's absence as shown in the dotted green patterned bars in figure 5. This is a critical observation as in most of the cases, the domestic mechanical ventilation is assisted by a heat exchanger and both models and monitoring are in agreement within 95%

Another observation is that SAP ignores the heat delivery in summer which is not always unwanted, especially if it is for free and the ambient air is not warm enough during the night or a relatively cold day. In reality, the MVHR+TSC delivered an extra 700kWh from June to September which accounts for approximately 7% of the annual heat demand and 20% of the MVHR+TSC annual heat delivery.

The two proposed methodologies for integrating a TSC into the SAP model refer to a house with a MV and a house with MVHR.

The first methodology requires to input the TSC efficiency and the vertical solar radiation falling to the collector. In the case study these parameters were calculated using monitoring data and were fed into SAP model; however, in a prediction exercise the collector's efficiency could be found in the manufacturer's specifications and the vertical solar in an appropriate weather database where horizontal radiation should mathematically be converted to vertical.

The second methodology demands the new system's efficiency (η') which is dependent on the exchanger's efficiency (η) and the ambient, extract and TSC temperatures. In this case study temperatures were monitored and η was calculated. In a modelling scenario, η can be taken from the MVHR manufacturer's specs, ambient air from an appropriate weather database and extract is the desired room temperature, suggested by building regulations and guidance. The only parameter that is hard to predetermine is the TSC delivered temperature which is affected by seasonal weather and demand variations, as well as TSC technical characteristics and flow rate. Software such as Swift and HTB2 can model a TSC and export an average monthly TSC delivery temperature in order to be used for η' calculations.

The heat delivered by the MVHR+TSC is greater than the MVHR alone; the only exception is during the night when sometimes the TSC panel could create a cooling effect on incoming winter air. This effect could be significant for external walls with very low heat losses and more investigation is required.

The heat delivered by a combined MVHR+TSC system will always be less than the sum of a stand alone TSC and a stand alone MVHR. There are two reasons that could explain this statement. The first is that the TSC will compromise the MVHR as it delivers part of the heat that the heat exchanger would deliver. The second occurs for high TSC temperature delivery (i.e. above the extract temperature), in this case, the MVHR would cool the delivery air down, exchanging heat in the opposite direction. This can be resolved by an MVHR which includes internal heat exchange bypass.

Conclusion

This study introduces two approaches that can be used in SAP in order to calculate the TSC heat contribution. The first method allows SAP to model the TSC as a stand alone system by simulating the panel as heat gains from an external wall. In order to apply this into SAP, TSC efficiency, area and vertical solar radiation should be input by the user. The second method is used when the TSC is connected to an MVHR system and allows SAP to model the combined system as an upgraded MVHR with a new efficiency (η'). The inputs for the second method are the heat exchanger's efficiency, and the averaged ambient, extract and TSC temperatures.

The paper also investigates the interaction between a TSC and an MVHR validated by monitored data. The equations' analysis and the results showed that although the TSC is beneficial, it does not accumulatively add its heat delivery to the MVHR heat delivery. The new system is not as effective as the sum of the two individual systems, and this can be quantified by both monitored data and modelling (dynamic and steady state).

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