ENERGY POSITIVE HOUSING

AN INTEGRATED SYSTEMS APPROACH TO MODELLING, TECHNOLOGY AND ARCHITECTURE

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MArch (Hons) and MSc (Hons)

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Abstract

Against the current background of dependence on fossil fuels, climate change, global population increase and finite resources; this thesis investigates a performance-driven design method that combines modelling, low carbon technologies and architecture design to achieve an Energy Positive Housing (EPH) model that could potentially decarbonise the new housing sector and help, with a bottom-up approach, achieving a future low carbon built environment. Literature review identifies the main design guidelines for the EPH method. For modelling, the need of a simple and uncomplicated pre-design tool; for technologies, the need of a systems approach to reduced energy demand, building-integrated renewable supply and on-site energy storage; and for architecture design, the need of a replicable, affordable and sustainable design suitable for the UK's climate and able to hit the mass market.

Initially, the EPH tool is developed as a versatile pre-design modelling tool to size renewable energy supply and storage integrated with the grid, to simulate the system's behaviour predicting demand, supply and storage profiles, and to evaluate the system's potential considering autonomy, supply/demand ratio and export/import ratio. Afterwards, the tool outputs are used to design the EPH system, which combines photovoltaic panels and lithium-ion batteries, for electrical energy; and transpired solar collectors and a compact unit with exhaust air heat pump, mechanical ventilation heat recovery and hot water tank, for thermal energy. Finally, the energy system is integrated into the EPH design, which is highly insulated and airtight, and built with innovative materials such as low carbon cement, structural insulated panels, insulated render and low-emissivity double-glazed composite windows.

The actual performance of the EPH method is examined to verify the tool's accuracy, the system's performance and the design assumptions, to provide future feedback for the EPH design's application and to establish improvements for future implementation. Therefore, the EPH design is built as a real case study, known as Solcer House, and monitored over different seasons for three years. The extensive set of data from the case study allows to validate and calibrate the EPH tool so it is accurate and reliable; assess the performance of each component of the EPH system comparing real performance against manufacturers' claims; and evaluate the holistic performance of the EPH design. When studying electrical energy, results indicate that the all-electric EPH design is energy positive achieving 70% autonomy, 1/1.03 supply/demand ratio and 1:1.13 import/export ratio, even though photovoltaic panels efficiency is lower than expected and batteries only use 25% of their full capacity. When examining thermal energy, results show components efficiencies to be 8% for the transpired solar collectors, 78% for the mechanical ventilation with heat recovery and a 3.78 COP for the heat pump; but working as a system all together achieve a 5.15 COP with a contribution of 42% from the transpired solar collectors and mechanical ventilation with heat recovery. Finally, when analysing the online survey to visitors, over 80% are impressed with the EPH replicable and affordable house model.

The findings suggest that the integration of energy modelling, technologies performance and architecture design has resulted in a successful and viable EPH method that could decarbonise the new housing sector and help solving, with a bottom-up approach, the energy trilemma of security of supply, affordability and sustainability. The proposed EPH performance-driven design method leaves room for creativity, it is not a quantitatively defined standard, but rather a performance-driven design strategy that pays attention to both the principles of passive solar and the direct and active use of renewable energy, in particular solar radiation, therefore liberating the EPH design from the limitations of purely passive strategies such as the Passivhaus standard.

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Abbreviations and acronyms

AAHP	Air-to-Air Heat Pump
AC	Alternate Current
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAPS	Buildings as Power Stations
BEIS	Department for Business, Energy & Industrial Strategy
BERR	Department for Business, Enterprise and Regulatory Reform
BIH	Better Insulated Housing
BIM	Building Information Modelling
BIPV	Building-Integrated Photovoltaics
BIST	Building-Integrated Solar Thermal
BRE	Building Research Establishment
BSRIA	Building Services Research and Information Association
CABE	Commission for Architecture in the Built Environment
CAD	Computer-Aided Design
CAR	Cambridge Architectural Research
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CSH	Code for Sustainable Homes
DC	Direct Current
DECC	Department of Energy & Climate Change
DECLG	Department of the Environment, Community and Local Government
DEFRA	Department for Environment, Food & Rural Affairs
DF	Daylight Factor
DHW	Domestic Hot Water
DUKES	Digest of UK Energy Statistics
EAHP	Exhaust Air Heat Pump
EPC	Energy Performance Certificate
EPH	Energy Positive Housing
EPS	Expanded Polystyrene
EPSRC	Engineering and Physical Sciences Research Council
ETSU	Energy Technology Support Unit
EU	European Union

EWI	External Wall Insulation
FES	Future Energy Scenarios
FIT	Feed-In Tariff
GJ	Giga Joules
GW	Giga Watts
HES	Household Electricity Survey
HP	Heat Pump
HVAC	Heating, ventilation, and air conditioning
ICT	Information and Communications Technology
KW	Kilo Watt
LCA	Life Cycle Assessment
LCBE	Low Carbon Built Environment
LCRI	Low Carbon Research Institute
LED	Light-emitting diode
LFP	Lithium-Iron-Phosphate
M^2	Square Metre
MVHR	Mechanical Ventilation Heat Recovery
MW	Mega Watt
NZC	Net Zero Carbon
NZE	Net Zero Energy
PCM	Phase Change Material
PV	Photovoltaic
RHI	Renewable Heat Incentive
SAP	Standard Assessment Procedure
SIPS	Structural Insulated Panel System
SOLCER	Smart Operation of Low Carbon Energy Regions
SPF	Seasonal Performance Factor
STC	Standard Test Conditions
TSC	Transpired Solar Collector
UK	United Kingdom
US	United States
WHQS	Welsh Housing Quality Standard
WSA	Welsh School of Architecture

1 Introduction

The need for a more sustainable way of living and a more decarbonised built environment is nowadays generally accepted. This involves not only a more efficient way of using natural resources that could lead to reduce the dependency on energy and fossil fuels, but also a more equal society in terms of access to natural resources and public services that could lead to a better and more sustainable quality of life with no fuel poverty.

The current scenario of generating energy by burning fossil fuels impacts at a global scale as well as at national, local and individual scales; with severe consequences to the economy, environment, health and quality-of-life. Consequently, it is necessary to immediately reduce the dependence on fossil fuels by using energy in a more efficient way and by generating energy from renewable sources. The built environment and its supporting infrastructures can have a major role driving these changes, especially in relation to the design of new buildings that have the potential of incorporating energy efficiency measures, building-integrated renewable energy generation and localised energy storage. Even though these are small-scale interventions, replicated across the built environment they could potentially have a significant impact on the energy industry level.

While the energy industry is predominantly top-down supply driven and grid based (Jones, 2017), this thesis investigates an alternative bottom-up approach to a low carbon built environment with a building-scale whole systems approach to reduced energy demand, renewable energy supply and localised energy storage.

1.1 Background

This section investigates current background energy related problems – i.e. scarcity of fossil fuels, impact of climate change, growth of population numbers, rise of fuel poverty, lack of housing stock, insecurity of national grid and increase of peak demand – to explain why an immediate change in the built environment is needed towards a more sustainable and decarbonised direction.

1.1.1 REDUCING DEPENDENCE ON FOSSIL FUELS

The concept of energy and its importance in our society is usually understated by people, who tend to forget how a society as complex and modern as ours was originated. The response is with energy, which is essentially the ability of a system to perform work. Most of the achievements of human history have succeeded by means of energy use; hence the origin of modern society is in the ability to harness energy. In revising the history of mankind, it is easy to link periods of exceptional growth and prosperity with improvements in the methods of controlling energy. For example, during thousands of years, great civilisations were thoroughly built using hundreds of humans and animals as labour, making the progress incredibly slow. It was only two hundred and fifty years ago with the Industrial Revolution when humans discovered fossil fuels as a source of energy to power machines to do the work of hundreds of persons in a fraction of the time. But, this unprecedented growth and success was only achievable by drawing the planet's vast stores of cheap, easily available fossil fuels.

The energy used by the world's population and industrial capital does not come from nowhere. It is extracted from the planet and it does not disappear. When its use is over, energy is dissipated as unusable heat or as pollutants. According to Meadows (2005), streams of energy flow from the planetary sources through the economic subsystem to the planetary sinks where waste, pollutants and heat end up polluting air, water and soil of the planet. However, there are limits to the amounts that the sources can produce or the sinks can absorb these flows without detriment to people, the economy or the planet. Economist Herman Daly (1996) suggested three main rules to define these sustainable limits:

- For a renewable resource, the sustainable rate of use can be no greater than the rate of regeneration of its source. For example, biomass energy would be used sustainably if the amount of deforested wood were equally replanted in woodlands.
- For a non-renewable resource, the sustainable rate of use can be no greater than the rate at which a renewable resource, used sustainably, can replace it. For instance, a

tonne of coal would be used sustainably if part of the profits from it were automatically invested in wind or solar farms, thus an equivalent amount of renewable energy is newly available when coal is gone.

- For a pollutant, the sustainable rate of emissions cannot be bigger than the rate at which that pollutant can be absorbed in its sink. For example, CO_2 can be sustainably emitted into the atmosphere no faster than carbon sinks, like oceans or forests, can absorb it.

According to Daly's rules, any activity cannot be sustained if it triggers a renewable resource stock to fall, a pollution sink to increase or a non-renewable resource stock to drop without a renewable replacement in sight (Daly, 1996). Regrettably, this is happening to human's activity, which greatly relies on fossil fuels. Consequently, not only a non-renewable source is consumed without being replaced with renewable energy alternatives, but also the planet's carbon sinks cannot absorb the resulting pollutants.

In terms of the limits of fossil fuels sources, considering that world's total annual consumption of all forms of primary energy increased more than ten times during the 20th century (Boyle, 2004), the question is "How long will the world's fossil fuel reserve last?". Reliable research models estimate that world's extraction of oil and coal reached a peak between 2005 and 2015, while extraction of natural gas is likely to reach its peak around 2030 (Laherrere, 2001). From then on, although large quantities of fossil fuels will still remain, the overall resource will decline and will be consumed by the end of the 21st century (de Sousa, 2008). Literature indicates that the proven world's reserves of coal should last for about 200 years, of oil for approximately 40 years and of natural gas for around 60 years, at current consumption rates (BP, 2015).

In terms of the limits of pollutants, the natural balance of the carbon cycle is overturned due to the burning of fossil fuels which produces pollutants, such as CO_2 emissions, that should be absorbed by the planets' carbon sinks but not quickly enough adding extra tonnes of CO_2 to the atmosphere over and above the natural flux per year (Smith, 2005). But also, pollutants of other types are emitted at every other phase of the fossil fuel flow, from discovery to extraction, refinement, transportation and storage.

Concerns about both limits and the adverse environmental and social consequences of fossil fuel use – i.e. air pollution or mining accidents – have been voiced intermittently for several decades and have been an important focus of research during the last fifty years. Figure 1 shows the evolution on the number of research publications, in Elsevier database, related with the fields of availability, social, health and environmental impact of fossil fuels. The graph shows that environmental concerns attract most of the attention, and this interest has grown rapidly since the 1980's. Although, social, health impact and scarcity of fossil fuels are investigated less, interest on them increased during the last decade.

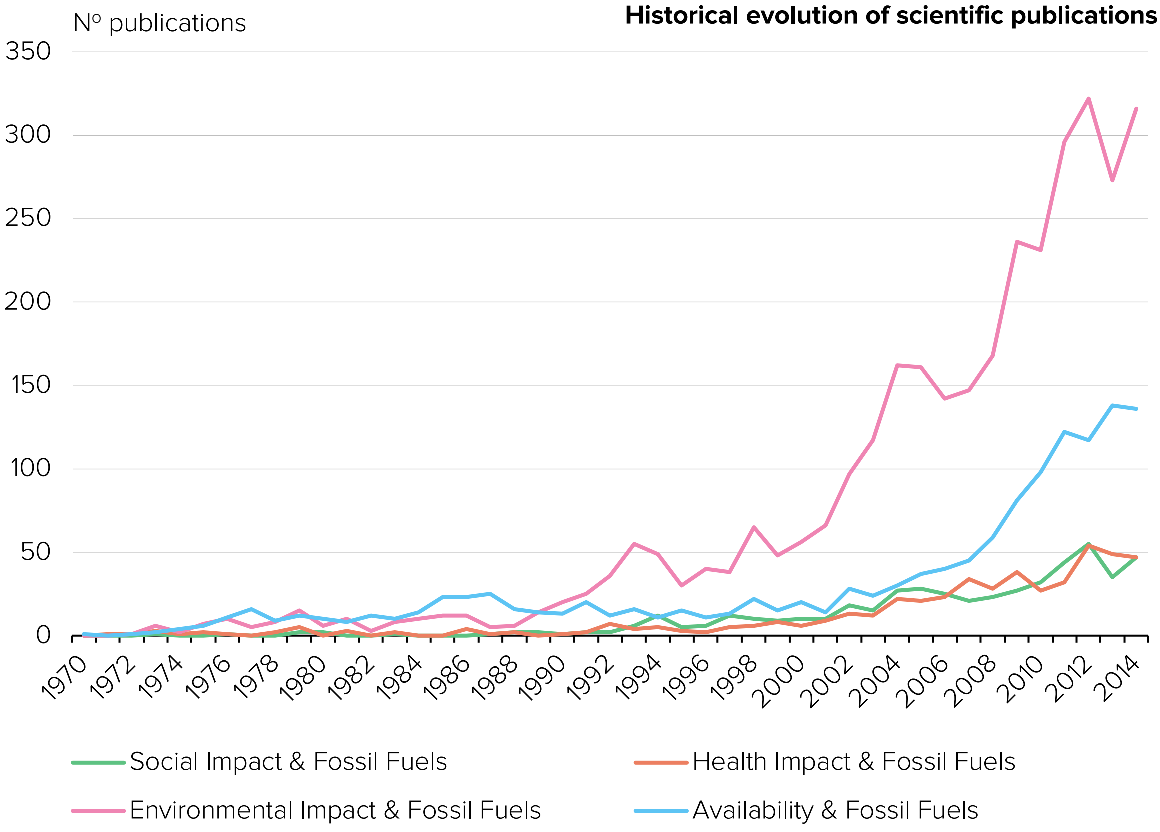


Figure 1 – Graph showing number of publications grouped by keywords – i.e. fossil fuels & social impact, health impact, environmental impact and availability – from 1970 to 2014. Data source: Elsevier.

In conclusion, there is only a limited amount of fossil fuels and our society, which nowadays increasingly relies on them, will have to modify the nature and intensity of its consumption. Growth during the last century is inherently unsustainable since fuels are consumed far faster than the planet can refill them, and this is where energy ties into capital growth. It seems that current society believes that its capital growth can continually and infinitely expand, dismissing that it is all driven by limited energy sources.

Before the end of the century, an alternative infrastructure will be needed to run exclusively on renewable energy such as electricity, biofuels and arguably nuclear. Fortunately, there are available more than enough renewable energy sources to meet world's needs (Lopez, et al., 2012), but the matter is "How are they harnessed?". Regrettably, the starting point is very low. In 2015, only 2.7% of the world's energy came from renewables; while the other huge fraction came from hydro (6.8%), nuclear (4.5%) and fossil fuels (86%) (World Energy Council, 2016).

1.1.2 MITIGATING CLIMATE CHANGE

The rise of concerns related with fossil fuels' environmental impact can be better understood in parallel with the history of the scientific discovery of climate change (Smith, 2005). Awareness about climate change began in the early 19th century when the natural greenhouse effect was first identified. By the 1970's, the negative effect of CO_2 emissions became increasingly convincing, but their impact was not clear. Most scientists, about 60%, published studies that warned of global warming; but some geologists and paleoclimate researchers argued that some temperature records suggested that there was a cooling trend caused by the smog – i.e. emission of aerosols into the atmosphere (Peterson, et al., 2008). During the 1980's the prediction about ice age had ceased, scientific opinion increasingly favoured the warming viewpoint and researchers focused their investigation on the causes and consequences of global warming. By the 1990's, as a result of computer model improvements, a consensus position was formed. Greenhouse gases and CO_2 emissions from human activities, mostly from combustion of fossil fuels, were hugely involved in most climate changes and were causing serious global warming consequences (Houghton, et al., 1990). This explains the clear increase of research on environmental impacts of fossil fuels by the end of the 1990's shown previously in Figure 1.

After a period when people were doubtful about the warning of climate change, today it is generally agreed that its detrimental effects will be unavoidable over the next century (Smith, 2005). For example, recent studies on the future climate scenarios for the UK indicate that summer temperatures could increase up to 7°C by the end of the 21st century (Kendrick, et al., 2012), which could cause overheating in free-running naturally ventilated buildings (Holmes & Hacker, 2007). These forecasts are not only based on hypothesis, on the contrary they are proved by evidences. For example, the UK's average temperature has raised by 1°C, twice of the worldwide average, in the last 30 years (Tarantano, et al., 2010). Consequently, summer temperatures are now warmer than the 1971-2000 average; and the possibility of unusual hot summers, like those occurred in 2003 or 2006, has increased (Jenkins, 2010).

To turn the climate change problem around and to drive the world towards a better direction, representatives from 160 countries met in Kyoto (Japan) in 1997 to set objectives and targets to lower carbon emissions. The Kyoto Protocol (United Nations, 1998), was the world's first legally binding climate change deal and was formulated to be a turning point in the battle against global warming. As a response, a debate about the likely consequences of climate change for the construction industry and future buildings designs started growing in the media. Under the agreement, most developed nations, except the US, committed themselves to targets for cutting or reducing their greenhouse gases emissions. Targets varied between nations according to their development status, thus some countries were allowed to increase their emissions while others were required to significantly reduce them. Today, more than fifteen years later, the success of the protocol is still doubtful. Some people may suggest it was a failure while others may prefer to think it was a good attempt. Figure 2 illustrates the Kyoto Protocol success rate per country showing the gap between each nation's percentage target and its actual percentage change in 2010. Among the 37 countries shown in the graph, 25 met the targets and 12 failed to do so.

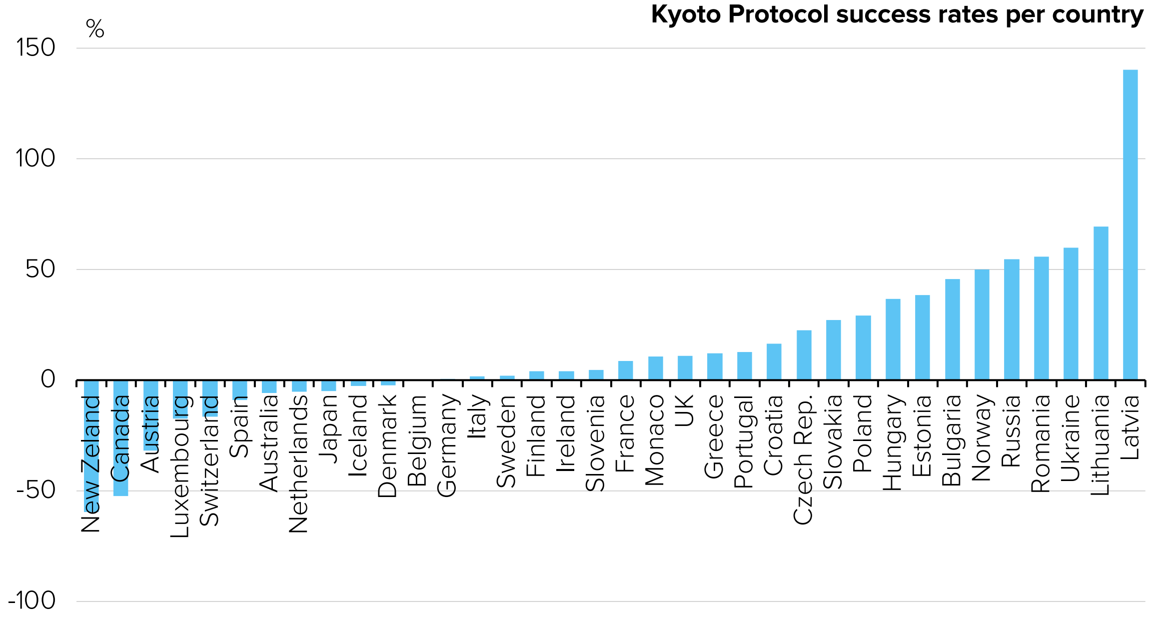


Figure 2 – Bar chart graph showing the Kyoto Protocol's successes (positive values) and failures (negative values) by indicating the gap between each nation's percentage target and its actual percentage change between 1990 and 2010. Land use emissions and sinks are included. Data source: (Clark, 2012).

In conclusion, one of the most serious threats to human society in the 21st century is climate change that, regrettably, has been created by human activity. A wide scale evidence of anomalous climatic incidents (Smith, 2005) coupled with the rate at which they are happening demonstrates the scale of the problem. With all these evidences, in 2003 scientists meeting in Berlin determined that "the planet could be on the verge of abrupt, nasty and irreversible change" (Bill Clark, Harvard University, quoted in New Scientist, 2003).

Nobody truly knows which end of the flow of fossil fuels will be more constraining, the source or the sink. Forty years ago, on the eve of the oil crisis, the source end appeared the biggest limitation. Nowadays, the focus is much more on climate change, thus the sink end seems more limiting. Nevertheless, the evidence given so far, plus much more contained in current research, plus media's daily reports, all show that the human economy is not using the Earth's stock and sinks in a sustainable manner.

1.1.3 INCREASING LOW-CARBON ENERGY SOURCES

It is clear that human activity is overloading our atmosphere with CO_2 and other greenhouse gases emissions, which trap heat rising up the Earth's temperature and create significant harmful impacts on our health, environment and climate. Alternatively, the solution to the problems of limited fossil fuels and their impact on health, society and environment, is to have renewable energy sources playing a higher role in the supply of energy.

Energy is one of the world's biggest issues. Current generations face a turning point in human history. Today living standards are unsustainable and have exceeded the Earth's capacity to replenish its energy stores. Not only that, as more countries try to follow the pathway of industrialisation, major problems are going to happen sooner than later. Whether this energy related problems will bring destruction of modern civilisation or a new sustainable era, this will depend on the capability of people to adapt and accept a new lifestyle (Roaf, et al., 2005). Non-sustainable energy temporarily powered our prosperity for the last two centuries; but now sustainable energy is the key to a decarbonised and unlimited future. However, it has traditionally taken society fifty years to make the transition from one-dominant energy source to another (Meadows, et al., 2005). All strategies for accommodating the fossil fuel decline require decades to have any significant effect (Nelder, 2009). Therefore, most of the renewable energy revolution will have to be undertaken in a scenario of ever decreasing fuel supply.

The challenge is therefore to overturn this situation by dramatically increasing the existing 2.7% fraction of renewable energy sources, so they can replace the 86% of fossil fuels, world's current primary energy source (World Energy Council, 2016). In 2014, electricity generation accounted for 30% of the UK's greenhouse gas emissions, with the majority being generated from fossil fuelled plants (DECC, Mar 2015). So, *what if renewable energies were used instead to match the electricity needed?* According to a report focused on the US case study, renewable energies could potentially provide 482,247TWh, 118 times the amount of electricity consumed by the US (Lopez, et al., 2012). Throughout the UK, strong winds, sunny skies, sea tides, plant residues, heat from the earth and fast-moving water could each provide a vast and constantly replenished resource of energy supply (Smith, 2005). Therefore, it seems that these various sources of renewable energy could have the technical potential to also provide all the UK's electricity demand many times over, even in a highly electrified future energy scenario where transport and heat sectors would be also electrified.

Renewable energy technologies –especially solar energy – were suddenly and briefly fashionable during the 1980's in response to the oil crisis of the 1970's, as seen in Figure 3.

But, the interest and support were not sustained and diminished again in the 1990's, overpassed by the increasing interest on nuclear energy. In recent years, however, dramatic improvements in the performance and affordability of solar cells, wind turbines and biofuels, have cemented the way for mass commercialisation of renewable energy technologies. This has led to an increase on researchers' interest on renewable energies; hence journal publications numbers have risen steadily from the beginning of the 21st century, being solar and wind energy the principal focus of attention.

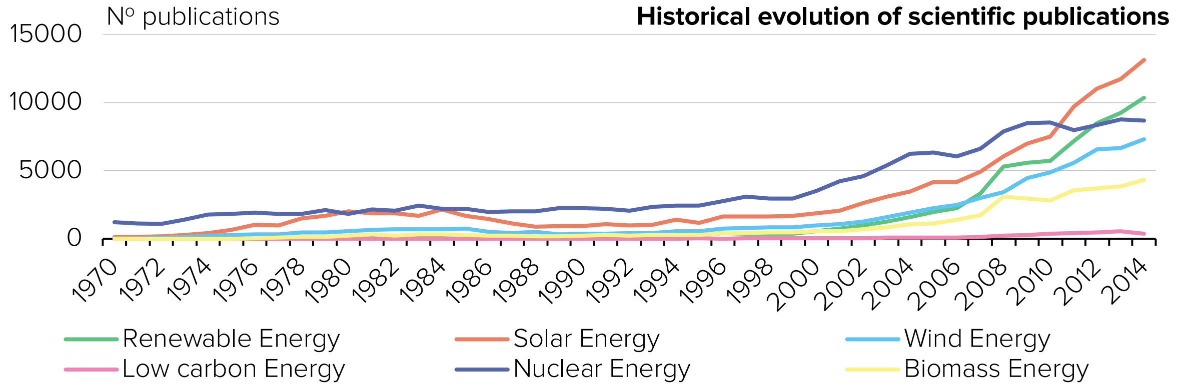


Figure 3 – Graph showing number of publications grouped by keywords – i.e. energy & renewable, solar, wind, low carbon, nuclear, biomass – from 1970 to 2014. Data source: Elsevier.

In conclusion, renewable energy technologies are now more available, can provide energy far more efficiently and cleanly than fossil fuels and could potentially cut carbon emissions by 60 to 80% (Flavin & Hull Aeck, 2005). The conversion of clean and nearly inexhaustible sources like wind, sun, earth's heat and arguably nuclear power into energy could, in the next century, meet most of the world's energy needs (Lopez, et al., 2012).

1.1.4 IMPROVING THE BUILT ENVIRONMENT

A correction is needed, and it seems that for industrialised countries the best rescue chance could lie with the built environment. Buildings operational energy represents about a third of the global energy use and a similar share of the world's CO_2 emissions (International Energy Agency, 2013). But, this proportion is even greater if the construction and infrastructures that support the built environment are included, representing 62% of energy use and 55% of CO_2 emissions (Anderson, et al., 2015).

The built environment is the sector that could most easily accommodate fairly rapid change without pain (Smith, 2005) thanks to buildings' significant potential to reduce energy use for heating, cooling, lighting and equipment, and to integrate renewable energy sources utilizing existing technologies (Ward, 2009). Therefore, improving the built environment is key to achieve a sustainable future and to meet global CO_2 emission reduction targets.

Projections show that the world's urbanisation combined with the overall growth of the world's population will add more pressure into the built environment. In 2014, the urban population in the world was 3.9 billion, representing 54% of the total, a ratio that is projected to rise to 66%, with an additional 2.5 billion people living in cities by 2050 (United Nations, 2014). Donella Meadows (2005), a pioneering environmental scientist, writer and social innovator; studied the causes and consequences of a population and economy grow past the support capacities of the Earth. Meadows described these capacities as sources – e.g. water, energy, materials or pollutants – and sinks – e.g. oceans or atmosphere – and concluded that when their limits are reached, the overshoot can lead to two different outcomes: a crash or a correction and turnaround. But crash should not be an option. Therefore, this thesis defends that a solution is still possible and focuses on a correction of the built environment.

Top-down and bottom-up concepts are increasingly used in relation to this transition to a low carbon built environment. Up until now the emphasis to improve the built environment has been on top-down solutions, which are usually led by governments, businesses or industry, and are driven by national and international agendas. Although they aim to address quality of life and efficiency of resources and theoretically could have the power to organise and trigger a rapid change towards a low carbon built environment; the problem is that they tend to protect their own interests and are in the direction of growth at any cost. Moreover, it seems that many of these top-down solutions have associated problems because they tend to be too generalised one-size-fits-all actions (Jones, 2017). For example, renewable energy intermittency, lack of large scale energy storage, electricity transmission grid problems, nuclear waste and safety, low success of smart metering, etc.

Alternatively, in response to the slow delivery of top-down driven solutions, there is presently a growing interest in bottom-up strategies towards a low carbon built environment. Bottom-up strategies aim to convince the general public and the communities to organise a change in direction from the bases. Although this avoids the autocracy implicit in top-down strategies, the problem is that it is very difficult to reach the general public, who also does not have the power to quickly change the systems related with the built environment. Nevertheless, bottom-up strategies, characterised by their community focus and realistic goals, have the advantage of being fast with a triggering and adaptive role in comparison with the slow and guiding role of a top-down approach, and of being led by local organisations and individuals that may be more kind to use innovative approaches (Jones, 2017). Moreover, bottom-up actions tend to result in multiple benefits that people can identify with, for example: creation of local jobs, reduction of energy costs, or improvements on the environment and health. Owning to these facts, in 2015, the World Energy Council argued that "a bottom-up approach to reduce global CO_2 emissions could ensure that all countries, developed and developing, contribute as they can to the achievement of the CO_2 targets" (World Energy Council, 2015).

In conclusion, it is not a matter of completely rejecting top-down solutions, but rather of linking top-down and bottom-up solutions so the latest can potentially make top-down approaches easier to manage by reducing the pressure on them. A rebalance between top-down and bottom-up approaches is needed to maximise the impact and the speed of the transition towards a low carbon built environment.

1.1.5 REDUCING FUEL POVERTY

A bottom-up approach to the built environment could led to significant reductions on the energy demand side with actions such as improvements in the building fabric, with more insulation or better windows, and in the energy efficiency of appliances, lighting or heating equipment. Energy inefficiency is a primary cause of fuel poverty (Boardman, 2010), thus any improvements in energy efficiency of the building fabric and equipment could potentially reduce energy bills while increasing comfort (Middlemiss & Gillard, 2015). This is a good example of how a bottom-up action at individual or community level, could have positive implications at a local level, by reducing fuel poverty risk, and at grid level, by reducing the pressure on the grid and increasing security of supply.

Considering that energy costs are continually increasing; an energy demand reduction could have a financial impact for operating buildings. For example, poorly energy performance buildings are not only more likely to have environmental issues that can affect wellbeing, health and productivity (World Green Building Council, 2013), but could also risk their future asset value (Jones, 2017). Despite all the evidences, the construction industry is generally reluctant to build to low carbon standards, probably due to a lack of awareness of what could be changed, a short understanding of the full benefits of these changes and a fear to the economic implications that these changes could have on a minimum-cost led industry.

1.2 Research scope and focus

Although energy related problems are occurring worldwide, this thesis mainly focuses on the UK without disregarding the research conducted in other countries. The UK is an interesting scenario, not only because of its mature economy and slow increasing energy demand, but also because it is one of the world's leading countries in terms of policy making to liberalise its energy markets, independently control its energy networks and establish CO_2 emissions reduction targets. The research presented in this thesis intends to be transferable and applicable to other countries, who could learn – for the good and the bad – from this UK case study how, and to what extent, the on-site management of electricity demand, supply and storage can or cannot be successfully combined and integrated into a competitive energy market environment.

While the impact of energy to the built environment comes from industry, transport, commercial and domestic sectors, the scope of this thesis is only the domestic energy sector. Over the past two decades, research in the field of low carbon built environment has focused on top-down driven actions led by governments, business and industry (BEIS, 2016); which tend to mostly impact on the industry, transport and commercial sectors. Alternatively, as a response to the slow delivery of top-down driven solutions, this thesis explores a bottom-up strategy for the domestic sector that could help to convince general public and communities to organise a change in direction from the base. This bottom-up strategy should aim to eliminate not only current problems of housing stock caused by the population growth, but also current problems of insecurity of energy supply, dependence on fossil fuels, fuel poverty among population and excess of CO_2 emissions.

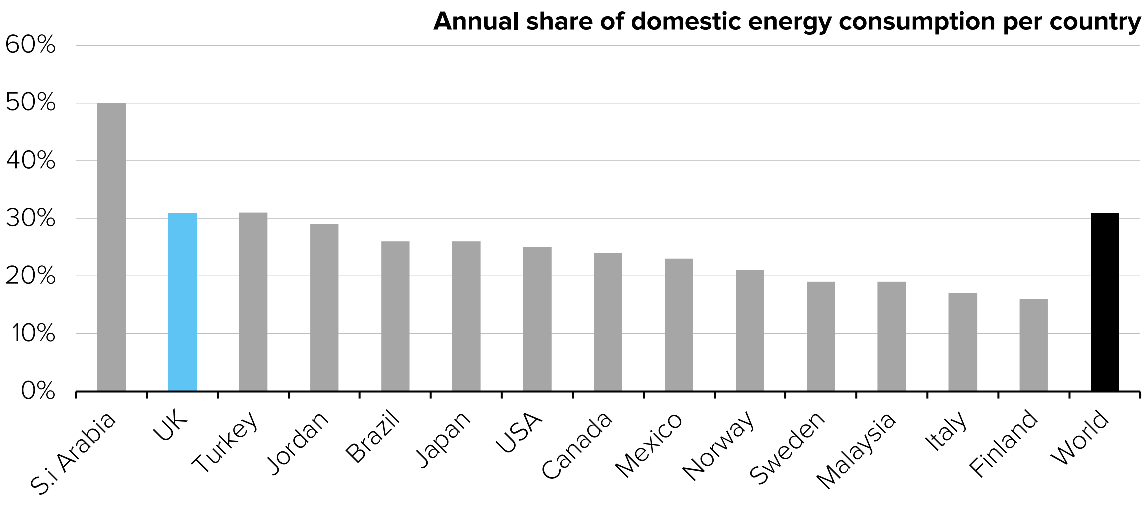


Figure 4 – Bar chart graph showing worldwide domestic energy consumption as a percentage of national energy consumption and in relative international form. Data source: (Saidur, et al., 2007).

Domestic demand represents a significant share of the total energy consumption, as shown in Figure 4. In the UK, it currently accounts for about 40% of gas and about 35% of electricity demand (National Grid, 2017). Moreover, direct CO_2 emissions from British households account for 18% of the UK's CO_2 budget (BEIS, 2017a) and their energy consumption accounts for 29% of the total consumption from all sectors (BEIS, 2017b). But these figures are inherently related with the number of homes in the country, therefore they could potentially rise as a result of the predicted increase in population (United Nations, 2014). Considering the UK Government's aim to build at least 200,000 homes a year over the next five years to solve the housing crisis (Federation of Master Builders, 2015); the effect on the UK's national carbon budget will depend on how these houses are constructed. Therefore, a change on the way to build new housing stock could have a potential upwards impact on the energy grid and the built environment.

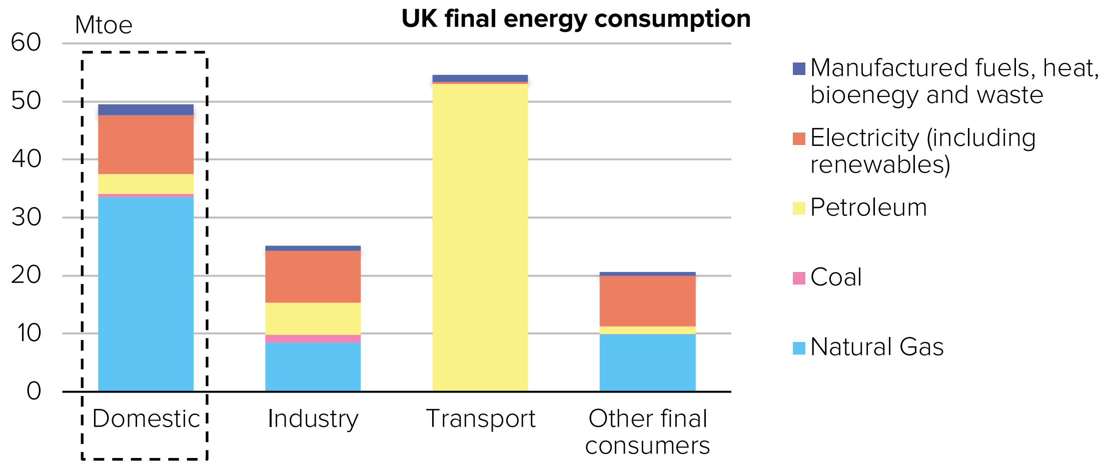


Figure 5 – Bar chart graph showing the UK's final energy consumption in 2013. Data source: (DECC, Jul 2015).

On the other hand, it is also important to consider the source of energy to satisfy the energy consumption from each sector, as shown Figure 5. For the domestic sector, it is clear that natural gas, used mainly for space and water heating, represents a big share of the total. All homes in the UK require heating and currently this heating is derived from gas in 80% of the homes (National Grid, 2017). Therefore, it is considered needed the implementation of low carbon technologies that can either reduce the need of fossil fuels by maximising systems' efficiency or replace them for electricity. In another note, although the focus of this thesis is the new housing sector, energy systems are carefully studied considering existing housing stock, so they could be implemented as a retrofit solution in future projects.

1.3 Research context

Despite the apparent slowness, the implementation of low carbon energy policies continues advancing. Following the European Council's ambitious objectives in relation to energy and climate change; the UK is legally committed to decrease national CO_2 emissions by at least 80% by 2050, relative to 1990 levels (CCC, 2008). The UK's energy systems have a large part to play addressing this reduction. Policy interventions by the UK Government will be essential not only to solve the multiple forthcoming difficulties, but also to encourage the large investment needed from the private sector. But time is running out. The UK's remaining coal-fired power stations have to reduce their hours of operation – under the European Union regulations on pollution (European Parliament, 2001) – so replacing that capacity is a matter of urgency.

The UK's energy systems landscape has to go through a significant transformation and faces a range of growing challenges. The UK's energy objectives are often referred to as its 'energy trilemma' goals of security, affordability and sustainability. 'Trilemma' because goals can conflict and policies can contribute or impact on more than one of its objectives. The energy trilemma concept was first coined by the World Energy Council in 2014, who later developed a report defining measures to accelerate the energy transition towards a low carbon built environment. The energy trilemma sums up the "difficulty in finding secure energy supplies and catering to rising demand without prices becoming unaffordable, all while reducing greenhouse gas emissions" (World Energy Council, 2016).

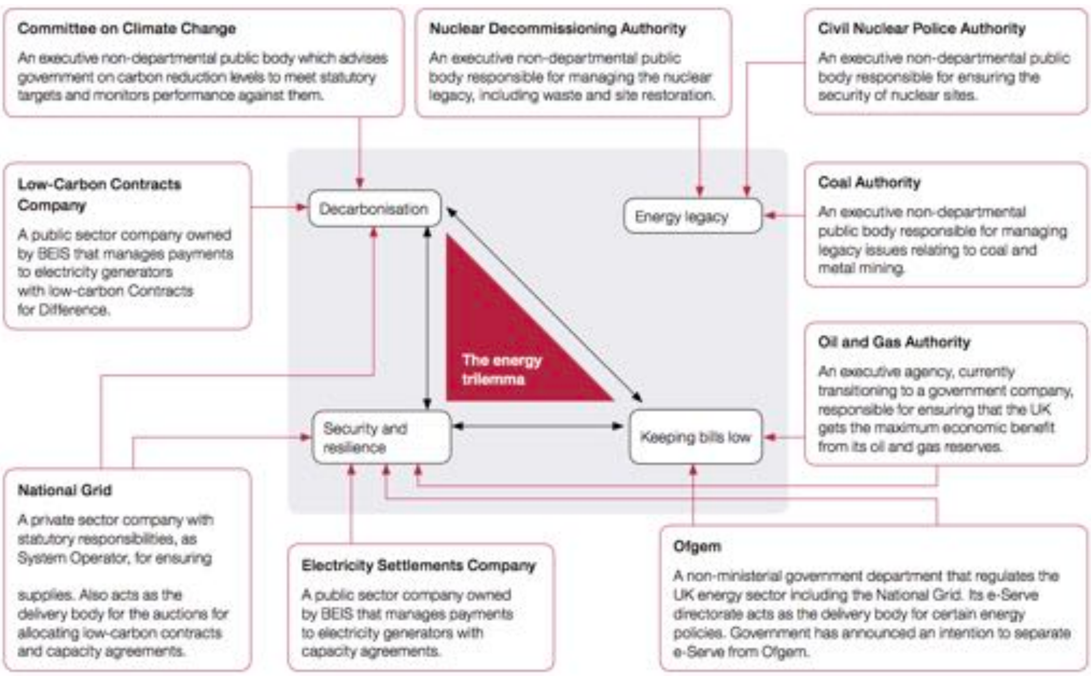


Figure 6 – Schematic of the UK Government's partners to deliver its strategic energy objectives (BEIS, 2016).

In order to transfer the trilemma goals into tangible actions that can accelerate the energy transition towards a low carbon built environment, five focus areas are highlighted in the report from the World Energy Council (2016): transforming energy supply, advancing energy access, addressing affordability, improving energy efficiency and managing demand, and decarbonising the energy sector. But, these are big actions which involve many stakeholders. Figure 6 is a schematic of the main stakeholders involved in the delivery of the UK Government's energy trilemma strategy and their role and actions. It shows that most of the stakeholders are national energy authorities and government institutions that focus on the supply-side – i.e. oil and gas, coal, nuclear, national grid, etc. This indicates that up until now the emphasis has been on top-down solutions driven by energy supply actions, which are usually led by governments, businesses or industry.

Alternatively, according to the report *'UK Future Energy Scenarios'* published by the National Grid (2017), "many buildings in this world would be able to act as mini power stations, with rooftop solar or small wind turbines, a battery and an integrated building control system linked to multiple smart appliances". This indicates that the next steps to achieve a low carbon built environment should be bottom-up actions, which offers new opportunities for studying the technologies and solutions needed for a more flexible and sustainable energy system. But this change will require radically new ways to generate, store and use energy at a local level, while maintaining its productivity, cost, comfort and security.

Decarbonising the domestic sector means reducing the share of fossil fuels while enlarging the relevance of electricity by creating new and heavier demand patterns of use, for example to power cooking appliances and heat pumps. This, together with an increase of intermittent localised renewable energy generation, will require a more flexible and responsive electricity transmission network in terms of design and operation, which will further increase its current complexity. The design and operation of this type of systems requires an understanding of their performance, especially of the dynamic balance between localised small-scale generation, distribution, storage and demand. However, certain things need to change in order to achieve a world where almost all consumers and business have enthusiastically invested in small-scale electricity generation (Allen, et al., 2008). For example, improving technologies to considerably reduce their cost and complexity of installation, subsidising appropriate low carbon technologies with tax relief support to increase their implementation or breaking the barriers of the usually sceptical supply chain (DECC, 2011).

As shown in Figure 7, electricity consumption in a low carbon built environment scenario in 2030 might significantly increase, but it will be generated in a much more sustainable way from renewable sources (DECC, Jul 2018). In other words, assuming that energy demand cannot be reduced, an alternative solution is needed to meet this demand with sustainable, decarbonised and affordable energy. And this is proposed by the National Grid (2017) with the 'Gone Green' scenario shown in Figure 7, with a 60% share of the energy coming from renewables and a 64% reduction of greenhouse gas emissions.

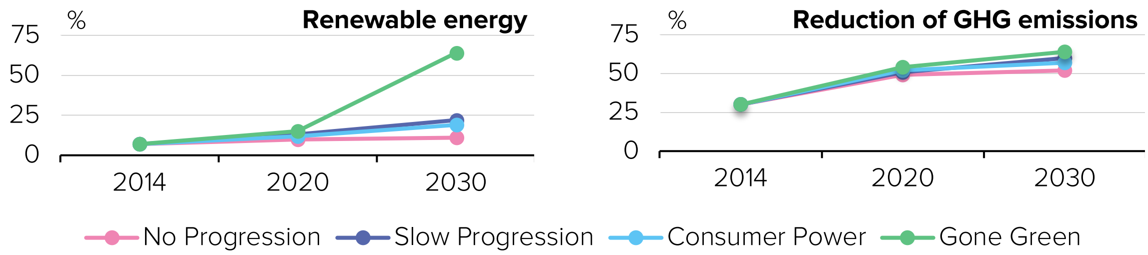


Figure 7 – Graphs showing annual demand variation from 2013 to 2035. Data source: (National Grid, 2017).

Considering that fossil fuels are limited and scarce, and that current economic and population growths are driven and rely on them; it seems that the Gone Green energy scenario should certainly be the future. This would potentially fulfil the energy trilemma of security of supply, affordability and sustainability; resulting on a growing economy, a domestic and international policy harmonisation, a long-term certainty, more renewables generation, more innovation, an engagement of consumers with energy issues and a heavier electricity demand pattern of use.

It is important to consider how different sectors contribute to the whole energy demand and how electricity and gas interact at a sector level. As shown in Figure 8, in a Gone Green scenario, electricity demand will initially decrease until 2022 at an average rate of 5TWh/year caused by a fall on the industrial demand which will continue through the period. Meanwhile, the residential electricity demand will remain initially flat due to a descent in lighting demand caused by the adoption of LEDs which is offset by a demand rise caused by the increase in the number of homes (National Grid, 2017). From 2020 onwards, total electricity demand will steadily rise mainly due to the electrification of the residential sector, which will move towards low carbon electric heating systems and electric vehicle charging points. By 2035, residential electricity demand will increase by 48TWh/year totalling about 385TWh/year. Consequently, the move of the residential sector towards decarbonised transport and heating will also reduce the domestic gas demand significantly. Figure 9 shows how the sharp reduction on the gas demand in a Gone Green scenario is mainly led by the residential sector and is caused by a high roll out of insulation, the replacement of old boilers with new A-rated efficient ones, the introduction of smart controls, progressive building regulations for new homes and the displacement of gas through electrification of heating (National Grid, 2017).

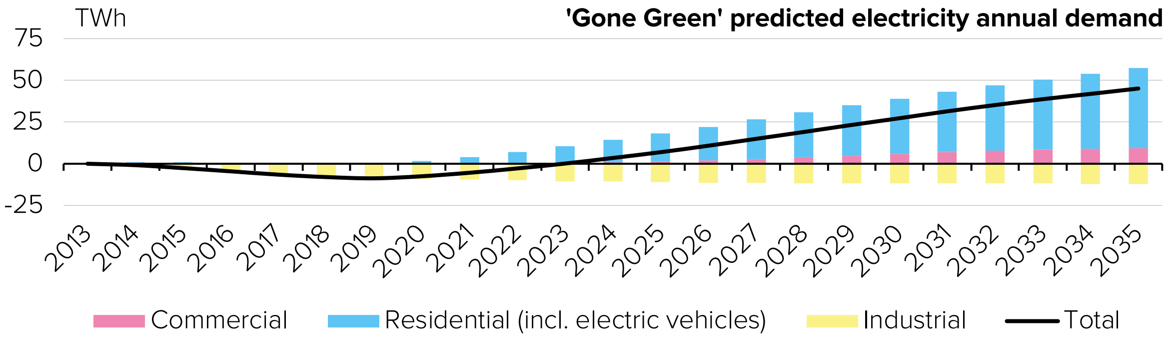


Figure 8 – Graph showing the Gone Green electricity demand variation from 2013 to 2035 by sector. Data source: (National Grid, 2017).

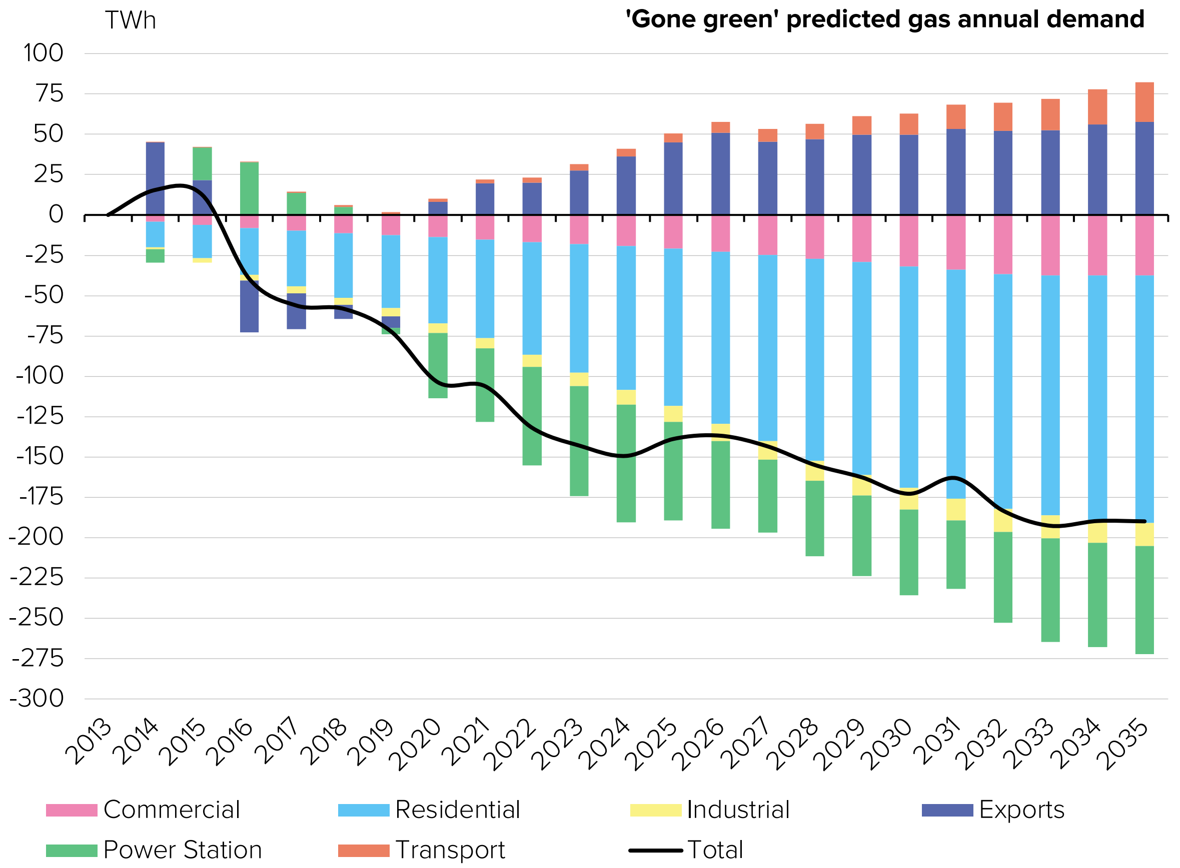


Figure 9 – Graph showing the Gone Green gas demand variation from 2013 to 2035 by sector. Data source: (National Grid, 2017).

In conclusion, a low carbon built environment future scenario should see a fall on heating demand, which currently dominates domestic energy demand, as a result of increased insulation, more efficient boilers and a shift to more electrical heating in the form of heat pumps. Consequently, residential electricity demand is expected to grow consistently, also due to a sustained increase on the number of households and population which will need basic appliances – e.g. refrigerators, cookers, audio visual appliances, etc. – but also every day more common goods – e.g. telecoms, tumble dryers and dishwashers. All these are big changes and represent big challenges for the housing sector.

1.4 Problem statement and research questions

Understanding the context is key to set up the research problem. Against the UK's current energy related problems such as scarcity of fossil fuels, impact of climate change, growth of population numbers, rise of fuel poverty, lack of housing stock, insecurity of national grid and increase of peak demand; this thesis investigates a bottom-up strategy for the housing sector and develops the concept of 'Energy Positive Housing' (EPH) as a carbon neutral house model for a low carbon built environment future scenario. It is important to clarify that a house without CO_2 emissions in all of its activities, is almost impossible to achieve. Carbon neutrality means zero net emissions of CO_2 or in other words; positive emissions in some aspects can be offset, to some extent, through natural carbon sinks and negative emissions in other aspects (Fay, et al., 2015).

The EPH concept represents a major shift in the way that energy is generated, stored and used in a building. It is the idea that every building, no matter the size, can be energy positive and play an active role in the electric power system rather than simply being a passive consumer, with renewable energy generation integrated into the building design. Some non-residential buildings are already being designed to function like small-scale power stations, with multi-megawatt photovoltaic power stations integrated in their roofs and excess generation capacity feeding in to the UK National Grid as 'Short Term Operating Reserve'. However, that is not often the case for domestic buildings.

It is anticipated that at the completion of this research, the proposed EPH design should be a sustainable house able to generate its own energy with renewable energy technologies, an energy positive house able to export surplus energy to the grid, an energy autonomous house able to store energy to be used during peak or night times, and finally an affordable house that could be built for the mass market with a long-term certainty.

However, this anticipated EPH design represents a big challenge difficult to achieve using traditional design methods for standard housing. Therefore, this thesis needs to investigate and alternative architectural design method that, contrarily to traditional design methods, can take a holistic approach towards the energy and thermal performances of buildings while ensuring that the use and aesthetic of the design are not dismissed. To achieve an EPH design, it needs to be driven not only by architectural principles, but also by energy modelling simulations and low carbon technologies performance.

The specific research questions that this research aims to answer are as follows:

- How to embed energy performance during the design process?
    - What are the current barriers and limitations experienced by architects that aim to design new housing in the context of low carbon built environment?
    - How is energy predicted by designers during early-design stages?
    - What modelling simulation tools are used by designers to assist the low carbon design process?
    - In response, how the EPH tool should be developed?
- How to integrate low carbon technologies during the design process?
    - What low carbon technologies are available on the market that can be integrated into housing-scale buildings?
    - How should low carbon technologies be combined together to work like a whole energy system?
    - In response, how the EPH system should be designed?
- How to design a house for a low carbon built environment?
    - Are there any good examples of previous low carbon housing projects that could be used as a reference?
    - Which design principles and guidelines should be used as a benchmark?
    - In response, how the EPH system should be designed?

It should be noted that this research was developed between 2014 and 2018, including monitoring data collection and writing up. During this period, numerous changes that affected the instruments and the guidance available to architects and designers were undergoing revision or coming to effect. The author has tried to update the research in order to reflect the latest events on the field.

1.5 Research aim and objectives

The aim of this research is to investigate the integration of energy modelling, technologies performance and architecture design, to achieve an EPH design that could potentially decarbonise the new housing sector and help solving, with a bottom-up approach, the energy trilemma of security of supply, affordability and sustainability. The EPH design should have a significant impact reducing the UK's domestic energy demand, thus demonstrate that a low carbon built environment can be achieved with a bottom-up approach, through the implementation of affordable solutions, existing low carbon technologies and local skills in the community and building scale.

The specific objectives that are needed to achieve this research aim are:

1. Identify the situation of current research and the barriers and limitations to develop the EPH design in relation to the context of low carbon built environment, in terms of:
    a. Energy: Identify patterns of energy demand, sources of energy supply and strategies of energy security.
    b. Modelling simulation: Identify influential factors, methods of modelling and users' behaviour to facilitate the understanding and inclusion of low carbon performance in buildings during design.
    c. Technologies performance: Review the growing market of low carbon energy to identify building integrated technologies and strategies to reduce energy demand.
    d. Architecture design: Review the historical evolution of green architecture focusing on housing case studies.
2. Develop an EPH design method that uses energy modelling to integrate and optimise low carbon technologies into a house design. Three steps are considered:
    a. Develop the EPH tool: Establish the design guidelines from the main outcomes of the literature review of energy and modelling simulation and synthesise them to achieve a modelling tool to help designers to integrate and optimise low carbon energy systems during early-design stages.
    b. Design the EPH system: Establish the design guidelines from the main outcomes of the literature review of low carbon technologies and synthesise them to design a low carbon energy system that is optimised with the outputs from the EPH tool and can be easily integrated in a house design.
    c. Design the EPH design: Establish the design guidelines from the main outcomes of the literature review of green architecture and synthesise them to design an EPH design that is optimised with the outputs from the EPH tool.

3. Apply the EPH design principles to build a real case study, named Solcer House, so it can be monitored for several years and over different seasons.
4. Evaluate the EPH method to reveal the accuracy of the modelling tool, the efficiency of the energy system and the success of the house design. Three points are considered:
   a. Validate the EPH tool: Compare the tool's results from the simulation of the Solcer House against the monitored data from the built Solcer House and investigate the factors that influence on the differences between predicted and real life data.
   b. Assess the EPH system: Compare the technologies' specifications claimed by manufacturers against the real specifications calculated using the monitored data of the Solcer House and investigate the factors that influence on the differences between predicted and real-life data.
   c. Assess the EPH design: Collect opinion from visitors of the Solcer House and evaluate the architectural aspects that have had more social impact.

1.6 Structure of the thesis

- Chapter 1: Introduction. Establishes the background, focus and context of this research by and the subsequent government targets for zero-carbon housing.
- Chapter 2: Literature Review. Provides a critical review and background knowledge of existing literature starting with the broad topic of energy and then focusing on the three topics directly associated with this research – i.e. modelling, technologies performance and architecture design. This chapter highlights and summarises the main gaps and limitations found in current research so these can become the main design guidelines.
- Chapter 3: Methodology. Explains the research method used and why it is appropriate.
- Chapter 4: Modelling simulation - EPH tool.
    - Analysis: Summarises the lessons learned from literature review to find out their gaps and limitations and uses these as guidance for the design of the EPH tool.
    - Synthesis: Describes the evolution and development of the EPH tool considering the inputs, calculations and outputs.
- Chapter 5: Technology performance - EPH system.
    - Analysis: Summarises the lessons learned from literature review to identify the appropriate technology components and solutions for the EPH system.
    - Synthesis: Describes the building integrated technologies used in the EPH system and how they work at a system level rather than at a component level.
- Chapter 6: Architecture design - EPH design.
    - Analysis: Summarises the lessons learned from literature review to establish the design guidelines for the EPH design.
    - Synthesis: Describes the architectural principles and strategies of the EPH design.
- Chapter 7: Evaluation, results and discussion.
    - EPH tool – Validation and calibration: Compares the EPH tool outputs against monitored data considering energy demand, supply and storage.
    - EPH system – Analysis of performance: Evaluates the Solcer House considering electrical and thermal technologies at a component as well as a system level.
    - EPH design – Social opinion: Summarises the results and main findings of the survey focusing on the quality, functionality, adaptability and novelty of the design.
- Chapter 8: Conclusions and recommendations. Findings from the evaluation stage are used to extract conclusions, respond the research objectives, propose improvements, justify the novelty of this research, identify its barriers and make recommendations.

1.7 Summary

Against the global background of dependence on fossil fuels, climate change, global population increase, finite resources and fuel poverty; this thesis focuses on the challenging goal of decreasing the UK's CO_2 emissions by at least 80% by 2050 (CCC, 2008) and investigates what the housing sector can do to accelerate this transition towards a low carbon built environment by proposing the concept of 'Energy Positive Housing' (EPH) as a carbon neutral house model for a low carbon built environment future scenario.

The UK's energy systems landscape has to go through a significant transformation and faces a range of growing challenges, which are commonly known as the energy trilemma goals of security, affordability and sustainability. Literature indicates that housing, which represents 27% of current UK's CO_2 emissions, is one of the sectors that could most easily improve and evolve towards a low carbon direction (BERR, 2008). Also, having described the challenge presented by climate change and the chances to generate decarbonised energy by means of renewable energy sources, it is now time to investigate how the housing sector can respond to that challenge. A low carbon built environment future scenario should see a fall on heating demand, which currently dominates domestic energy demand, as a result of better building fabric and a shift to electrical heating technologies such as heat pumps. Consequently, residential electricity demand is expected to grow consistently, also due to a sustained increase on the number of households and population. All these are big changes and represent big challenges for the housing sector.

In conclusion, Chapter 1 introduced the aim of this thesis: the integration of energy – through modelling simulation, technologies performance and architecture design – into an EPH design that could be affordable and replicable in the UK, could decarbonise the new housing sector and could help to achieve a low carbon built environment with a bottom-up approach. The objectives needed to achieve this aim were also outlined: to investigate the design, optimisation and integration of solar and wind energy technologies into a house design and to identify the barriers and consequences of this implementation into the UK's domestic energy sector. Responding to these objectives, two main research questions were also outlined: "How does the EPH design need to be?" and "How to design the EPH design?". Although an endless number of solutions could be investigated and suggested, it is important to bear in mind that research needs to fit into the time and other resources available for the studies (Braxler, et al., 2001).

2 Literature Review

Understanding previous research and literature is key to answer the research question: "How to design energy positive houses with building integrated energy technologies so they can be the housing pattern of a low carbon built environment and solve the UK's energy trilemma?"

A wide range of factors affects the design, optimisation and implementation of energy positive houses. Chapter 1 concluded that to achieve an EPH design, its design needs to be driven not only by architectural principles, but also by energy modelling simulations and low carbon technologies performance. These three topics –i.e. modelling, performance and design – are therefore key for the EPH design. They all influence each other in a reciprocal direction and have to be well integrated in order to achieve a successful EPH design. For example, modelling simulation should be used as guidance on the architectural design and the selection of technologies, architecture details should inform the modelling process and the selection of technologies, while technologies should be well integrated in the architecture design and should also be introduced in the modelling simulation. There is one main concept that links and joints the three topics together, and this is energy, which is embedded in each of the topics.

The following literature review, which is summarised in Figure 10, moves through the broad and relevant concept of energy, before focussing in the three topics directly associated with the research in this thesis – i.e. modelling simulation, technologies performance and architecture design.

First, energy is reviewed by studying the energy demand loads, the sources of energy supply and the strategies of energy security. Secondly, modelling simulation is reviewed by studying the three main lines of research on the field: factors, methods and behaviour. Then, technology performance is reviewed by exploring the building integrated low carbon energy technologies available on the market, the strategies to reduce energy demand and the growing and evolving market of energy storage. Finally, architecture design is reviewed focusing on the historical evolution of the green architecture concept and analysing several housing case studies.

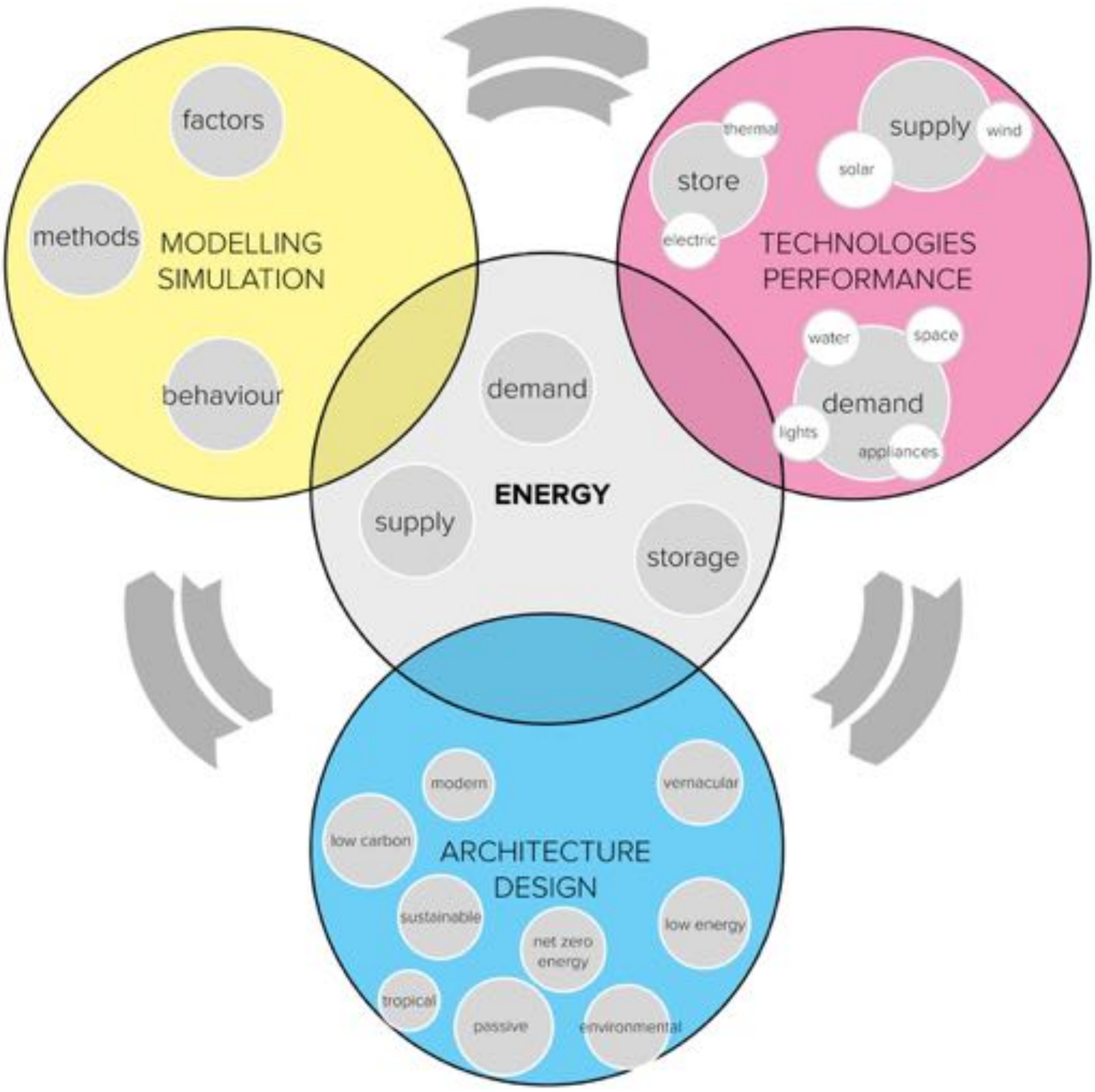


Figure 10 – Systematic approach used in the literature review.

In conclusion, this literature review uses a systematic and holistic approach to study the domestic sector energy challenge that focuses on modelling simulation, technologies performance and architecture design. Therefore, although these topics are individually reviewed, there are many interconnections between them which help to understand the overall scene of this research.

2.1 Energy and housing

Understanding the concept of energy is a substantial task because energy is involved in all life cycles and exists in various forms such as chemical, nuclear, elastic, gravitational, radiant, thermal, sound, mechanical or electrical energy (Boyle, 2004). But understanding energy's role is key to achieve a rational use of it (FAO, 1991).

According to a report from DECC named *'Energy balance: methodology note'*, an overall energy balance is "an accounting framework for the compilation and reconciliation of data on all energy entering, exiting and used within the national territory of a given country. (…) In the energy balance, all energy flows should be accounted for, and the balance is based on the first law of thermodynamics (…)" (DECC, Aug 2010). The first law of thermodynamics, law of conservation of energy, says that energy cannot be created or destroyed (Boyle, 2004). In other words, the world is full of energy, and its total amount is fixed, although it may change from one form to another.

Demand and supply of energy means converting energy from one form into another. Energy flows through systems in a number of forms implying intermediate steps of transformation between the primary energy source and the final use. The best way to optimise these systems, both in terms of energy demand and energy supply, is by understanding how this energy transfer occurs among them (DECC, Aug 2010).

2.1.1 ENERGY DEMAND

It is important to reduce our dependency and consumption of fossil fuels in every sector of the economy, not only in relation to global issues of climate change and security of energy supply but also as part of a future low carbon built environment and sustainable living for society in general. The domestic sector is a substantial consumer of energy in every country, in the UK it represents 31% of the total energy demand (Renewable UK, 2018), therefore efforts should focus on reducing its energy consumption.

Energy demand of other main sectors such as transportation, commercial, industrial or agriculture are better understood than the domestic sector thanks to their more centralised ownership, self-interest and expertise in reducing energy consumption, and high levels of regulation and documentation (Swan & Ugursal, 2009). Instead, the domestic sector is an unclear energy sink due to its wide variety of building characteristics – i.e. sizes, geometries or materials –, impact of occupants' behaviour, data privacy issues and lack of detailed sub-metering of household (Swan & Ugursal, 2009).

A good understanding of the domestic sector's consumption characteristics will help guiding the sector's energy use in a gradually energy conscience world; in views of supply, efficient use and effects of consumption. In response to the context of climate change, high-energy prices and energy supply/demand mismatch; this thesis intends to understand exhaustively the domestic sector's consumption characteristics to reduce households' energy demand by promoting conservation, efficiency and technology implementation.

This way, domestic sector could play a key role helping to reach the UK Government's targets of a 20% reduction in greenhouse gas emissions by 2020 (European Parliament, 2008); a 40% reduction by 2030 (European Commission, 2013); and an ambitious 80-95% by 2050, all compared to 1990 levels (European Commission, 2011). The UK is not alone; many other countries have targets and goals for the reduction of energy consumption and CO_2 emissions. Official publications often agree that a reduction of the total domestic energy demand will significantly help meeting these targets. Indeed, in 2009 a UK report stated that domestic energy efficiency measures could reduce CO_2 emissions by 50 million tonnes per year or around 10% of the UK's current total emissions by 2022 (CCC, 2009).

Meanwhile, if transport and heat sectors are electrified over the coming decades of decarbonisation, the future of energy demand will gradually be synonymous to the future of electricity demand, which will undoubtedly be influenced by technological changes and innovative solutions in different areas. Therefore, the scale of the decarbonisation challenge will mainly depend on the drivers of energy demand. However, projections of domestic energy demand by 2050 are widely variable depending on the predicted population growth and increasing wealth, and consequently give rise to big variations in the required amounts of electricity generation. Understanding how to predict future domestic energy demand will be important for energy suppliers and policy makers. For example, by predicting the impact or savings as a result of retrofits and new materials or technology, decisions can be made to encourage incentives on energy supply, retrofit and technology, new building regulations, or even demolition and re-construction.

2.1.1.1 Energy demand by end-use

This section considers the purposes for which energy is used in the domestic sector and the drivers of domestic energy demand that can potentially lead to more or less energy being consumed. The domestic sector consumes secondary energy, which is that energy received in a convenient form so it can be used directly by the householders. The main end-use groups of secondary energy in a household are as follows:

- Space heating and/or space cooling: Energy needed to counteract thermal losses of the building fabric due to radiation, conduction and air infiltration/ventilation to maintain a comfortable temperature and air quality in the household.
- Domestic hot water: Energy used to heat water to a suitable temperature for occupants and/or appliance uses.
- Lighting, cooking and appliances: Energy to run household appliances and lighting.

The proportion of each of these groups on the overall energy demand is greatly dependent on many factors such as climate, physical building characteristics, appliances and systems characteristics, ownership, and occupant behaviour (Yao & Steemers, 2005).

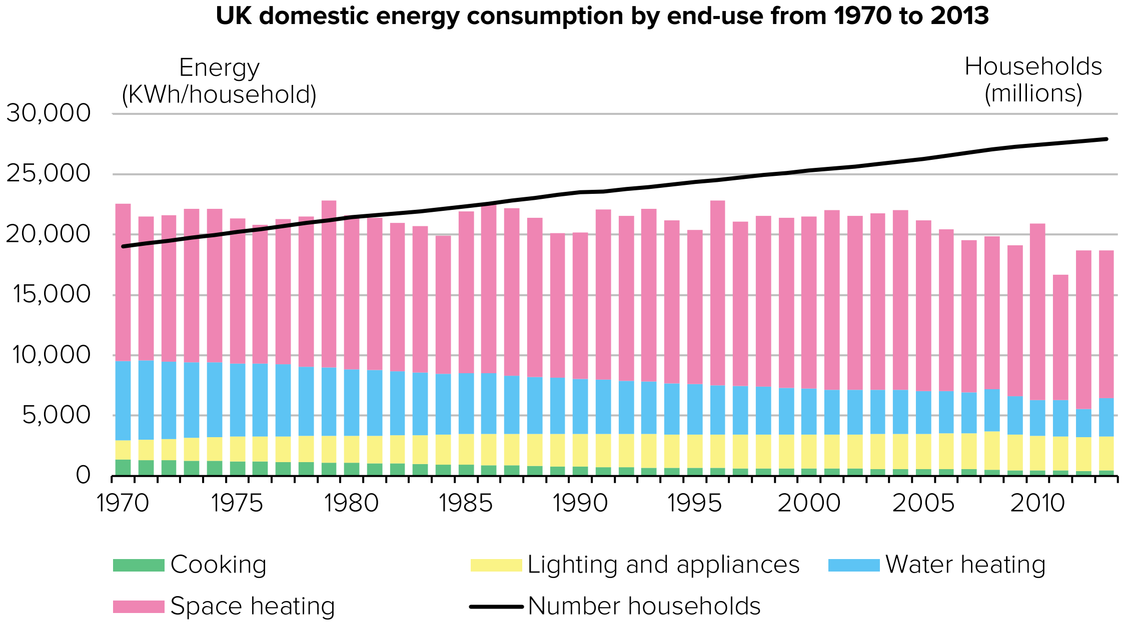


Figure 11 – Graph showing the UK's domestic energy consumption from 1970 to 2013 by end use per household unit (DECC, Jul 2015) plotted against the number of the UK's households (Office for National Statistics, 2013).

Figure 11 shows the UK's domestic energy consumption by end-use per one household unit between 1970 and 2013. The plotted data is the result of the historical UK's domestic energy consumption by end-use (DECC, Jul 2015) divided by the number of households in the UK (Office for National Statistics, 2013). It can be seen that energy consumption per household unit has slowly decreased by 18% from the 1970's until 2013, reaching its lower peak in 2011 which included the UK's second warmest winter since Mett Office records began in 1910 (Prior & Kendon, 2011). The graph does not give information regarding CO_2 emissions – i.e. different fuel types lead to higher or lower emissions– nor gives information about energy spending – i.e. each fuel type has a different price. However, total energy use is a simple indicator of how much energy is used in the UK's homes over time and it is a good place to start getting an overview of housing energy demand.

As shown in Figure 11, in the UK the majority of energy consumed by the domestic sector is for space heating, which accounted for 65% of all energy demand in 2013 (DECC, Jul 2015). Space heating consumption is largely dependent on outside temperatures that cause year-to-year fluctuations, internal comfort temperatures that increased from 13ºC in 1970 to 18ºC in 2000 and central heating that raised from 5.6 million homes in 1970 to 21.7 million by 2000. All these factors have led to a small decrease on energy demand from space heating since the 1970's, only about 6%, despite the significant improvements in new buildings fabric and insulation (Eyre & Baruah, 2015). The other energy end-uses in a household are domestic hot water, cooking, lighting and appliances. Between 1970 and 2013, energy consumption in lighting and appliances increased immensely by 70%, as a result of increases in the total number of appliances and lights per household (DECC, Jul 2015). For example, in 1970, few homes in the UK would have owned a dishwasher and the range of computing and communications devices used today (see Figure 13 and Figure 15), while the single bulb in a room has, in many homes, become a series of recessed halogen spotlights (Monreal, et al., 2016). Oppositely, energy use has fallen in cooking by 75%, due to a change in lifestyle (Hager & Morawicki, 2013), and in domestic hot water by 52%, due to an improve in water heating technologies.

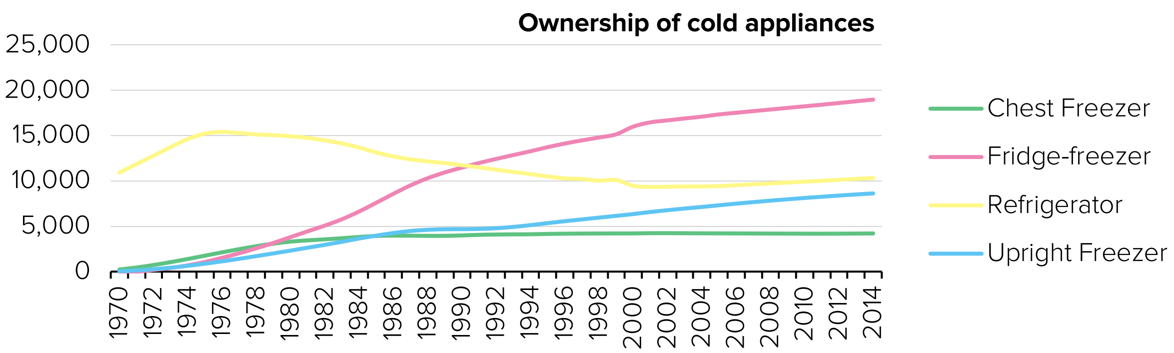


Figure 12 – Graph showing the number and typology of cold appliances owned by the UK's households from 1970 to 2014. Data source: (DECC, Jul 2015).

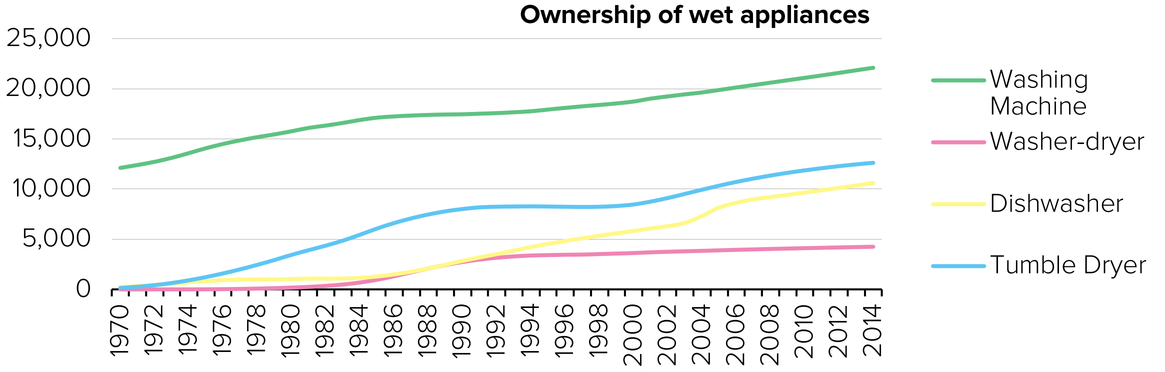


Figure 13 – Graph showing the number and typology of wet appliances owned by the UK's households from 1970 to 2014. Data source: (DECC, Jul 2015).

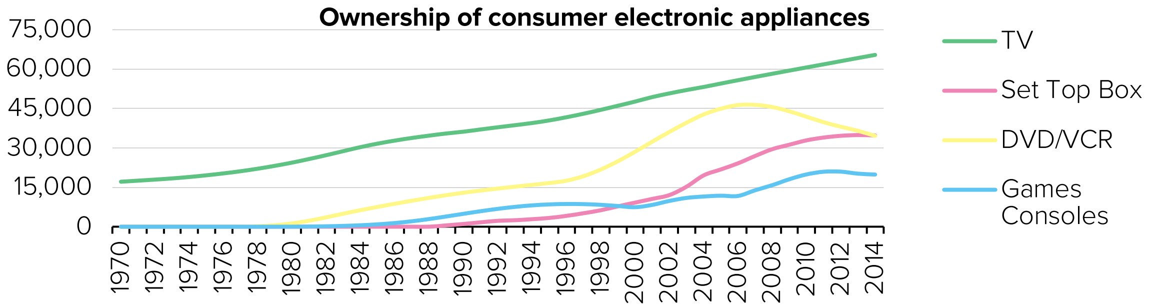


Figure 14 – Graph showing the number and typology of consumer electronic appliances owned by the UK's households from 1970 to 2014. Data source: (DECC, Jul 2015).

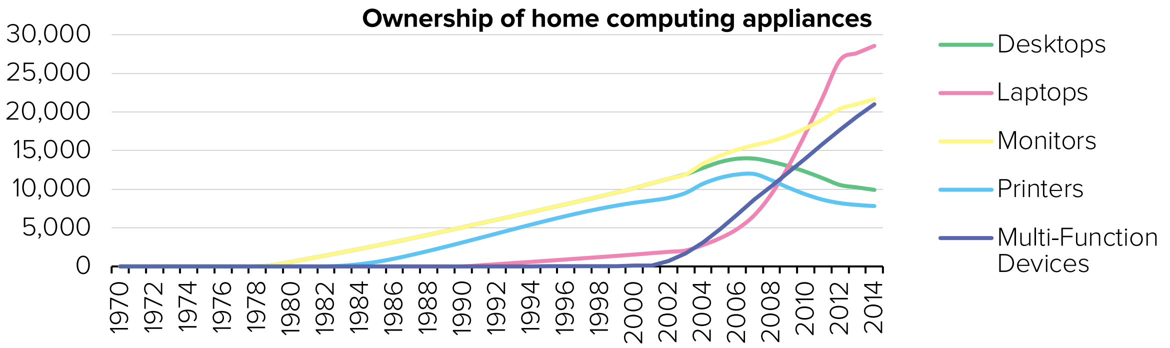


Figure 15 – Graph showing the number and typology of home computing appliances owned by the UK's households from 1970 to 2014. Data source: (DECC, Jul 2015).

It is important to understand how energy is used at home and for which uses this is for. However, it is also important to know which type of fuel is used to cover this demand, since this will have a big influence when looking for more sustainable alternatives. This is analysed in the next section.

2.1.1.2 Energy demand by fuel type

The fuel mix for domestic energy demand has significantly changed since 1970 when the main fuel source was coal (39%), followed by natural gas (24%) and electricity (18%). Nowadays, the situation is very different as shown in Figure 16. The domestic sector is the first main end-user for natural gas with a 62% of the domestic consumption and is used mostly for space and water heating in gas boilers. This is followed by electricity (25%) and petroleum (7%), while coal has disappeared completely (DECC, Jul 2015).

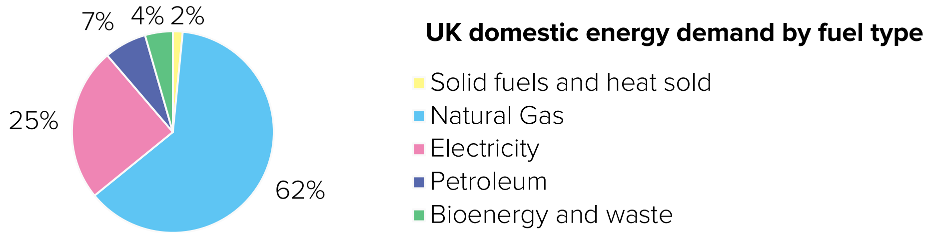


Figure 16 – Pie chart showing UK's domestic energy demand by fuel type in 2014. Data source: (DECC, Jul 2015).

2.1.2 ENERGY SUPPLY

The nature of the energy supplied to a household largely depends on the fuel type and its characteristics, which means that the supply must be done in different ways and over different timescales. For example, a householder who uses pellets, wood or oil for heating will order them once or twice a year because they can be safely stored in the house for a later use. Instead, natural gas and electricity will normally be supplied instantly from the main grid because the householder has no storage capability. In this case there is a permanent dependency on the grid; energy cuts on the gas or electric supply result on a household with no lights, appliances or heating during an uncertain period of time.

On the other hand, the requirement to generate 20% of the UK's heating needs from renewable sources by 2020 (DECC, 2010) means a massive reduction on the use of natural gas and a parallel increase on the use of electricity as a source for heat energy generation. The potential of electricity to be clean energy generated from renewable energy sources and to be stored for a later use, makes it a much more attractive candidate for the EPH design; hence the way it is generated and supplied from the grid to the households, is reviewed in depth in the next sections.

Electricity is the most flexible and easily controlled form of energy. At the point of use, it is almost free of losses and pollution, while at the point of generation it can be cleanly produced from renewable energy sources such as sun, wind and water. Without electricity, modern society would be completely different. There would be no artificial lighting, no long-distance travelling, no mass media or large-scale production. Until now, the analysis has focused on how much electricity householders consume and where does it go within a household. *But, where does it come from?*

2.1.2.1 Identifying the problems of current electricity market

To get a full picture of where the power comes from, it is important to consider how electricity was generated in the past and how it is generated nowadays because the change in energy mix has been radical. At the beginning of the 20th century, coal represented almost the only energy source used to produce electricity, see Figure 17. Later on, in the 1970's, coal was still the main source accounting for about two-thirds of all electricity, but other energy sources, such as oil and nuclear, were gaining importance. Apart from a sharp drop in the mid 1980's, because of the UK miners' strike, coal use fell most dramatically and continuously during the 1990's due to the commonly named 'Dash for Gas'. The same happened with oil, its use also fell sharply, from more than 13 million tonnes in 1970 to just 1.5 million tonnes by the end of

1990s'. Therefore, Dash for Gas caused a dramatic change in the UK's energy market, with a major shift by the newly privatised electric companies towards generation of electricity using natural gas, which at the end of the 1990's was almost 30% of the electricity generated. Today in the UK, electricity is generated from different fuel sources and technologies to have a constant supply and not only rely on one type of power generation. As it can be seen in Figure 17, this variety is very wide and it has changed and evolved differently during the last decade.

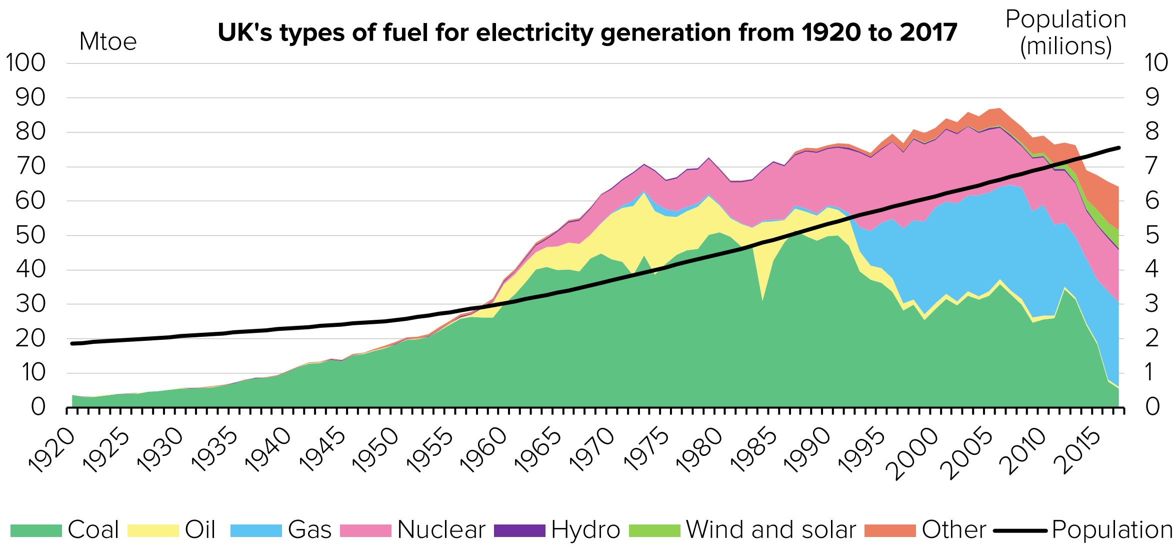


Figure 17 – Graph showing the UK's different fuel sources for electricity generation from 1920 to 2017, data source (DECC, Jul 2018), and world's total population from 1920 to 2017, data source: United Nations, Population Division.

Current electricity market scenario is facing different types of energy sources, which generate different amounts of electricity in different ways, and is dealing with a wide variety of problems. The main current issues are:

- Dependence on fossil fuels: In 2017, half of the UK's electricity was made by burning fossil fuels – i.e. coal (8.6%), natural gas (38.3%) or oil (0.8%) – in power stations that are approximately 40% to 65% efficient, major emitters of CO_2 and highly contribute to global warming. When analysing the trends of consumption from 2010 to 2017, coal has dramatically decreased by 78%, oil by 58% and gas by 23% (DECC, Jul 2018). These differences between trends are mainly due to changes on fuel prices which mainly depend on factors out of the UK's control, hence are hard to predict. Also, the country is now more worryingly reliant on fuel imports than ever before, with imports over 60%. For example, coal is mainly being imported from Russia, Colombia and US; and gas from Netherlands, Norway and Qatar (DECC, Jul 2015). On the other hand, it is important to highlight that fuel sourced from the UK represented a 35% in 2012, but compared to a 43% in 2011, the reduction was significant (Good Energy, 2014).

- Outdated nuclear plants: In the late 1990's, nuclear reactors provided around 25% of total annual electricity generation in the UK (see Figure 17), but this gradually diminished as old plants have been closed down and ageing related problems have affected the number of plants available. In 2016, there were 16 operating reactors in the UK totalling 10GWe capacity, which represent about 23% of the UK's electricity generation (DECC, Jul 2018). Again, the UK needs to import the fuel – i.e. uranium – which involves price fluctuations, but in this case costs are more stable. Over the next decade, the current UK's nuclear power stations will close gradually with all but one expected to stop running by 2025 (DECC, Jul 2015). Several companies have proposed a new generation of reactors, the first of which could be running by 2018. These new nuclear power stations would help the UK reduce its greenhouse gas emissions by 80% by 2050 and secure its energy supply (BERR, 2008). However, to develop around 16 GW of new nuclear power stations, a huge economic investment will be required. Companies such as EDF Energy, Hitachi and NuGeneration have already shown their intentions and started the construction assessment process (DECC, 2014).
- Deficiency of renewable energy: Renewable energy power plants generate electricity from natural and inexhaustible energy sources such as wind, waste, water or sun. Renewable technologies are rising, both in number and efficiency. In 2010, they represented a 7.4% of the electricity generated; they increased to a 10.7% in 2012 and to a record of 17.8% in 2014 (DECC, Jul 2015). This was mainly as a result of a 49% increase in offshore wind capacity, a 38% increase in onshore wind capacity and a 4% increase in the capacity of sites fuelled by biomass and waste (see Figure 18). As generation from renewables is increasing, generation from fossil fuels is declining. This brings on a slightly more optimistic note; the UK's dependency on fossil fuels was at a record low in 2012 at 86.8% and 84.6% in 2014 (DECC, Jul 2018).

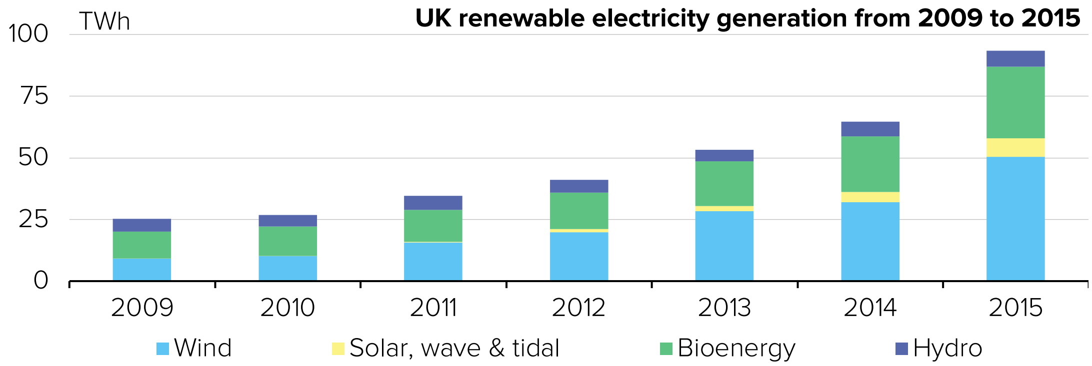


Figure 18 – Bar graph showing the UK's renewables electricity generation by energy source type from 2009 to 2015. Data source: (DECC, Jul 2018).

- Dependence on electricity imports from overseas: The UK does not generate enough electricity to meet its demand; hence it heavily relies on electricity imports. The UK is a net importer of electricity since the interconnector with France opened in 1986. In 2014, the UK's electricity trade net import reached its peak, accounting for almost £900 millions (DUKES, 2015). The UK's electricity network is connected to France (73Km), Ireland (55Km), Holland (260Km), and soon Ireland (262Km), Belgium, Denmark, Norway and Iceland. These power imports should help the National Grid to level out peaks from renewable energy generation and deal with the UK's diminishing electricity margin. According to National Grid, in the future the UK will need to import more power from neighbouring countries as the country's electricity margin, which represents the safety cushion of spare power generating capacity, continues to tighten more every year (Ratcliffe, 2014).
- Stability of energy security: To avoid power blackouts, electricity demand must equalise electricity supply at all times. This is a difficult task since both demand and supply, especially renewables being weather dependent, fluctuate and are constantly changing on a daily, weekly and seasonal basis. In the UK, this task is done by the National Grid, who continuously balances electricity supply and demand second-by-second, minute-by-minute, hour-by-hour and day-by-day; to guarantee that electricity is released at a frequency of 50 Hz, with severe consequences if that is too low or too high. It is essential to exhaustibly plan for every event or circumstance that might influence the electricity demand; examples include a TV pick up, a sports competition or a solar eclipse to name a few. A lack of forecast could end on a sudden loss of energy supply. This is known as energy security. Across literature, there are multitude definitions of energy security, which makes it hard to measure and difficult to balance. Winzer (2012) thoroughly reviews the 'security of supply' definition from existing literature and finds a common concept to define energy security as "the continuity of energy supplies relative to demand". Energy security should guarantee the energy needs of consumers at any time and for a reasonably constant price (Roaf, et al., 2005). Current energy security in the UK remains positive and strong due to a combination of its liberalised energy markets, firm regulations and extensive North Sea resources. Moreover, the country has a number of tools to balance the National Grid such as a 2GW interconnector with France or a 3.5GW of pumped storage in reservoirs. However, this relative resilience to energy security faces inevitable on-going risks that could be partially mitigated but are entirely unavoidable – e.g. severe weather, technical failures, terrorist attacks and industrial actions (DECC, Nov 2012).

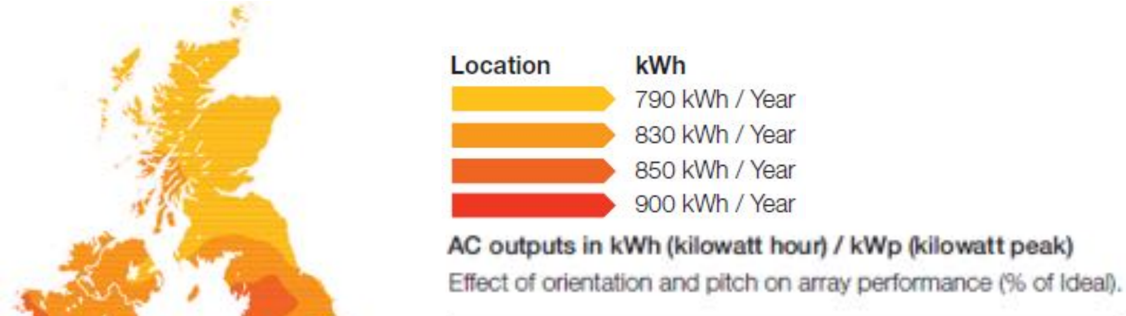
2.1.2.2 Identifying the alternatives to current energy market

By 2020, the UK has to meet the 15% renewables energy target agreed at European Union level. There are a number of ways to meet this legally binding target, but in 2009 DECC finally proposed an action plan that postulated that by 2020, 30% of electricity demand would have to come from renewable sources (UK Government, 2009). Owning to that fact, renewables are the future, though a future unlikely to arrive tomorrow if the current top-down approach is followed (Jones, 2017).

Nowadays, renewable energy plants are mainly off-site and of a large scale, hence they are costly top-down solutions. Although renewable's technologies have achieved optimistic cost-reductions, they are still relatively expensive, lack energy density and frequently require enormous transmission network expansion. Furthermore, policy has failed to support business models for sustaining mass efficiency improvements (Jones, 2015). The market and government policies are working to address and solve these problems, but apparently not as fast as nuclear plants retire. Alternatively, smaller-scale bottom-up solutions, like the proposed EPH approach, could help achieving the UK's challenging targets. When considering the building scale, the renewable energy sources that could be more appropriate for local generation of electricity are solar and wind (Smith, 2005). Jacobson & Delucchi (2009) stated: "Because the wind blows during stormy conditions when the sun does not shine and the sun often shines on calm days with little wind, combining wind and solar can go a long way toward meeting demand (…)".

For solar, in 1931 Thomas Edison already said: "I'd put my money on the Sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that". Regrettably, more than 80 years later, in the UK solar energy only accounts for 8% of the total generation from renewables (see Figure 18), hence it seems that Edison's hopes were not listened. But the potential of solar energy is unquestionable, with more energy falling on the Earth's surface every day than the currently use in 27 years, it is estimated that 30 km^2 of photovoltaic panels could potentially produce as much energy per year as a 1GWe fossil fuelled plant (University of Exeter, 2012).

Despite all these positive evidences and potentials, solar energy generation also faces some major drawbacks. For example, material availability issues – i.e. shortage of semiconductor grade crystalline silicon – and high manufacturing costs (Ming, et al., 2015). When considering the smaller-scale of buildings, even more challenges seem to be influencing on solar energy lack of popularity (Baborska-Narozny, et al., 2016). For example, the lack of building integration with PV installations that are clearly add-ons, the lack of harmony with the buildings they sit on and the extra cost that they involve. However, many of these issues could be easily solved with building integrated solar solutions which, by replacing existing roofs, could offer many advantages such as multi-functionality, cost savings, reduced weight, no roof perforations, less wind vulnerability, increased PV area or reduced CO_2 footprint (Ikedi & Okoroh, 2015).



	Vert	80	70	60	50	40	30	20	10	Horiz
East	58	65	70	76	80	84	86	88	90	90
SE	69	77	84	89	93	96	96	96	94	90
South	71	80	87	93	97	100	100	98	96	90
SW	67	75	82	87	92	95	96	96	94	90
West	56	63	69	74	78	82	86	87	89	90

Figure 19 – Map showing the average annual solar radiation ($kWh/m^2/day$) in the UK and Ireland (Kingspan, 2018).

For wind, the UK scenario is much more optimistic since wind is currently the major source of renewable energy generation, accounting for as much as 54% in 2014 (see Figure 18). As the US Department of Energy (2016) states, the advantages of wind power are many; for example, it is clean, domestic, sustainable, cost-effective, creates jobs and can be built in rural areas boosting their economy. On the other hand, some challenges are also identified; for example, it requires from a high initial investment, new transmission lines and suitable land, and it might cause noise, aesthetic pollution and damage to local wildlife (Smith, 2005). However, Bennett, Friends of the Earth's CEO, dispelled all these 'myths' by stating that wind turbines kill less bats and birds than windows, tall buildings, power lines and cats; they are intermittent but are active about 80 to 85 % of the time; their noise problems have been solved with newer technologies; they are totally safe with very few cases of turbine blades flying off; and they are as aesthetically unpleasant as other power plants such as nuclear or coal (Independent & Bawden, 2015).

Despite all these challenges, in the UK, that is now driven by the need to reduce CO_2 emissions and secure homemade energy supplies, wind energy is the fastest growing renewable energy type. For instance, 995 operational wind farms were installed in the country until 2016, and larger plants are currently being build or will be built in the future. The majority of these projects are onshore wind farms, accounting for 8,577MW capacity, and offshore wind farms, accounting for 5,098 MW more. Together, they are capable to produce around 34 million MWh per year, thus to meet the annual demand of 31% from the UK's housing, about 8.2 million homes (Renewable UK, 2018).

Considering the smaller-scale, around 25,000 small and medium wind turbines were already powering many UK homes, farms and business in 2005 (Renewable UK, 2018). Reaching up to 55 metres tall, medium-size turbines have the potential of producing enough energy to power an entire community, while small-size turbines can cover the demand of a household; either using the energy directly on-site, storing it in batteries for later use or feeding it into the grid. These micro-generation technologies are receiving increasing interest, but their overall potential and their optimised conditions are frequently not entirely clear. To address this, Carbon Trust commissioned research from the Mett Office and Entec to determine the UK's potential carbon savings from small-scale wind energy (Carbon Trust, 2008) and how small wind turbines can best be sited to save most carbon (Mett Office, 2008). Therefore, the UK has well understood its wind potential and the market is growing fast. But considering that about 40% of all wind energy in Europe blows over the UK (Energy Saving Trust, 2016), it seems that the country could take even more advantage of this huge potential.

2.1.2.3 Identifying the solutions towards a future low carbon electricity market

The energy system is constantly advancing and growing in complexity. The wider variability of power generation capacity presents new challenges, while security of supply is every day more important (Walker, et al., 2014). The future energy system should be more interlinked, more efficient and more flexible (European Commission, 2015). At the moment, there is very limited ability to shift demand in a co-ordinated way. Only a few large industrial electricity users are on interruptible contracts, receiving discounts in return for being switched-offable if the grid has a shortfall in supply (Ofgem, 2010). In the future, a smart grid could shift timing of millions of pieces of demand, to help balance the grid (Good, et al., 2017).

The introduction of low carbon energy from renewables, which are intermittent in terms of supply, poses new operational challenges for the vast, interconnected and interdependent network of technologies that make up the national grid (Brandmayr, et al., 2017). The UK's future electricity market (see Figure 20) will not only comprise passive customers buying centralised electricity from large and remote power stations; instead, it will increasingly rely on distributed electricity which will be generated, owned and operated by the consumers who install renewable supply energy technologies at the building scale. This new localised electricity generation will not displace neither the need of big power stations and networks nor the need for decarbonising the large-scale electricity network.

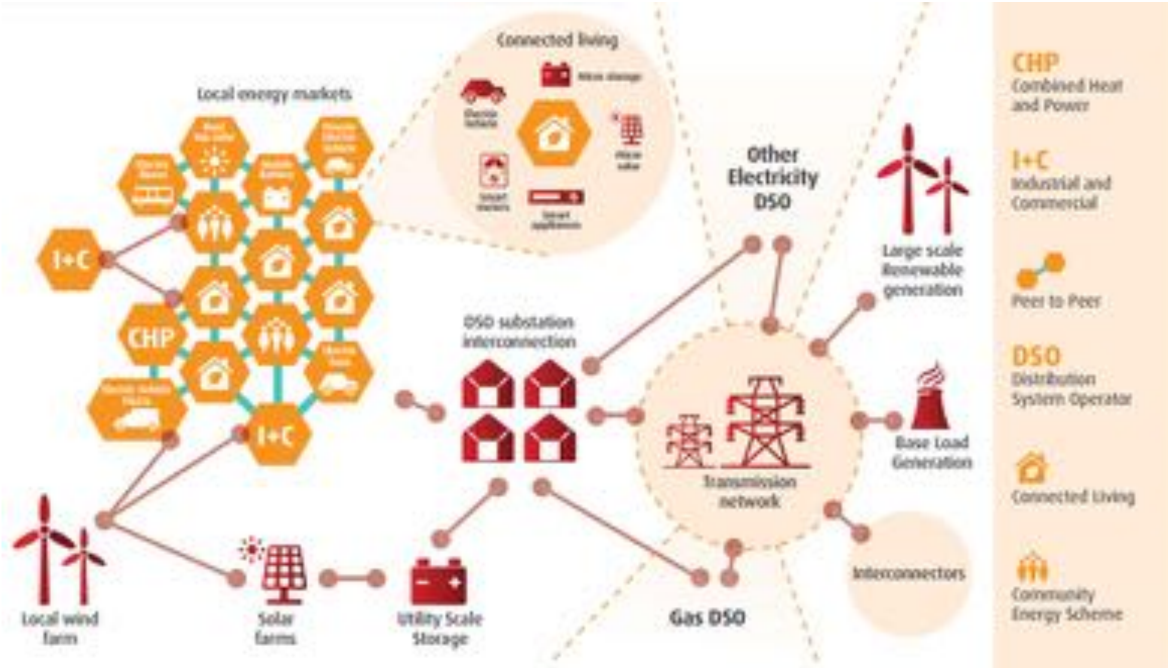


Figure 20 – Schematic showing how the UK's electricity market could be in a low carbon scenario (UKPN, 2018).

The UK's future energy market is entering a new era where the user really could take control. Up until now, subsiding schemes were driving the low carbon energy market. But with the fast evolution of technologies, with low cost batteries and with efficient and affordable photovoltaic panels; payback will be shortened and the government may lose the ability to constrain small-scale low carbon technologies by limiting subsidy schemes. Moreover, the UK's energy system faces a great deal of change as existing infrastructure closes, domestic fossil fuel reserves decline and the system adapts to meet our low-carbon objectives (Harvey, 2016). These changes will create new challenges for the UK's energy security in the years ahead (Walker, et al., 2014; Roaf, et al., 2005).

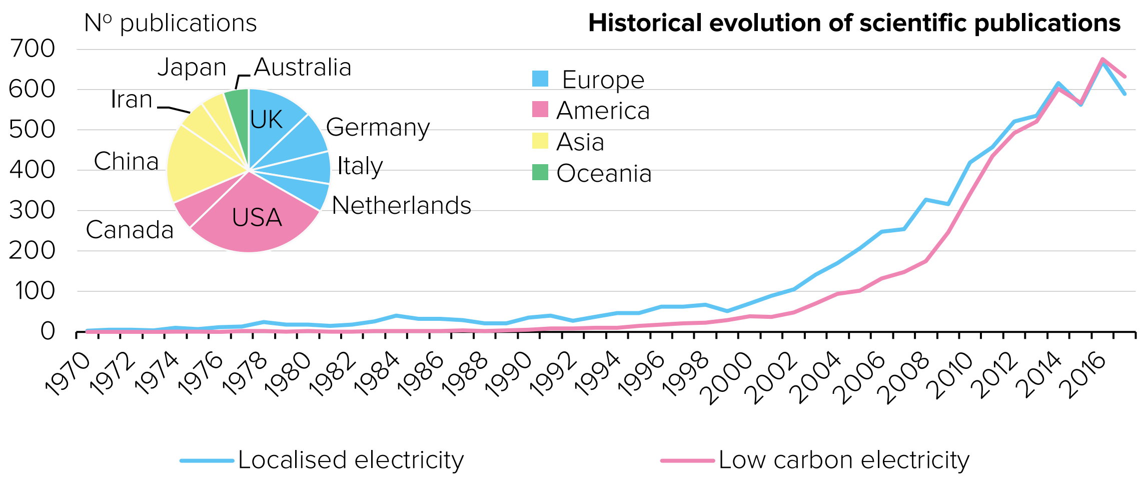


Figure 21 – Linear graph showing number of publications grouped by keywords – i.e. localised energy and low carbon electricity – from 1970 to 2017. Pie chart showing the top 10 countries leading these publications. Data source: Elsevier.

Due to the significance of transition challenges, research on the field of local electricity distribution has grown significantly during the last decade and the UK has been the third country in the world leading on this type of research (see Figure 21). For example, Walker, et al. (2014) created a simplified electricity network model to evaluate the UK's grid performance under different low carbon transition scenarios; Fuchs & Hinderer (2016) investigated the strategic bottom-up actions that local communities in Germany are leading towards a decentralisation of energy production and a low carbon future; and Hu, et al. (2018) identified the barriers to large-scale integration of renewable supply into the European electricity network. In general, most publications agree that, while traditional electricity is generated in large-scale power plants and is supplied with centralised structures, the transition towards a low carbon built environment future scenario is transforming the electricity market with an increase on renewable energy generation and decentralized energy supply.

In conclusion, during the last decade energy has become front-page news, which means that the future of energy market for the UK has never been so important. However, no one can certainly know how the energy future will progress and if this uncertainty could continue for decades. Rising domestic energy bills; 2.38 millions living in fuel poverty in 2012 (DECC, May 2015); anti-fracking activists chaining themselves to protest at plans to extract shale gas (Vaughan, 2014); warnings of potential power blackouts from government and energy companies (Ball, 2014); and 13 out of 16 the UK's nuclear power plants reaching the end of their expected lifetimes in less than a decade time (World Nuclear Association, 2014). The UK's energy sector has not tackled such a tremendous combination of dreadful problems since the 1970's world's energy crisis (Roaf, et al., 2005). The planning of electricity generation is critical and the UK must invest £110bn in energy infrastructure (DECC, Apr 2014).

2.1.3 ENERGY STORAGE

Energy storage is the capture of energy produced at one time for use at a later time. Energy comes in multiple forms such as radiation, chemical, potential, electricity, latent heat and kinetic. Therefore, energy storage involves converting energy from forms that are difficult to store to more conveniently or economically storable forms.

For the purpose of this research, this thesis focuses on energy storage technologies for electricity energy and for thermal energy. Since the discovery of electricity, humankind has sought effective methods to store that energy for use on later demand. Over the last century, the energy storage industry has continued to evolve and adapt to changing energy requirements and advances in technology.

Recent changes in feed-in tariffs regulations, not only in the UK but also in Europe, and big reductions on this remuneration scheme, mean that using renewable energy directly by the building on-site is becoming more attractive than feeding it into the grid. However, the simultaneity of renewable energy supply and energy demand from the building and its occupants is limited. Interest on energy storage is growing rapidly and incentives from foreign countries are being offered to develop these technologies, for example German grants of 25 million euros are being used to subsidise battery costs installed together with solar PV systems (Moixa Technology, 2013). It is expected that this will become a major growing area for research and development. Batteries have the potential to be secure, stable and balanced energy systems that not only reduce stress on the grid, but also provide greater autonomy and security to householders and building operators.

In May 2015, the European Commission (2015) organised a round table to discuss about the required actions to guarantee future energy security. It was agreed that energy storage should be an important element in the energy system offering flexibility and security. The storage element could "bring more benefits to the energy system, provided that the technological progress is made and long-term objectives are adequately reflected in the design of the markets and regulations" (European Commission, 2015).

In the meantime, the UK is confronted with the energy trilemma of security of supply, affordability and sustainability. Intelligently used, energy storage could be one of the very few technologies to meet all three aims (REA, 2015). There are a number of benefits that energy storage could offer. For example, less use of fossil fuels enabling the integration of more renewables in the energy mix, less need to invest in new conventional generation capacity, less need to import electricity via interconnectors, less energy loss during transmission and distribution, more system stability during electricity outages, fewer and cheaper electricity transmission and distribution system upgrades, or cheaper energy prices by storing it when prices are low and using it on site when prices are high (REA, 2015). Owning to that fact, in July 2017, the UK's energy department unveiled plans for a more flexible energy system and launched the Faraday Challenge, £246m of funding for battery research, £45m of which would be used to create a national battery institute, which would be a virtual grouping of universities across the UK. Hence the UK pioneered energy innovation through batteries in homes (Vaughan, 2017).

2.1.5 LESSONS LEARNED

When studying energy demand, the relationship between energy end-use and energy fuel type is key to understand the huge change on the energy market that the UK has experimented during the last decades. After reviewing current statistical data and literature, it was found that nowadays the two main fuels supplied to the UK's households are natural gas (62%) used mainly for space and water heating, and electricity (25%) used mainly for lighting and appliances. Together they represent 87% of the energy demand of a household, while the rest is covered with oil, solid fuels and bioenergy.

Heating represents the major energy user within a household, therefore any change on the way that this space heating is supplied will have a big impact on the fuel demand distribution (Gupta & Irving, 2014). Certainly, domestic heating is a big challenge in the UK, not only because it has the difficulty of a climate that is cool and temperate, so that heating is a much more important energy service than cooling; but also, because the energy supply infrastructure is deep-rooted with a very high diffusion of natural gas, which has traditionally been economical (Eyre & Baruah, 2015). On the other hand, the requirement to remove all direct CO_2 emissions from space heating by 2050 (DECC, 2010) means a massive reduction on the use of natural gas and a parallel increase on the use of electricity as a source for heat energy generation. This is extremely challenging and means that any heat produced at building-scale must be generated from renewable energy. When considering the building scale, the renewable energy sources that could be more appropriate for local generation of electricity are solar and wind.

Electricity has the potential to be a clean energy generated from renewable energy sources and to be stored for a later use. The EPH approach is inconceivable without being linked to energy storage. Therefore, the EPH concept needs to incorporate energy storage systems to ensure the use of electricity and heat at times when the renewable energy systems are not generating. Storage batteries are needed to allow the excess of electricity generated by renewables during the day to be used later at night. In this way, households equipped with a battery system can increase self-consumed renewables electricity while reducing the energy drawn from the grid, thus increase their self-sufficiency and autonomy.

2.2 Modelling simulation of energy

In any project, it is important to have good precise models of the building energy systems to design and optimise the components and to simulate their performance. A state-of-art review of the significant modelling tools developed and adopted to model the energy system of buildings by researchers around the world is presented in this section.

A range of methods is available to create load models or energy consumption models that simulate a building energy system for prediction of energy loads or cost savings. These models vary in scale, e.g. from modelling of a single wall to modelling of a whole building by modelling all rooms exposed to temperature variations. Sinha & Chandel (2014), in a review of software tools for building energy systems identify and compare 19 different software tools: HOMER, Hybrid2, RETScreen, iHOGA, TRNSYS, iGRHYSO, INSEL, HYBRIDS, RAPSIM, SOMES, HybridDesigner SOLSTOR, ARES, HySim, HybSim, IPSYS, HySys, Dymola/Modelica and SOLSIM. Their limitations, availability and outputs are compared. Among all these tools, HOMER is considered to be the most widely used tool as it offers more combinations of renewable energy systems and is able to perform optimization and sensitivity analysis. Turcotte et al. (2001) classify these software tools in four categories:

1. Pre-feasibility tools: to size systems and produce financial analysis (e.g. RETScreen).
2. Sizing tools: to optimize the size of system's component and provide detailed data about energy flows among them (e.g. HOMER).
3. Simulation tools: to analyse the behaviour of the system, however the user needs to specify the details of each component (e.g. HYBRID2).
4. Open tools: to modify the algorithms of the individual components (e.g. TRNSYS).

A large number of parameters can influence and act upon the building energy systems. These are often difficult to define accurately, are always complexly interconnected and usually vary widely in magnitude and direction during a 24h period. Harish & Kumar (2016) proposed a list with all the significant parameters used while developing an effective energy system model. These are solar radiation, outside air temperature, inside air temperature, thermo-physical properties of construction elements, wind characteristics and precipitation, cloud conditions, internal heat gains, ventilation rate and building location. All these factors would have an impact on the building energy demand; therefore, with a view to establish a building energy system modelling, the primary target of such energy models is to estimate building energy demand.

Energy demand modelling of buildings aims to quantify their energy requirements, hence to predict building's energy consumption. Models may be used for a wide variety of purposes. The most common models use either top-down methods considering the macro-scale to determine regional or national energy demand requirements, or bottom-up methods considering the micro-scale, for example to evaluate the change in energy consumption of a particular dwelling due to an upgrade or addition of technology (Swan & Ugursal, 2009). The two modelling scales are useful as they can guide decisions of policy regarding the residential stock, both old and new.

According to Zhang et al (2012), when reviewing existing literature there are three themes of research focusing on residential energy consumption in the UK. For the purpose of this review, a similar categorisation is followed:

1. Factors influencing domestic demand: Uses statistical techniques to identify the factors influencing residential energy consumption; for example the studies from Utley & Shorrock (2008), Summerfield et al (2010), Baker et al. (1989), Baker & Rylatt (2008), Kelly (2011), and Palmer et al. (2013b)& (2014).
2. Methods used to model domestic demand: Considers the load profiles of domestic buildings and analyses the factors causing the different types of energy load curves; for example findings from Yao & Steemers (2005), Stokes et al. (2004), Zimmermann et al. (2012) and Palmer et al. (2013a) & (2013b).
3. Behaviour influence on domestic demand: Focuses on the pro-environment behaviour of residential energy consumers' and how a change of this behaviour can reduce households' energy consumption; for example research from Mansouri et al (1996), Wood & Newborough (2003), Brook Lyndhurst (2007) and DEFRA (2008).

The systematic review presented on this section uses books, UK's Government reports and two electronic sources for journal papers, Web of Science and Scopus; all of them chosen for their popularity and relevance in the subject area. The literature search was deliberately broad to allow all relevant publications indexed in the two databases to be identified. The final search was performed in April 2016 and includes publications available online until the date. Figure 22 shows that, in total, 640 papers were selected for the initial review process, being research on 'simulation modelling methods' the most popular among researchers (43%). It also shows that although publications on the subject started to appear in 1975, it was not until the early 2000's that the subject became more popular, reaching its peak during this last decade. The initial selection of literature was followed by manual title and abstract screening that completed the selection process.

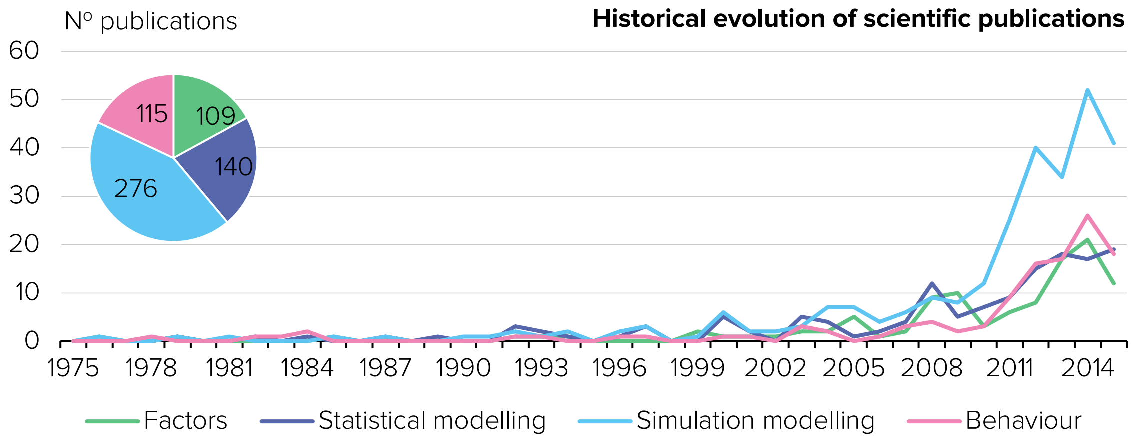


Figure 22 – Linear graph showing number of publications grouped by keywords – i.e. energy demand & factor, statistical modelling, simulation modelling, behaviour – from 1970 to 2016. Pie chart showing distribution of total published papers per line of research. Data source: Elsevier.

2.2.1 FACTORS INFLUENCING DOMESTIC DEMAND

It is clear that many factors can influence residential energy consumption in the UK; for example, dwelling characteristics, heating systems, occupant characteristics and economic factors (Summerfield, et al., 2010). But a better and more detailed understanding is needed. To answer this key question, research on this theme uses various statistical methods from different approaches.

$$\mathbf{Q_{HS} = N\ [\ 97.84 + (\ F_S * \{year\text{-}1970\}\ ) - (F_T * Te) - (T_L * \Delta H) - (\ F_H * \Delta E\%\ )\ ]}$$

Where:

QHS = housing stock consumption (PJ) including heating, hot water, appliances and lighting
N = Number of households (millions)
F_S = Increase of 2.18GJ per year as result of increasing levels of services or standards of comfort
F_{TE} = Increase of 3.28 GJ per ºC change to reflect the variations to be expected from fluctuating external temperatures.
Te = Winter average external temperature (ºC).
F_H = Decrease of 0.28 GJ for each 1W/ºC of improvement on the heat loss.
ΔH = Improvement in the average dwelling heat loss relative to 1970.
FE% = Decrease of 1.56 GJ for each percentage point improvement in the heating efficiency.
ΔE% = Improvement in the average heating efficiency relative to 1970.

Figure 23 – Equation to predict housing stock energy use (Utley & Shorrock, 2008).

Utley & Shorrock (2008), in the report from BRE titled *'Domestic Energy Fact File 2008'*, modelled the predicted housing stock energy demand by considering the influence of factors such as the number of households, winter temperatures, improvements on building fabric and improvements on efficiency of heating systems; but not considering the fuel type. First, they developed an equation (see Figure 23) capable of describing the changes in the energy consumption since 1970, and then they validated it by comparing their predictions against the actual data of the domestic energy use of subsequent years. They applied a term increasing each year to allow for increased levels of services demanded by households (F_S

= 2.18), the external temperature (F_{TE} = 3.28), the improvement in the average dwelling heat loss (F_H = 0.28), the improvement in the average heating efficiency ($F_{E\%}$ = 1.56) and the number of households. The predictions of the equation were in quite good agreement with the real consumption.

Summerfield et al (2010) developed an improvement to the BRE. The new model, named ADEPT, removed some factors that were not statistically significant as predictors and added a new factor to the equation, the adjusted inflation on energy price. Both models are strong when predicting the residential energy consumption of all the UK's housing stock and the findings can potentially be useful when drawing energy policy implications at macro-scale, for example at national level. However, they use a top-down method based on aggregation that focus on recognising the cause-effect relationship between the aggregated variables and the residential energy consumption of the housing stock, and this can be very limiting in terms of local energy policy making (Kelly, 2011). For example, they consider the UK's housing stock to be homogeneous and they also ignore regional, local or even individual variables such as fuel type, social-demography, physical characteristics, energy technologies and occupants' behaviour.

For the purpose of this thesis, bottom-up methods that consider the micro-scale of the individual household unit are considered more appropriate to help on the modelling of the EPH unit. Therefore, the focus is on micro-scale energy demand modelling tools or bottom-up methods. Normally, bottom-up methods require a much wider high-resolution set of data containing comprehensive specific characteristics of households such as social-economic (e.g. household income), demographic (e.g. family size), physical (e.g. SAP rating) or even behavioural (e.g. environmental attitude). This big demand on data requirements makes this type of method more difficult, hence there are a limited number of studies of this type. Also, the difficulty of incorporating behavioural factors into the models represent a significant limitation, especially when their use for local energy policy making aims to influence householders' behaviour (Hitchcock, 1993).

Baker et al. (1989) did one of the earliest bottom-up studies found. They analysed the effect of two social-economic factors (i.e. family income and house size) on individual household energy demand for both gas and electricity. They followed an empirical approach to survey data, by considering the '*Family Expenditure Survey*' (FES) during the period 1972 to 1983 for over 50,000 housing units.

Baker & Rylatt (2008) studied two new variables, in their case a socio-economic factor (i.e. home-working) and a physical factor (i.e. number of bedrooms), and their impact on the annual gas and electricity energy demand of households. They first used a survey approach gathering data from individual household questionnaires and then they compared this data against the annual gas and electricity meter readings and the estimated floor-areas from a GIS database. Results show a significant influence.

Kelly (2011) used a statistical approach to the *'1996 English House Condition Survey'* and the *'1996 Fuel and Energy Survey'* to develop the first known application of structural equation modelling (SEM) to investigate which were the main drivers of residential energy consumption in England. As a result, the study proofed that the main influencing factors were number of occupants, household income, energy pattern, floor area, temperature difference and SAP rating (see Figure 24). For example, each extra occupant results on £88 more per year, while each extra $10m^2$ means £23 increase or each extra 1°C of internal temperature represents £2.5 more per year.

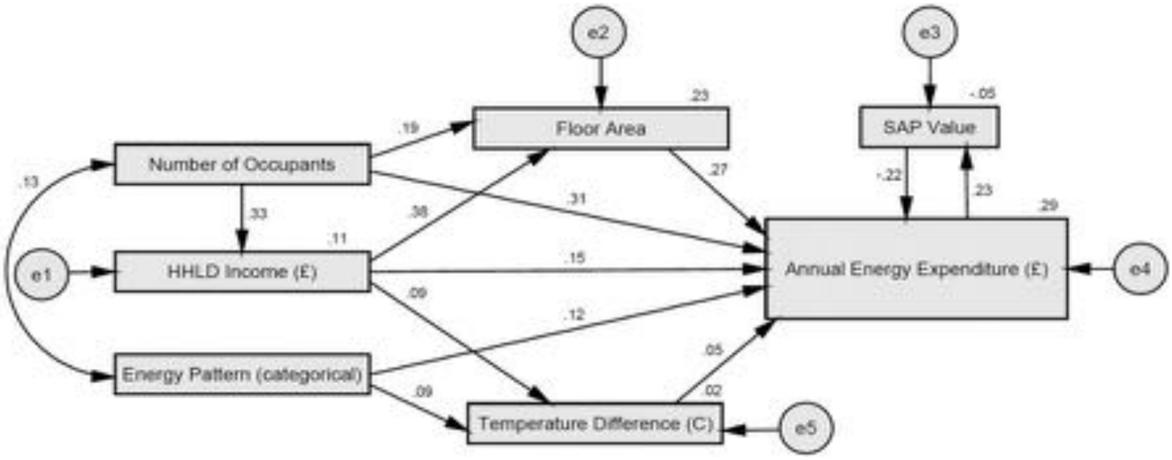


Figure 24 – Path diagram of the Structural Equation Model (SEM) (Kelly, 2011).

Palmer et al. prepared a series of very thorough reports, such as *'Electrical appliances at home: tuning in to energy saving'* (2013b) and *'Powering the Nation 2'* (2014), which studied the main factors influencing on the ownership of appliances and the impact on the households' energy consumption. These reports analysed the data collected with the '*Household Electricity Survey'* (HES) (Zimmermann, et al., 2012), a project funded by DEFRA, DECC and the Energy Saving Trust and carried out across England from May 2010 to July 2011. The main households' characteristics identified as having an impact are:

- Social status: Certain socio-demographic groups are more likely to own a specific type of appliance. For example, there is an enormous difference with dishwashers, which are owned in 93% of households from upper-middle class (grade A), in 59% of households as average or in 35% of households from working class (grade D). A similar result is found for tumble dryers.

- Employment status: While 80% of part-time employed people are more likely to own a dishwasher, only 42% of retired people do.
- Age of household representative person: This factor has an impact on the percentage of ownership as well as on the age of appliances. For example, 78% of people aged between 45 to 54 years tend to own a dishwasher, compared to the average 59% or to the 32% of retired people. On the other hand, those retired have older washing machines (mean 7.5 years old), whereas younger people own newer machines (mean 3.5 years old). Similar results are found for cold appliances and TVs.
- Household size: This is the most consistent factor. Households with one person are less likely to own appliances. For example, dishwashers (34% compared to 59% for all homes), tumble dryers (31% compared to 55%), refrigerators (40% against 51%) and microwaves (86% compared to 91%). Oppositely, households with four or more people are more likely to own these types of appliances. Consequently, this has a big impact on the total electricity use per household. Figure 25 shows that there is an 'economy of scale', so larger households have lower electricity use per head.

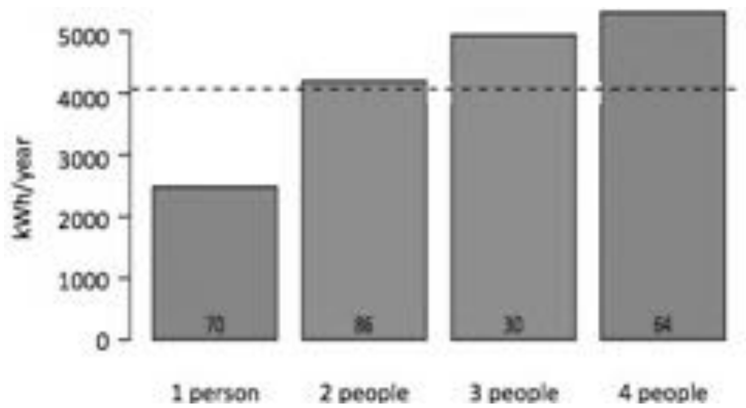


Figure 25 – Graph showing the UK's household electricity demand by number of occupants (Palmer & Terry, 2014).

The chart shown in Figure 26 brings together the main factors identified by the study to correlate to total energy use in the surveyed homes. Factors like single occupancy, smaller dwellings or retired people, are identified as drivers linked to low average use; while factors like bigger dwellings, unemployed people, higher occupancy or higher class, are linked to above average energy demand. So, all these factors are considered when defining the energy demand profile with the EPH tool. On the other hand, the study identified the household consumption of the lowest (562 kWh/year), the average (3,479 kWh/year) and the highest users (14,485 kWh/year).

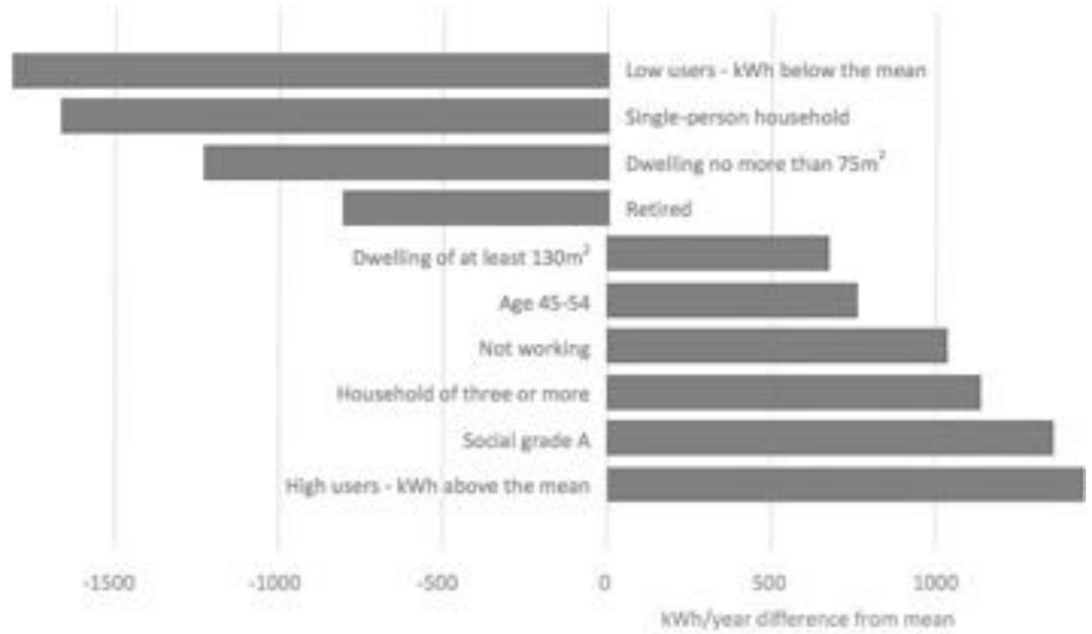


Figure 26 – Graph showing the factors influencing on household's electricity demand (Palmer & Terry, 2014).

2.2.2 METHODS USED TO MODEL DOMESTIC DEMAND

Energy demand load profiles can be used for a wide variety of purposes (Svehla, 2011). One purpose is for operational support to the main energy providers, so they can forecast and plan their energy supply to meet demand as it arises. This is a key task because electricity is very sensitive and a mismatch between supply and demand has an impact on the grid's voltage, which even for a short outage can result on switching off equipment like computers or alterations to industrial applications (Lee Willis, 2004). In the UK, National Grid is the 'System Operator' of the electricity transmission system and manages this in a real-time basis to ensure that supply matches demand and to address any issues with transportation and delivery.

However, trading and settlement of electricity is done in half hour chunks of time, called *'Settlement Periods'* (Elexon, 2015). For each half hour, those with demand of electricity (e.g. suppliers) will forecast what the demand will be and will buy the needed volume of electricity form the generators. To produce a high-quality forecast, suppliers install half-hourly (HH) meters on sites with high consumption as well as non-half-hourly (NHH) meters to sites with smaller consumption, for example a domestic residence. NHH may have its meters read only once or twice a year, hence data has to be split and profiled into half-hour chunks. To generate a load profile, NHH meters are classified into one of eight profiles class, being only two of them for domestic premises: class 1 (domestic unrestricted customers) and class 2 (domestic economy 7 customers). For example, the figure below shows daily and annual profile for Class 1 (Elexon, 2013).

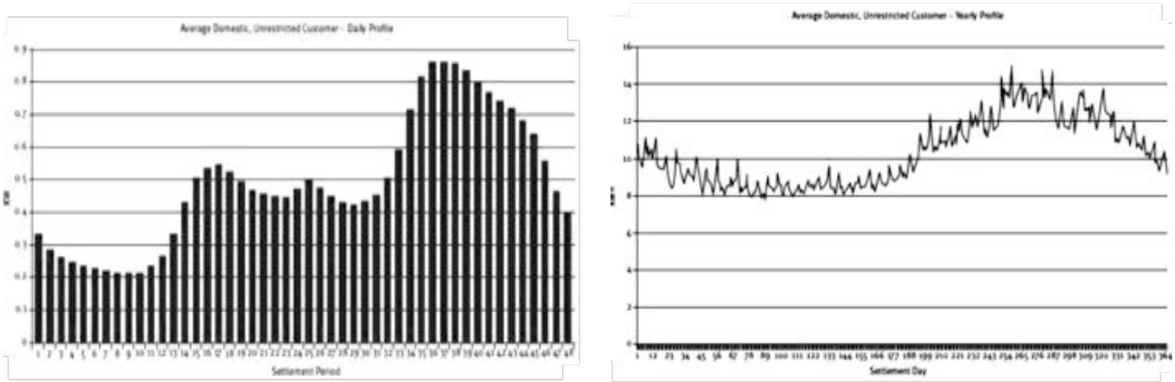


Figure 27 – Graph showing profile Class 1 electricity demand pattern daily (left) and yearly (right) (Elexon, 2013).

Another important purpose of demand profiling is for developing and validating energy demand models. In this review, energy demand profile models or tools are classified in two different categories: statistical models – those that estimate the energy profiles based on simple parameters such as house type, temperature and number of occupants – and simulation models – those that complexly simulate real energy flow and human behaviour.

2.2.2.1 Statistical models

Statistical models can use two different approaches. A survey approach, which measures real load profiles for dwellings and then applies statistical variations by considering the relationship with possible drivers such as temperature, day length, floor area or number of occupants. The second approach, end-use approach, generates domestic demand profiles from monitored data on end-use and adds some probabilistic variations to consider the diversity of timings in different households.

Yao & Steemers (2005) developed a simplified statistical model to predict the demand profile of all the energy used in a typical house in the UK, by analysing the occupancy energy patterns in relationship with the national surveys data for household size and appliances ownership. As a result, this survey approach study presented five different scenarios of occupancy pattern for electrical appliances, domestic hot water and heating demand. For appliances, the statistical data from Mansouri et al. (1996) on electric cooking, cold, audio-visual and wet appliances, was reviewed and used to calculate the average annual energy consumption of appliances in the UK. However, only the methodology used is valuable for current research, because appliances ownership and energy consumption has changed dramatically since 1996 as it has previously been explained in section 2.1.1.1 and Figure 15. For domestic hot water, the consumption per person per day data from Mash (1996) and a mathematical equation (see Figure 28) were used to generate the demand profile. Consumption results were calibrated against monitoring data of a three-person family house considering water consumption and temperature for baths, dish washing and clothes washing. However, no details were given on the number of data sets or collection conditions. Finally, the space heating load was simulated using a thermal resistant method based on the energy balance studies from Yao & Baker (2000) and Baker & Yao (2002). In this case, the used equation (see Figure 29) was validated against the thermal simulation tool ESP-r, developed by the University of Strathclyde.

$$E_{DHW} = [\, Cp\, \rho\, V\, (T_{out} - T_{in})]/3600$$

Where:

E_{DHW} = domestic hot water load (kWh/day)
Cp = specific heat capacity of water (4.187 kJ/kg K)
ρ = density of water (1000 kg/m3)
V = daily volume of hot water consumed for each component (m3/day)
T_{out} = water output temperature (°C)
T_{in} = water input temperature (°C)

Figure 28 – Equation to calculate domestic hot water daily energy demand (Yao & Steemers, 2005).

$$C = \Phi heat/cool + \Phi cond + \Phi vent + \Phi solar + \Phi sp$$

Where:

C = thermal capacity
Φheat/cool = auxiliary heating/cooling energy of the room
Φcond = conductive heat transfer through the building envelope (wall and window)
Φvent = ventilation heat transfer through the building
Φsolar = solar gain
Φsp = internal gain from electrical lighting, people and appliance

Figure 29 – Energy balance equation to calculate heating energy demand profiles (Yao & Steemers, 2005).

However, heating demand modelling is not as straightforward as the previous equations from Figure 29 could suggest, because it depends on many user-dependent factors such as fuel type, temperature, occupancy pattern or perception of comfort, as well as on many other factors like wind, solar gains, internal gains or thermal mass (Svehla, 2011). Therefore, turning the heating on does not necessarily generate an instant and predictable demand on the grid. For example, there could be a delay on the time profile as a result of the thermal mass of the building and furnishings storing and releasing heat (Mavrigiannaki & Ampatzi, 2016), or there could be internal gains from electric appliances, water heating losses, solar radiation or people's activity; which could represent on average around 50% of the heating load required, according to BREHOMES energy model and Utley & Shorrock (2008). Therefore, in the case of heating demand profile modelling, it seems that statistical models that use a survey approach are not the most adequate, at least in the UK.

Similar attempts have been done in other countries such as Sweden, Japan or Korea. In Sweden, Olofsson et al. (1998) built a neural network model capable to search for patterns and correlations within the monitored heating data of 8 houses over two years, and then estimate the annual demand for space and water heating. In Japan, Yu et al. (2010) developed an overall energy demand predictive model based on a decision tree method as well as on the data collected from 55 dwellings, which is capable of predict demand at an accuracy level of 93% according to the authors. In Korea, Chung & Park (2010) studied mixes of 12 different types of buildings by collecting measured data from the country's major cities, and then developed a systematic tool with Microsoft Access that was capable of calculating and generating the electricity, heating, cooling and domestic hot water load profiles of groups of buildings. However, none of the tools or applications of these papers are available neither they give any details about how the generated profiles looked like.

An alternative approach to statistical models is the end-use approach. Looking only at lighting demand, Stokes et al. (2004) developed a model based on half-hourly data measured for a sample of 100 British homes for the period March 1996 to April 1997. The analysis of the data concluded that the annual trends have a clear relationship with the solar cycle caused by the variations in the sunrise and sunset times and the weather annual patterns. During the night, the study found that the demand is almost constant with no variations between seasons; while during the day, there are no peak levels of demand. Interestingly, a typical evening in summer was flat and low, while in winter it was flat and high. As a result of the study, a numerical formula of half-hourly demand was developed dividing the 24 hours of one day into 4 different steps: night (23:00-6:00), sunrise (6:00-8:00), day (08:00-17:00) and sunset (17:00-23:00).

Later in 2012, the *'Household Electricity Survey'* (HES) previously mentioned in section 2.2.1 was carried out across England from May 2010 to July 2011 and is the most detailed monitoring of electricity use ever done in the UK. Electricity consumption was monitored at an appliance level in 250 owner-occupied English dwellings, while also analysing appliances ownership, labels, actual efficiencies and potential for savings in different social groups. From this report, many outcomes considering the end-use have been published.

Zimmermann et al. (2012) prepared the main full report, titled *'Household Electricity Survey: A study of domestic electrical product usage'*, which was managed by Intertek and presents all the results of the survey. Ipsos selected the participating households on the basis of the life-stage of the occupants. Of the 250 dwellings surveyed, 26 were monitored for one-year period while the rest were monitored at intervals for periods of one month during the same year. Also, an Energy Performance Certificate (EPC) was done for each household and the occupants needed to complete a survey about their environmental attitudes and diaries of use for some of the appliances. Afterwards, Enertech checked, analysed and compiled all the project data into a database. The results, presented per m^2 and per person, include total household consumption and the average for various dwelling categories and inhabitant types. Moreover, three types of demand were considered: households without electric heating, with additional electric heating and with primary electric heating.

Palmer et al. (2013a) wrote the *'Early Findings: Demand Side Management'* report. As part of the *'Further analysis of the HES'*, DECC and DEFRA asked Cambridge Architectural Research (CAR), Loughborough University and Element Energy to re-analyse the HES to improve understanding of how and why electricity is used in homes. In particular, report considers the power used in peak periods and how this could be switched to periods of lower electrical demand, and it studies the base load power (i.e. when occupants are asleep) and standby power (i.e. when appliances are left on but not active). The report includes 24-hour demand profiles for the 250 households, examining peak power and demand shifting, standby power, base load power, secondary electric heating, and 24/7 appliances. Power demand is grouped into different categories – i.e. lighting, cooking, cold appliances, washing/drying, space heating, water heating, showers, audio-visual, ICT, other, and not known – and profiles are shown for specific household types. The report also assesses the potential for demand shifting of different types of appliances and analyses the summer and winter base-load demands.

Cambridge Architectural Research (2013) developed the *'24-Hour Profile Chooser Tool'*, which accompanies the previous *'Early Findings'* report. It was developed to create a simple, user-friendly tool capable to draw summary profiles of electricity use through the day for specifically selected sets of households that took part in the survey. The tool shows hourly used electricity per day, classified into eight appliance types. Data is graphically presented as a profile of electricity use for a single day, representing either the average profile over the year, or a single month, or the hottest or coldest day. For example: "What was the average 24-hour electricity consumption profile of semi-detached homes in the sample in the month of June?" (see Figure 30) or "What was the average 24-hour electricity consumption profile of homes with electric primary heating in the sample?" (Figure 31).

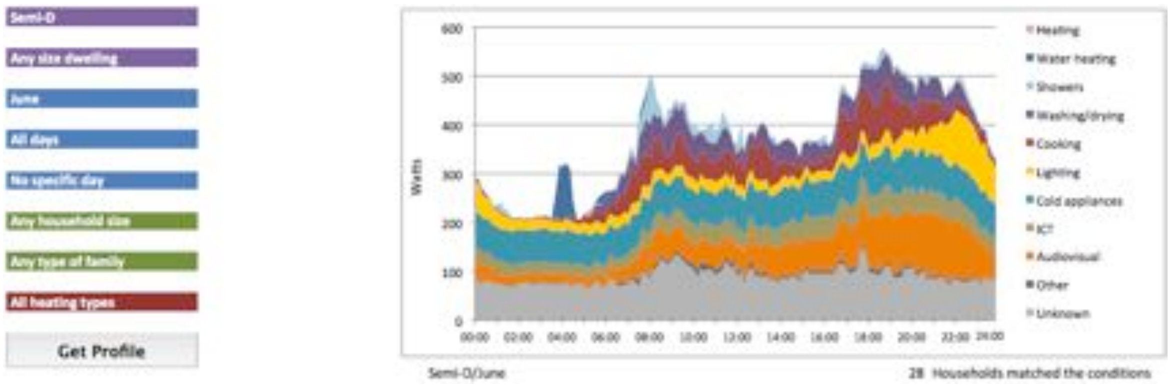


Figure 30 – Screenshot of the 24-Hour Profile Chooser tool, showing average hourly profile of semi-detached households in June. Data source: (CAR, 2013).

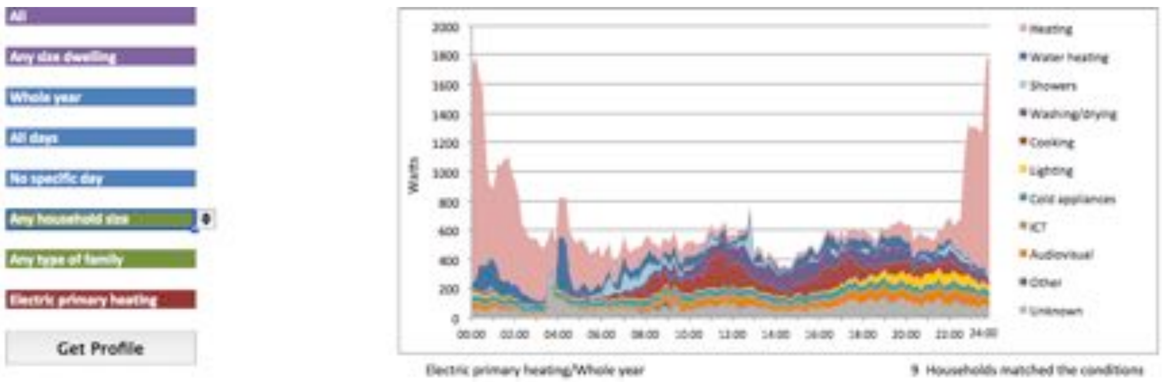


Figure 31 – Screenshot of the 24-Hour Profile Chooser tool, showing average hourly profile of households with electric primary heating. Data source: (CAR, 2013).

Palmer et al. (2013b) also prepared the *'Electrical appliances at home: tuning in to energy saving'***.** As part of the *'Further analysis of the HES'*, DECC and DEFRA asked again CAR, Loughborough University and Element Energy to analyse the ownership patterns for appliances and how these appliances are used, but on this occasion in a more detailed and complex approached. The aim of the report is to answer fourteen different topics or questions which for example include an analysis of annual purchase and replacement rates, energy ratings, the associations of use of different appliances, potential savings from small appliances and as assessment of the rebound effect.

Hughes & Garcia Moreno (2013a) wrote the report *'Consumer archetypes'*. Also, as part of the *'Further analysis of the HES'*, DECC and DEFRA asked Element Energy Ltd to perform a comprehensive analysis on the data from the survey to cluster the 250 households into a series of distinct consumer archetypes based on their attitudes to the environment, demographics, building details and electricity usage characteristics. As a result, the report presents seven archetypes: profligate potential, thrifty values, lavish lifestyle, modern living, practical considerations, off-peak users and peak-time users. The characteristics of each group are shown in Table 1.

Table 1 – Characteristics of the seven household clusters. Quantities shown in brackets reflect the average value for the cluster (Hughes & Garcia Moreno, 2013a).

		1. Profligate Potential	2.Thrifty Values	3.Lavish Lifestyles	4.Modern Living	5.Practical Considerations	6.Off-Peak Users	7.Peak-Time Users
Occupant Characteristics	Current beliefs (z-score)[2]	Very Green (0.36)	Not Green (-0.68)	Very Green (0.56)	Moderately Green (0.16)	Very Green (0.79)	Not Green (-0.35)	Moderately Green (-0.19)
	Current actions (z-score)[2]	Moderately Green (0.01)	Moderately Green (0.11)	Not Green (-1.25)	Very Green (0.65)	Moderately Green (0.00)	Very Green (0.22)	Not Green (-0.22)
	Beliefs about the future (z-score)[2]	Moderately Green (0.07)	Very Green (0.43)	Moderately Green (0.18)	Not Green (-0.41)	Very Green (0.27)	Not Green (-0.66)	Moderately Green (-0.15)
	Social grade (average NRS grade)	Low (C2)	Low (C2)	High (B)	High-Medium (B-C1)	High-Medium (B-C1)	Medium (C1)	Medium (C1)
	Household occupancy (average no. of people)	High (3.4)	Low (1.7)	High (3.3)	Low (1.2)	High (3.6)	Medium (1.9)	Medium (3.0)
Building Details	Building age (average age band)	Older (1930-1949)	Older (1930-1949)	Medium (1967-1975)	Newer (1983-1990)	Older (1930-1949)	Medium (1950-1966)	Medium (1967-1975)
	Building floor area (average m^2)	Medium (112)	Small (78)	Large (169)	Small (77)	Medium (107)	Medium (111)	Medium (97)
Electricity Usage	Electrical appliances (average no. of devices)	Many (53)	Few (27)	Many (53)	Few (31)	Medium (43)	Medium (48)	Medium (47)
	Total electricity use (kWh/year)	Very High (7839)	Low (2254)	High (5567)	Low (1868)	Medium (4084)	Medium (3491)	High (5871)
	Percentage of electricity used in the 6-7pm peak (%)	Low (5.6)	Medium (6.3)	High (6.9)	Medium (5.8)	Medium (6.2)	Low (5.5)	High (7.1)
Technical Potential	Efficiency potential (kWh/year)	Very High (1546)	Low (344)	High (719)	Low (323)	Medium (652)	Medium (516)	High (791)
	Peak shift potential (kWh/year)	Medium (31)	Low (11)	High (36)	Low (8)	Medium (24)	Low (14)	Very High (124)
	Fuel switch potential (kWh/year)	Medium (483)	Low (243)	High (530)	Very Low (62)	Low (321)	Medium (425)	Very High (1,049)

The same authors, Hughes & Garcia Moreno (2013b), prepared *'Increasing insight and UK applicability'*, again as part of the *'Further analysis of the HES'*. This time they were asked to increase the insights that could be extracted from the survey and to scale them to the UK and particular regions. The report uses a large spatially resolved demographic dataset and clusters the demographic regions into 15 groups, to calculate the potential for electricity savings and demand side response for each of the 7 archetypes established on the *'Consumer archetypes'* report.

Cambridge Architectural Research (2014a) developed the *'Lighting Tool'*, which allows the user to compare estimates of energy use generated using different energy models against actual energy use recorded in the HES survey.

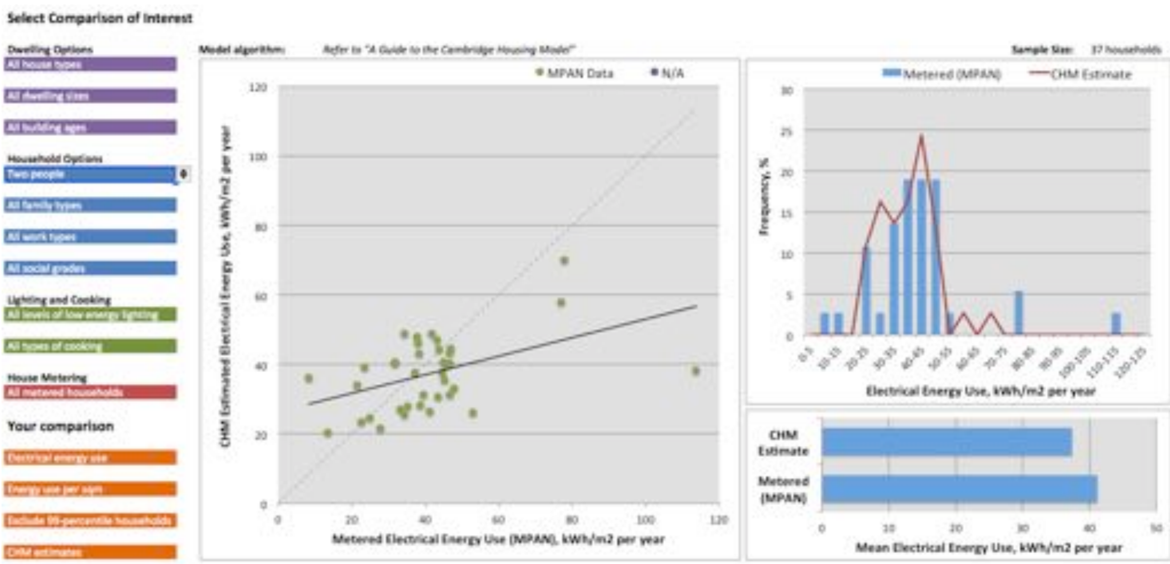


Figure 32 – Screenshot of the 24-Hour Profile Chooser tool, showing average hourly profile of households with electric primary heating. Data source: (CAR, 2013).

Cambridge Architectural Research (2014b) also developed a *'Model Tester Tool'* that compares the estimates of energy use generated using two different energy models, HES Best Fit and Cambridge Housing Model, against actual electricity use for different dwellings recorded in the HES survey. For example: "What was the average annual cooking electricity use on households with electric oven and hob?" (see Figure 32).

Finally, Palmer & Terry (2014), in *'Powering the Nation 2'*, summarised the main findings and recommendations from all the previous reports and research undertaken on the potential for energy savings and reducing peak electricity demand. The data collected on the HES survey together with the reports and tools that have been published as an outcome of the survey have been highly analysed and reviewed by the author to integrate and apply the survey data into the of the demand modelling of the EPH tool. One of the main considerations is the heating fuel type, because this has a huge impact on the electric demand load distribution (see Figure 33).

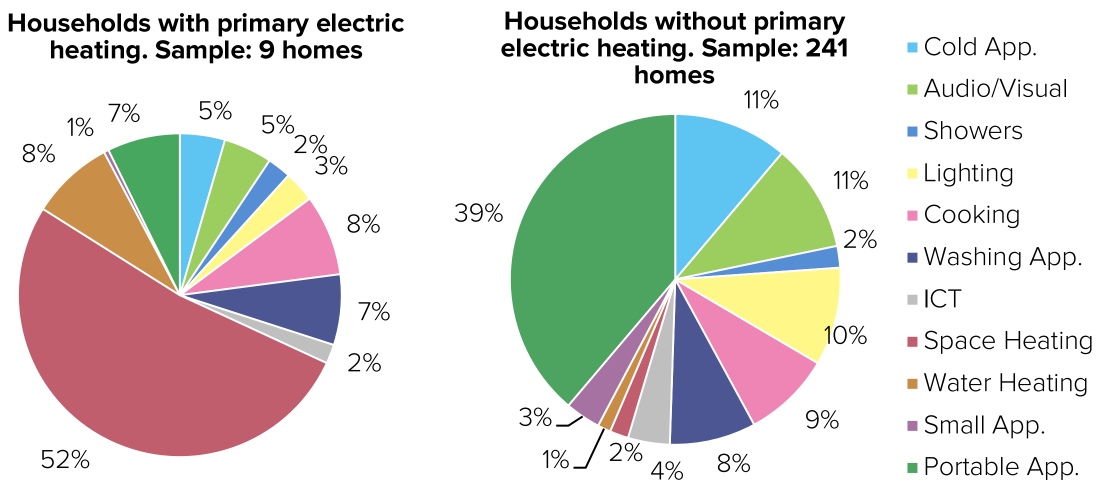


Figure 33 – Pie chart graphs showing the annual average electricity breakdown for households with primary electric heating (left) and without primary electric heating (right). Data source: (Palmer, et al., 2013b).

Outside the UK, the statistical modelling with an end-use approach is also popular. In the US, Walker (1982) developed a first attempt to introduce the effects of the occupants' behaviour by calculating statistical functions to determine the house's likely occupancy and the appliances' tendency to be used. This type of model, which could be very useful for exploring different scenarios for energy use or savings, has the limitation of relying on data that is difficult to obtain such as the behaviour of people in their homes.

In Italy, Capasso et al. (1994) proposed a model of electric residential end-use to establish the load profile of a residential area by a process of synthesis and validates the modelled predicted data against both monitored data and mail-survey data of real households' energy use.

In Finland, Paatero & Lund (2006) developed a bottom-up load model in which the hourly household load is composed by individual appliances or appliances groups. The end-user input consisted on two sets of data, the hourly measured electricity consumption from 702 apartments for one year and from 1082 apartments more during winter, all of them with no electric heating. To provide more accuracy, daily and weekly cyclical components from the monitored profiles were identified, removed and compensated for weather. To validate the model, this was then used to predict the total hourly demand profile of 10,000 households, assuming that each had an average electricity consumption and owned an average number of appliances with standard power rating.

In France, Neu et al. (2013) developed a bottom-up approach model for the specification of operational data with a detailed space-time resolution, which was then capable to generate multi-zone residential building archetype models. The study used the national Time-Use survey resident activity data as an input to the energy demand, and then ran the archetype building models through the EnergyPlus simulation software to obtain results of the load profiles of occupancy, lighting and disaggregated electrical appliances, together with their associated heat gains. Therefore, this study used a commercially available simulation model to test and create the energy profiles collected with a statistical modelling approach.

In Denmark, Marszal-Pomianowska et al. (2016) developed a bottom-up high-resolution model based on the combination of monitored and statistical data; which accounted for the effect of factors such as the number of occupants, their environmental attitude, weather conditions and even local/national events (e.g. TV shows). The validation of the model was done against two sets of data from 89 households.

2.2.2.2 Simulation models

Simulation models, which complexly simulate real energy flow and human behaviour, represent the second category of energy profile modelling tools. Building simulation is the process of using a computer to construct a virtual model of a building and its component parts, and then simulating its performance by taking the model through the weather conditions of a whole year. In a way, building simulation allows to quantitatively forecast the future, so if performed correctly it has lots of potential uses. Simulation models are usually classified into two groups: load-design and energy-analysis. There are hundreds of simulation models available, especially for energy-analysis, however for the purpose of this section's review, only the load-design models are relevant and are further reviewed.

Lewis & Alexander (1990) from the Welsh School of Architecture (WSA) developed HTB2, an advanced computational model for simulating buildings' energy to inform the design process at an early stage, when major decisions are made and their impact is greatest. The software allows simulating the thermal energy performance of buildings under varying weather and occupancy conditions; therefore, it is particularly useful when modelling heating and cooling energy load profiles. However, electric appliances, lighting and appliances load profiles need to be manually introduced as part of the input data. Therefore, the HTB2 software is good when generating heating/cooling profiles, but not for the other types of energy demand. The flexibility, ease of modification and availability of HTB2 have made it highly suited for use in the fast-evolving field of energy efficiency and sustainable design of buildings, and 91 scientific publications have used it up to date (REF, 2014). Moreover, the model has adapted to the evolution of the design and construction sectors through a continuing process of extension, testing, and modification which led to a first revised version of the software in 2007, v.2.1 (WSA, 2007) and a latest revised version in April 2017 (WSA, 2017).

Energy Systems Research Unit (2007a) part of the University of Strathclyde developed a series of tools named *'Electricity and Heating Demand profile generators'*, which is capable to generate communities demand profile, both in terms of electricity and heating loads, considering social factors such as consumer behaviour or occupancy pattern. The package consists of two Excel spreadsheets, named E.D.p. and H.D.p, which are freely available online from University of Strathclyde (2007c) and (2007c). The availability of all the data that has been used as an input for the tool as well as of the calculation methods, operations and results; makes these tools of huge interest for the purpose of this thesis, thus have been deeply analysed and reviewed to extract the most of them.

The E.D.p is based on probability models that predict the chance of each household of the community to run a certain number of appliances on a certain time of the day for different end-users according to different occupancy types. The tool's database is based on the National statistical data for electricity used in appliances in the UK's households, surveyed data from a community of 1015 households in Sterling (University of Strathclyde, 2007b) and other research in the UK (Mansouri, et al., 1996), (Baker & Yao, 2002), (Yao & Steemers, 2005) and (Huamani & Orlando, 2007). The user of the tool needs to first input either the community census when modelling a community or the household type when only modelling one household unit, and then input the estimated annual electricity consumption. From this data, the tool runs the operations as shown in Figure 34 and generates the hourly electric demand profiles.

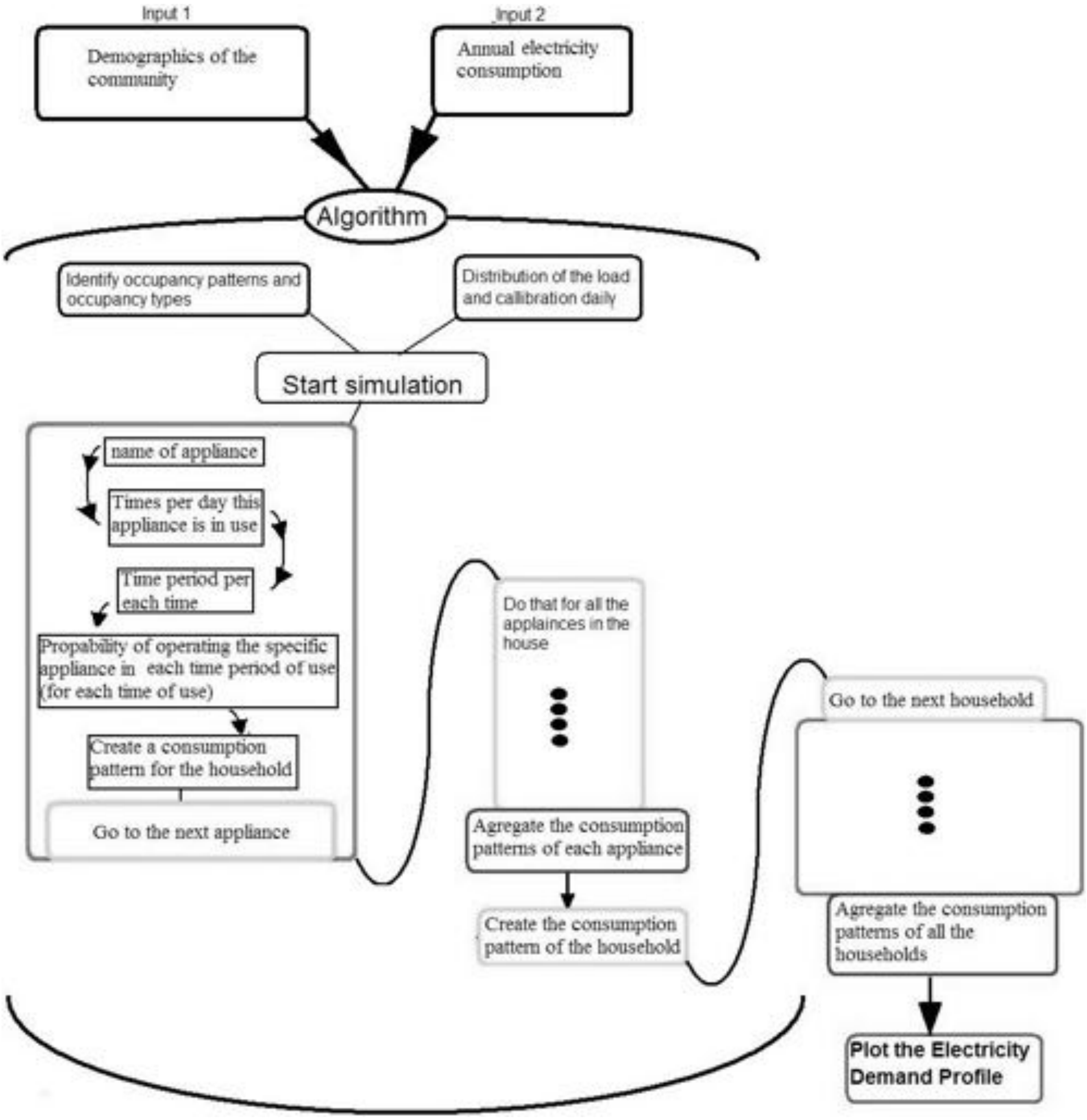


Figure 34 – Schematic showing E.D.p. tool method (University of Strathclyde, 2007c).

The H.D.p tool considers the heating load instead. The tool's database is based on the housing stock of the community of 1015 households in Sterling (University of Strathclyde, 2007b) and the Scottish building construction data. Combining both parameters, the household type and the construction type, 480 archetypes were built and modelled with the ESP-r software, which as a result generated a database for this building stock with details about the daily heating energy load profile of each type of house. Finally, once the entire database was gathered, the authors developed an algorithm that allowed presenting this huge amount of data with a user-friendly interface. Similar to the previous tool, the user of the H.D.p. tool simply needs to insert the community census when modelling a community or the household type when only modelling one household unit, and then input the more details about the construction typology. From this data, the tool runs the operations as shown in Figure 35 and generates the hourly heating demand profiles.

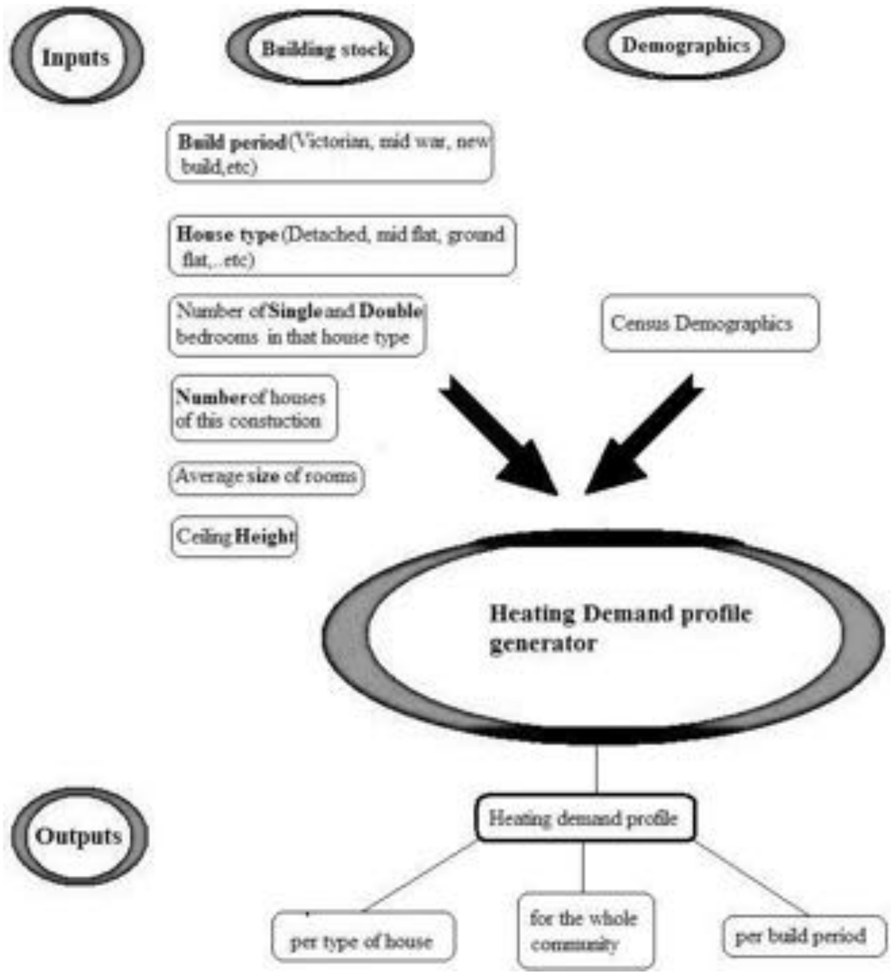


Figure 35 – Schematic showing H.D.p. tool method (University of Strathclyde, 2007c).

After reviewing both tools in depth, it can be concluded that the methodology used to develop them is of more use than the tools themselves, which have based their databases in data that now is a bit out-of-date, the case of E.D.p., and that depends on location, H.D.p.

Outside the UK in France, Neu et al. (2013) developed a bottom-up approach model for the specification of operational data with a detailed space-time resolution, which was then capable to generate multi-zone residential building archetype models. The study used the national Time-Use survey resident activity data as an input to the energy demand, and then ran the archetype building models through the EnergyPlus simulation software to obtain results of the load profiles of occupancy, lighting and disaggregated electrical appliances, together with their associated heat gains.

During the last decade, simulation models have become increasingly popular and, in many occasions, have become worldwide available via software commercialisation. For example, the BEST Directory from the US Department of Energy currently lists a total of 125 software and among those, 27 are specialised on Load-Calculation. After reviewing this wide list, the author has done a first selection process considering factors such as flexibility, availability and popularity to select the most relevant software for the purpose of this thesis and its focus on residential energy use. As a result, 9 building modelling and simulation software were finally selected and were later analysed, tested and evaluated in detail. Table 2 shows the summary of this evaluation and the main parameters that have been compared.

Choosing a building energy modelling program depends on its application, number of times it is used, experience of the user and hardware available to run it. The first criterion is the ability of the program to deal with the application. For example, if the influence of battery storage into the building self-sufficiency is to be analysed on a building that also has PV panels and a small wind turbine, the ability to analyse each detached component is an absolute requirement, regardless of any other factors. Therefore, to simulate a building model, the most appropriate software is required. As said, there are hundreds of options and it is very difficult if not impossible to choose which software is best because each of them has its pros and cons. For example, some software may have very good functionality but poor interface, while others have excellent interfaces and restricted functionality. Therefore, the selection really depends on the final purpose. Despite the variety, it seems that all software tends to require from similar inputs:

- Building location: weather data, altitude and orientation;
- Building geometry: floor area, dimensions, shape, etc.;
- Building materials: walls, windows, u-values, g-values, shading coefficients, etc.;
- Building operation: schedules and use;
- Internal load values: lighting, appliances, occupancy numbers and activity level;
- Zoning requirements;
- System types: wet or air-systems, natural or mechanical ventilation, etc.

But all these input requirements are a major question and it seems that too much data is required to generate the load profiles. For example, “Why should users be inputting data related to internal loads for lighting and appliances if this is part of what they are aiming for?”.

Table 2 – Comparison of 9 modelling tools for energy demand load simulation.

	Design Builder	Energy Plus (E+)	Autodesk Green Building Studio	IES Virtual Environment
General Description	Whole building energy use analysis simulation tool. It is the oldest, easiest and most powerful graphical user interface to E+	It is DOE's whole-building energy simulation engine. It includes advanced simulation features	It is Autodesk's core whole building energy simulation engine. Aims to optimise energy efficiency and carbon neutrality	Powerful, in-depth suite that allows the design and operation of comfortable buildings that consume less energy
Expertise & Background Required	Basic to advance on: - Building physics - Mechanical engineering	Basic to advance on: - Building physics - Mechanical engineering	Basic to advance on: - Autodesk Revit for 3D-CAD/BIM model geometry creation - Energy analysis	Training required, and also advance on: - Building physics - Mechanical engineering
Audience	- Architects - Engineers - Building designers - Teaching - Students	- Engineers - Building designers - Building auditors - Energy-efficiency programme admin. - Portfolio managers - Policy analysts - Researchers	- Architects - Engineers - Construct. Managers - Energy simulation consultants	- Architects - Engineers - Sustainability and energy consultants - Building owners - Facilities managers - Contractors
Input	- Building description - Database: materials, occupancy, internal gains, weather, air movement, systems - Weather - Systems to be included - Internal gains - Occupant behaviour	- Building description - Weather - Format: ASCII text files - Visualisation tool: IDF-Editor - Optional: graphical user interfaces	- Imported 3D-CAD or BIM geometry model and materials info. - Minimum inputs - Default values based on ASHRAE and CBECS data - Optional: historical weather data and utility billing data	- Imported 3D-CAD or BIM geometry model - Graphic interface - Database: materials, occupancy, internal gains, weather, air movement, systems
Output	All packages: - Sensitivity analysis - High quality technical and rendered results - Energy consumption - Carbon emissions - Thermal comfort - Daylight availability Architectural package: - Solar shading - Renewable techno. - Test façade options Engineers package: - Mechanical systems	Summary and detailed reports: - Visual comfort: glare and illuminance - Condensation and thermal comfort: Surface temp. - Sub hourly time step - Format: unstructured text, CSV, HTML, and SQLite. - Visualization tool: EP-Compare.	Customisable charts: - Heat/cool loads - Energy-end use - Energy cost - Dry Bulb Temperature - Wind Data Graphic reports: - Parametric Studies - CO_2 footprint - Renewable energy potential (PV & wind) - Weather data sum. - Natural ventilation strategies - Export files: gbXML, DOE-2.2 and IDF	Graphic results: - Tabular, video, colour 3D geometry, realistic images - Reports fully detailed to meet LEED, BREEAM or Building Regulations - Statistical output: energy, day-lighting and solar shading
Strengths	- Easy to use - Linked with BIM - Easily compare design alternatives - Design optimisation at any stage - Simplifies E+ thermal simulation	- Detailed building physics algorithms - Broad range of building and mechanical system - Broad range of HVAC and lighting control strategies	- Early design process - Hourly results - Flexibility - Optimise systems - Speed - Flexible cloud based service	- Comprehensive - Results are linked between systems - What-if assessments - Integrated data model - Immediate result updates
Country	US	US	US	UK
Last update	February 2015	September 2015	August 2015	June 2015
Pricing	50% disc. academia Full Package: £3,500	Open source	Free trial for 30 days Free for academic	Free trial for 30 days Full Package: £18,000

Ener-Win	HTB2	ESP-r	TAS	HOT2000
Energy design tool for residential or large and small commercial buildings. Performs whole-building energy analysis for 8760 hours/year	Simulation of thermal energy performance, particularly useful when modelling heating and cooling energy load profiles.	Integrated modelling of building energy performance to support researchers undertaking detailed studies.	Industry-leading building simulation tool, that performs fast dynamic thermal simulation to large and complex buildings	Detailed energy analysis for homes and low-rise residential buildings
Basic to advanced: - Building design - Building physics - Energy concepts - HVAC zoning	Training required, and also advance on: - Building physics - Energy concepts	Training required, advanced on: - Building physics	Basic to advanced: - Engineering - Architecture	Basic on: - Construction - Operation of residential buildings
- Architects - Engineers - Energy analysts - Building inspectors - Students	- Researchers - Education - Designers	- Engineers - Building designers - Researchers - Education	- Architects - Engineers - Building services	- Builders - Design evaluators - Engineers - Architects - Code and Policy makers
- Select 1 of 3 ASHRAE Energy Perf. Standards - Sketch of building plans - Building envelope thermal prop. - Hourly use profiles - Hourly indoor temp. control	- Format: .txt files - Building description - Systems to be included - Internal gains - Lighting and appliances loads - Occupant behaviour - Weather data	- Location of plants & control systems - Internal furnishings thermal mass - Systems to be included - Internal gains - Occupant behaviour - Weather data	- Imported 3D-CAD geometry model - Database: materials, climate data, occupiers' schedules, plant characteristics - Graphical interface - Imported files: gbXML, INP and IDF	- Graphic User interface - Building geometry - Materials - HVAC and DHW spec. - Geographical location - Fuel costs - Economic data
- Tabular reports and graphs - Monthly loads - Annual loads - Energy, peak loads - Electric displacement by day lighting - Lifecycle costs - Annual CO2 emissions - Weather summary - Optional: Hourly loads and weather data	- Format: .csv files - Room air and radiant temperature. - Comfort parameters. - Fabric temp. - Humidity levels - Heating system use. - Ventilation rates. - Zone to zone energy flows.	Detailed studies: - Heat, air, moisture, light and electrical power flows - User specified spatial and temporal resolution	Customisable reports: - Comfort conditions - Plant sizing - Energy use - Natural ventilation - CFD microclimate variation - Export files: Excel, Word, Publisher, etc.	Reports on: - House analysis: monthly and annual - Weather file - Economic and financial conditions - Fuel costs - Comparison between 4 house files at once
- Graphic interface - Hourly weather data generator - Generous use of defaults for materials, windows, profiles, costs, lights, etc.	- Finite difference heat transport model. - Detailed analysis - Speed. - Customisable - Hourly data	- Detailed analysis - Flexibility - Research outputs - Validated on large scale projects	- Concept development - Responsive - Accurate - Speed - Robust - Customisable	- Speed - Thermal bridging - Air infiltration - Heat loss - Model 5 fuel types - Models HVAC, MVHR and HP - Hourly data
US	UK	UK	UK	Canada
March 2015	January 2017	January 2016	July 2015	August 2011
Free trial for 30 days	Free for non-comm. & academic	Open source	No information available	Free for non-comm. & academic

2.2.3 BEHAVIOUR INFLUENCE ON DOMESTIC DEMAND

Occupants of residential buildings can have a substantial influence on the real building energy demand, especially on the heating load, caused by their operation of the building and its systems (Haas, et al., 1998), (Guerra-Santin & Itard, 2010) and (Morley & Hazas, 2011). Research from the last decade has allowed for a better understanding of the effects of space heating controls (Wei, et al., 2014), windows operation (Fabi, et al., 2012) or natural ventilation (Roetzel, et al., 2010). Also, building performance simulation models used to simulate before and after scenarios to predict the impact of behavioural changes have been widely used as a helpful method to enhance buildings' energy efficiency. For example, Shorrock & Dunster (1997) used BREHOMES to predict the energy savings due to the retrofit of the building construction and systems; Love (2012) focused on heating operation and building efficiency; De Wilde et al. (2013) explored the impact of doors retrofit and curtains operation; Kim & Altan (2013) studied the impact of heating operation, heating system and external insulation retrofit; and Jones et al. (2013) presented different potential retrofit strategies for the UK's housing stock.

Previously mentioned in section 2.2.2.1, Palmer et al. in the reports titled *'Electrical appliances at home: tuning in to energy saving'* (2013b) and *'Powering the Nation 2'* (2014), studied the main factors influencing on the ownership of appliances and the impact on the households' energy consumption. As part of the study, they explored the impact on households' energy consumption of the following factors:

- Occupants' environmental concern: When focusing on the environmental concern, the analysis showed small difference on the ownership of efficient appliances between very concerned and fairly concerned households. The only exception was cold appliances, where all owners of A+ rated refrigerators were very concern about the environment. This was a surprising result, which could be partially due to the higher cost of more efficient appliances. So, it seems that cost and volume of the appliance, and what models were available at the time of purchase, may be more important factors.
- Standby power: The analysis suggested that standby power accounted for a range of 343 to 591 kWh/year per household. According to the report the electricity bill of an average house is about £530, which means that standby power demand could account for 9 to 16% of a household's electricity bill. This is higher than the 5 to 10% that previous research on the field suggests (McCarthy, 2011). This figure includes devices such as computer routers that may be left on all the time but do not have a

true standby mode because they are always active. Modems and routers were recorded with much higher continuous power use than the true standby for other computer equipment – around double the next-highest device. Continuous use means there may be opportunities for using timers on modems and routers.

- Appliances left on when not in use: Nearly 80 of the 250 households in the survey left some lights on overnight, and this lighting used an average of 11.8 W, equivalent to 23-37 kWh per year for each household. If 1 million households could be persuaded to turn off all lights overnight, this would save from 9 to 14.5 MW, or 23-37 GWh over the year. At least 18 households left appliances on in empty rooms for more than one hour/day. These households appear to be wasting from 62 to 250 kWh/year each, and TVs and computers are the most common appliances left on when not in use. Looking across all homes, it is estimated that switching off unused appliances would achieve typical savings in the range from 10 to 44 kWh/year per home.

2.2.4 LESSONS LEARNED

As energy-related problems require the delivery of increasing reductions in the energy demand from buildings, a far greater emphasis on empirical evidence is needed to develop robust energy demand models. Overall a more integrated and scientific approach should be adopted, much as is standard practice in the health sciences. It is needed a clearer awareness of the uncertainty in the results at the individual building and a better understanding of the extent and conditions where energy models are wrong, so it can be determined how useful they can be for improving energy performance (Summerfield, et al., 2011).

Even though the advantages of using energy modelling simulation are widely accepted in literature, it is also clear that there are difficulties in incorporating modelling in traditional design methods. This review has helped to identify the main gaps and limitations of the energy modelling tools existing on the market, which are:

- Complexity to use with no-user friendly interface.
- High expertise required on the field of energy simulation and modelling.
- Require in-depth technical specifications of the building design that are not yet decided at early-stages of the design process.
- Require specifications of the energy systems that are unknown by architects.
- Results are often too difficult to read and interpret by building designers.

As a result, the author identifies the need of an alternative energy modelling tool specifically developed to simulate, optimise and model the performance of EPH designs. The proposed EPH tool should be:

- Simple to use with a user-friendly interface, suitable for all the members of a design team at the early design stage.
- Capable to run dynamic simulation of a house's energy system without a high level of expertise required on the field of energy simulation and modelling.
- Require a limited amount of technical specifications of the building design that could be easily decided at early-stages of the design process.
- Require a limited amount of specifications of the energy systems that are unknown by architects.
- Results generated automatically, with high level of detail and easy to read and interpret by building designers.

Therefore, it seems that the two main reasons for developing a new EPH energy simulation tool are necessity and practicality. For the proposed EPH design, a model that can work with only limited information available is necessary. It is also a practical approach because occupant's behaviour, location and weather variations can have a large impact on a household's energy demand. These big variations can completely dismiss the relatively minor variations caused by using more detailed system's specifications. Therefore, because the purpose of this research is to measure the EPH design's energy performance relative to broad objectives, a simple and easy to use model is more appropriate.

2.3 Technologies for low carbon performance

This thesis proposes the implementation of existing and emerging low carbon technologies into the EPH design through a systems-based approach by integrating energy demand, supply and storage. This section reviews existing and emerging low carbon technologies and the policy incentives to implement them by focusing on technologies for energy demand reduction, renewable energy supply and energy storage.

2.3.1 TECHNOLOGIES TO REDUCE ENERGY DEMAND

As explained in section 2.1.1, domestic energy demand is used for heating, lighting and appliances. Therefore, in this section technologies are reviewed following the same classification.

2.3.1.1 Space heating

The way heat is used is very different from the way electricity is used. While heat is not bought and sold as a product in the UK, electricity is delivered in its final form ready to use. It is not common for households to buy warmed air, hot water or steam directly. Instead, householders buy fuels (predominantly gas, oil or solid fuels) or electricity and convert them on-site into heat with boilers, gas heaters or electric heaters for example (DECC, Mar 2012). While in the majority of the UK's homes, heating space and water means burning gas in a boiler, the change to low carbon is already beginning. Low carbon heating technologies are cleaner and often more efficient alternatives that will prepare our homes for a future sustainable and secure heat supply. For example, many new homes are now fitted with a heat pump, able to operate three to four times more efficiently than a gas boiler while providing both heat and cool depending on the season (Energy Saving Trust, 2016; Energy Saving Trust, 2008).

The UK needs to start building the market for low carbon and renewable heat, both to achieve the goal of supplying 15% of the UK's energy from renewables by 2020 (DECC, 2010) and to deliver affordable, efficient low carbon heat in the future. And that is what the proposed EPH aims to encourage. In 2010, the UK's heat pump market alone was worth almost £50m, and the solar thermal market grew 24% to £25m (DECC, Mar 2012). If the UK could lead this way to a low carbon heating future, that would be an opportunity to lead this growing market by attracting investment, bringing down costs and building up supply chains.

By 2050, the UK needs to remove all direct CO_2 emissions from space heating (DECC, 2010). This is extremely challenging and means that any heat produced at building scale must be generated with low carbon technologies. To meet this tough target, DECC introduced the Renewable Heat Incentive (RHI), the first scheme in the world to promote the use of renewable heat (Ofgem, 2014). The original idea was that owners, domestic or non-domestic, of newly fitted systems would be paid a rate for each kilowatt-hour of heat produced from renewables (Connor, et al., 2015). But in 2010 with a new UK Government, the scheme was reviewed to exclude domestic owners from getting the output-related subvention, but instead to be paid a fixed one-off payment, the Renewable Heat Incentive Premium Payment (RHPP). Another change was implemented in 2014 when the RHPP payment was replaced for the Domestic RHI that provides financial support to the owner of the renewable heating system for seven years (Energy Saving Trust, 2016).

Low carbon heating technologies can be categorised by the energy source that they use to generate heat, giving three technology groups:

- Solar: Heating systems that capture heat from the sun to provide space and water heating. Greening & Azapagic (2014) revised this type of system for the UK context concluding that they can provide a substantial share of a building's heat demand, especially in milder months and in highly insulated houses; but in most cases, these systems may need to work together with a supplementary space heating system to guarantee winter heat demand. Combined with inter-seasonal heat storage, solar systems can be particularly effective in reducing heating peaks in winter months.
- Biomass: Boilers that burn biomass fuels, such as wood pellets or bio-methane, can be a practical and more localised solution to supply heat to individual or clusters of buildings, especially in more rural areas (Hendricks, et al., 2016). This solution is already supported by Government policy (DECC, Nov 2013), but this approach is unlikely to supply a major proportion of the UK's heat by 2050; since biomass supply could be constrained and contested, with feedstock likely used as transport fuels and industrial heat, where higher energy densities are required (Proskurina, et al., 2016).
- Electricity: Electricity, that will become low carbon as it is decarbonised, can generate heat, either with resistive heating or heat pumps. Electric heating technologies hold particular potential, especially as electricity is universally available and technologies are relatively recognised. Furthermore, the high efficiency of heat pumps, combined with improved building fabric and renewable technologies, could offset the relatively high costs of electricity. This could make electrical heating an affordable option, especially if the cost of heat pump manufacturing and installation comes down as volumes increase.

The low carbon heating technologies eligible for the Domestic RHI subventions are solar thermal panels, biomass boilers, and air or ground to water heat pumps (Ofgem, 2016). Many other technologies such as air-to-air heat pumps (AAHP), exhaust air heat pumps (EAHP), biomass stoves or hybrid PVT were not initially supported by RHI (Energy Saving Trust, 2016). For example, according to chapter 4 of the government's RHI announcement, EAHP were excluded because they "use air extracted from inside the building, for example from kitchens or computer server rooms, as their air source. They are particularly useful in very well insulated buildings that require mechanical ventilation. However, they are not classified as renewable under the RED as they do not rely solely on outside air and therefore will not be eligible for the RHI" (DECC, Mar 2011). However, some of these exclusions are now being revised, especially because the UK only achieved a 2.3% of heat demand from renewable energy sources in 2014 (DECC, Oct 2014), very far from the 20% target by 2020 (DECC, 2010). This is the case of reversible air to air heat pumps (RAAHP), which were reviewed in a report prepared by DECC in 2014, but is not the case of heating only AAHP, due to the risk of incentivising the installation of separate heating and cooling AAHP (DECC, Oct 2014).

To produce heat, thermal panels use solar energy and biomass boilers use pellets or wood, hence they do not have any negative impact on the energy networks. Instead, domestic heat pumps use electricity to generate heat and the potential effects of a substantial increase in the number of these systems are worth of consideration, both for their effects on the electricity supply and for their contribution to carbon emission reduction. Many research publications have appeared on this field not only considering the UK scenario (Gupta & Irving, 2014), (Kreuder & Spataru, 2015) and (Eyre & Baruah, 2015), but also in other countries where popularity of heat pumps dates from earlier times and has also increased; for example Canada (Tamasauskas, et al., 2015), Denmark (Nyborg & Røpke, 2015), Norway (Kipping & Trømborg, 2015) and (Dar, et al., 2014), or Belgium (Patteeuw, et al., 2016).

2.3.1.2 Ventilation

To reduce space heating demand, low carbon efficient buildings are built with highly insulated building fabric and increased air tightness, as part of a fabric first approach. As a result, continuous mechanical extract ventilation is needed in order to satisfy minimum ventilation rates and guarantee good health conditions for the occupiers (Howieson, et al., 2003). However, research has shown that mechanical ventilation can cause numerous issues such as noise (Siddall, 2014), misunderstanding – e.g. users stopping the system – (Brown & Gorgolewski, 2015), perceived freshness – e.g. users opening windows – (Macintosh & Steemers, 2005), or poor maintenance. These issues threaten building's actual performance, the expected energy savings and the users' health; hence, the gap between design intention and actual performance should be minimised (Baborska-Narozny & Stevenson, 2015).

There are different low carbon solutions for mechanical ventilation systems. For example:

- Mechanical Ventilation with Heat Recovery (MVHR): The most common strategy, widely used for a long time in residential projects located in more severe climates such as Canada and Scandinavia (Alonso, et al., 2015) and becoming more popular in the UK (Macintosh & Steemers, 2005). This system tends to comprise of concealed ducting in ceiling voids leading to the heat exchanger unit in the loft or another void in the house. MVHR units normally have air filters to prevent pollen and pollutants entering the building, run continually at about 80% efficiency and are inaudible during normal use.
- Passive Ventilation with Heat Recovery: A review of heat recovery technologies for passive ventilation applications from O'Connor, et al. (2016) attempts to determine the major factors preventing the integration of heat recovery technology into passive ventilation systems. From all the heat recovery devices reviewed, only two have been released to the market to date. On one hand, the Cool-Phase system provides intelligent control of ventilation through night cooling, uses phase change materials (PCM) to store and release thermal energy and therefore provides free cooling at low running and maintenance cost (Monodraught, 2018). On the other hand, the Ventive system uses passive stack effect and wind to silently drive fresh air into the building which is then heated with a dual-flow heat exchanger.
- Supply-air windows: The principle is based on the air renewal circulation between the glazing of a windows before entering the building. The air warms up by recovering some part of the heat loss from the building and also by solar radiation absorbed through the glazing (Gloriant, et al., 2015). However, this technology is only used to supply air, hence it needs to be associated with an air extraction system.

2.3.1.3 Water Heating

Water heating demand from showers, baths and sinks is around 3,600 kWh per year per household and represents over 20% of all heat demand from buildings (DECC, Jul 2015). There is a wide variety of software tools to model hot water consumption (Marini, et al., 2015), but there is a small scope to reduce its consumption because hot water demand is largely unaffected by improvements to the building fabric, and is fairly consistent throughout the age of buildings, and between seasons (Energy Saving Trust, 2008).

There are mainly two ways of improvement. These are behavioural change approaches that could reduce hot water demand – e.g. quicker shower times or fewer baths – (Palmer, et al., Nov 2012) or implementation of demand reduction low carbon technologies. There are few low carbon water heating technologies available, the most relevant ones are:

- Wastewater heat recovery systems: This extracts the heat from the water that showers and baths send down the drain and re-uses this heat to warm the incoming mains water. However, the installation of this technology costs around £1,000 and it saves around £20 per year, which means an unattractive payback time of around 40 years typically (The Green Age, 2016).
- Low-flow showerhead: This technology can save an average of 28 litres of hot water, resulting an energy saving of 1.1kWh per shower, or around 800kWh per year taking two showers per day (Palmer, et al., Nov 2012). The implementation of this technology is very easy and costs around £50, which means a payback time of less than one year.
- Hot water recirculation pump: For water-based systems, this technology adds pressure to the system to ensure that hot water is available as quickly as the user demands it, thus reduces water wastage and increases comfort. This system costs around £200 to install, £5 to £30 to operate, has a heat waste through the additional pipe of around £200 and saves around £4 to £50 per year (Paster, 2011). This gives a negative return on investment; thus, it is not recommended from and environmental perspective.

Once demand reduction has been achieved, the next step is to supply hot water from low carbon technologies, in particular solar, biomass or electric systems. These systems are used for both space and water heating and were described in previous section 2.3.1.1.

2.3.1.4 Lighting

Lighting is found in every room of the house, with an average of around 34 lights per household (Energy Saving Trust, 2012). The ban on the sale of incandescent light bulbs in 2012 following EU directive (Smith, 2010) combined with the reduction in cost and subsidised promotion of energy efficient light bulbs such as compact fluorescent bulbs (CFLs) and LED lighting, has led to a reduction on the domestic energy demand from lighting. Figure 36 shows how CFL and LED lighting are the most efficient lighting technologies when comparing their percentage share of the total installed bulbs against their wattage consumption (Energy Saving Trust, 2012).

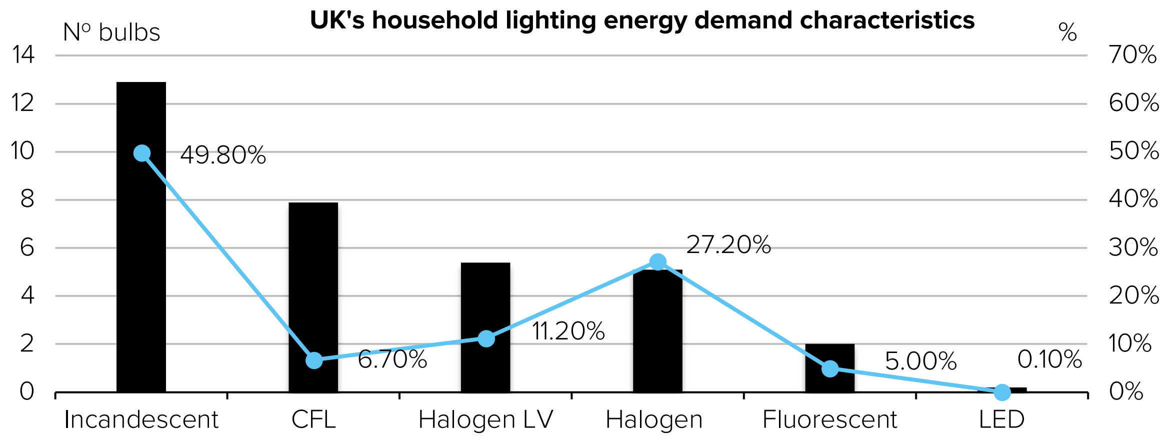


Figure 36 – Graph showing the average number of light sources (bar chart) and the lighting demand percentage per type of light bulb technology (linear graph) per household in the UK. Data source: (Energy Saving Trust, 2012).

Another approach to reduce lighting demand is the implementation of control mechanisms. For example, mechanisms to detect people's presence such as PIR and microwave sensors, to detect ambient daylight such as photocell sensors, or to time lighting according to occupancy patterns.

2.3.1.5 Appliances

Palmer & Terry (2014) prepared an extensive analysis about home appliances which lead to many publications and studies. Among them, '*Electrical appliances at home: tuning in to energy saving'* (Palmer, et al., 2013b) is the most comprehensive report analysing in detail all the types of appliances and the energy consumption for each technology type. The most relevant finding regarding energy efficient appliances is that "modern advances in technology, coupled with the success of the EU energy label, have seen this power demand per unit drop in recent decades".

Regarding cooking appliances, the majority of buildings in the UK use some gas for cooking, whether in a gas oven or using gas-fired hobs (Palmer & Terry, 2014). But in a low carbon built environment scenario, as the housing sector moves to electric heating, the small quantities of gas needed for cooking may not be sufficient to cost-effectively maintain the local distribution gas grid, and more electric cooking appliances will be required. Among the available electric cooking technologies in the market, induction hobs are the most energy efficient (90% efficiency) using less than half the energy of standard coil elements (55% efficiency) (Cernela, et al., 2014) because they transfer electromagnetic energy directly to the pan, leaving the cook-top itself relatively cool. The same happens with cooking units with ceramic-glass surfaces, which use halogen elements as the heat source, making them the next best choice from an efficiency perspective.

2.3.2 TECHOLOGIES TO SUPPLY RENEWABLE ENERGY

Previous section considered the technologies to reduce energy demand, which should always be the first step when designing green buildings with low energy consumption and CO_2 emissions. For example, maximizing energy efficiency of new buildings, improving energy efficiency in existing buildings, using energy efficient appliances and lighting or making behavioural changes in the use of a building.

The second step is then to implement renewable energy technologies capable to collect the energy flows that occur naturally in the environment and that are effectively inexhaustible and use them to generate thermal or electrical energy free of CO_2 emissions. Thomas Edison, father of electricity-intensive living, was also a green pioneer whose ideas about renewable energy still are relevant today. At the turn of the 20th century, Edison was already aware that fossil fuels wouldn't last forever, observing: "We are like tenant farmers chopping down the fence around our house for fuel when we should be using Nature's inexhaustible sources of energy – sun, wind and tide". Since these early years, scientists and inventors like Edison were modernizers who disliked the inefficiency of letting abundant energy sources, like wind or sun, go unused. Many technologies have been invented throughout time, but not all of them are appropriate for buildings in the UK. This review investigates the latest technologies available in the market, appropriate for the UK's climate and integrable for residential scale buildings.

2.3.2.1 Solar energy technologies

2.3.2.1.1 Building Integrated Photovoltaic (BIPV)

There are mainly seven types of BIPV technologies, depending on the way that they are integrated and their location within the building skin. These are mainly 7 types:

1. PV tiles for roofing systems: This technology is used for new builds and for retrofits to re-roofing slope rooftops, especially in locations where it is important to maintain the natural look and aesthetic of the home.

Figure 37 – Solar PV tiles for roofing systems: a) Metrotile system, b) Powertile system, c) Tegosolare system. d) Tesla solar roof system.

- Metrotile – Photovoltaic shingles: The PV shingles are available in multiple colours, lightweight, safe, and easy to install. The system provides a waterproof roof with no penetrations, a long-term reliability and low maintenance costs.
- Powertile – Photovoltaic 'S style' clay tiles: This technology is a BIPV solution for clay tiles roofs, preserving a sophisticated roofline for existing homes or new construction. The clay tiles are built with high performance materials, glass-free and impact-resistant, and are installed like standard clay tiles with no penetrations.
- Tegolasolare – Photovoltaic 'roman style' clay tiles: This technology integrates a small PV panel made of 4 mono-crystalline cells in the flat area of the tile. This solution allows installing PV panels on every tile or only on specific tiles, while preserving the aesthetic of the roof. The PV clay tiles are all interconnected underneath to form the equivalent of one large PV system.
- Tesla Solar roof – Photovoltaic tiles: Made with tempered glass, this PV tiles are three times stronger than standard roofing tiles. This system can only be installed in a roof pitch of at least 14 degrees and is available in four types of tiles: textured, smooth, Tuscan and slate. It allows for solar output customisation by using two types of glass tiles that look the same from street level – i.e. solar tile and non-solar tile.

2. PV cladding for roofing systems: These tend to be versatile technologies, suitable for pitched and flat roof applications on new build or refurbishment projects.

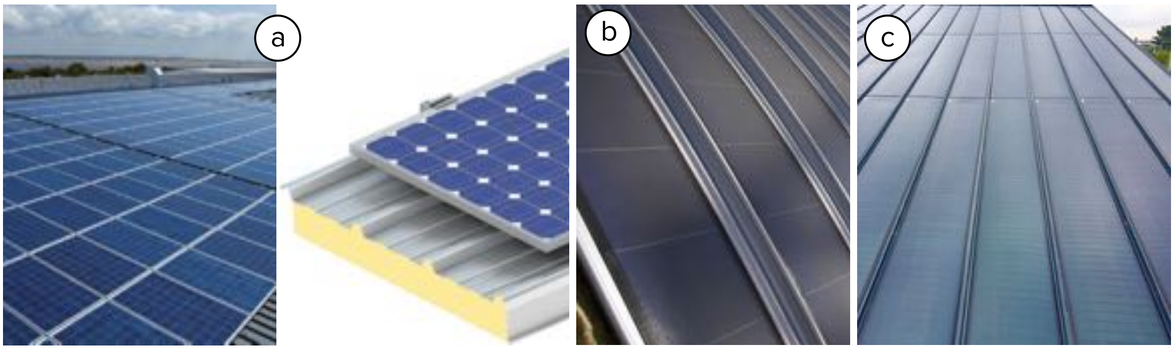


Figure 38 – PV cladding for roofing systems: a) Kingspan rooftop solar PV system, b) Kalzip Aluplus Solar system, c) BIPVco system.

- Kingspan Rooftop Solar PV system: This is a building attached PV system that allows to fix crystalline PV panels, either mono-crystalline or poly-crystalline, into the majority of Kingspan's insulated roof cladding systems.
- Kalzip Aluplus Solar: This is a BIPV system that integrates flexible ultra-light PV modules based on silicon solar cells from DAS energy, which are customisable in size, form and colour. The PV modules are glued, riveted, screwed or mounted onto the roof substructure using magnets or existing eyelets. This keeps the weight of the solar system extremely as lows as 2.5 kg/m^2.
- BIPVco: This is a BIPV system that integrates MiaSole CIGS (Cooper Indium Gallium Selenite) cell and its junction box onto a pre-coated metal roof or membrane substrate. This allows to install the BIPVco system in the same way as any conventional roofing system. Unlike silicon modules, CIGS thin film does not require that sunlight hits perpendicular to the module, performs better in low light conditions, has better shade tolerance and produces more energy in high temperature conditions.

3. In-roof integrated PV panels: These technologies can be employed as a whole roof solution or to replace an area of the proposed roof finish working with all types of covering, from slate and clay to concrete interlocking tiles.

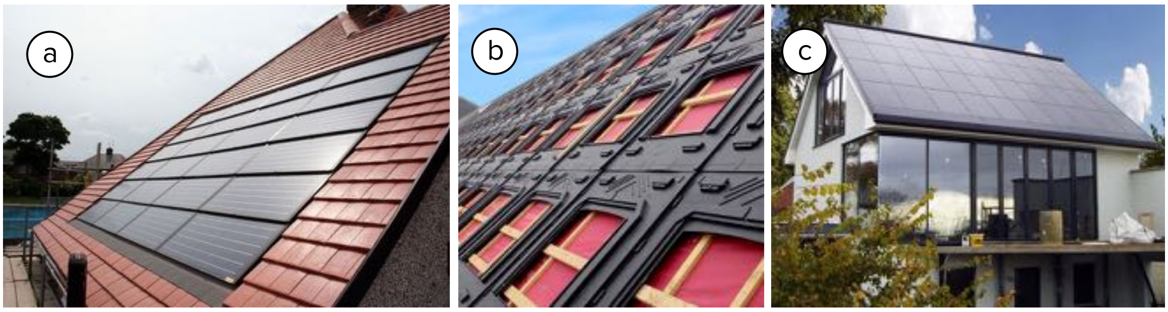


Figure 39 – In-roof integrated PV: a) Romag system, b) GSE system, c) RIS system.

- Romag roof-integrated solar: This system combines a unique solar roof tile with a simple to install fixing system, which is completely watertight, resistant to wind lift and suitable for all roof types.
- GSE integration system: This is a fixing system for framed PV panels that is simple, lightweight, watertight and inexpensive. It is compatible with almost all PV panels on the market, which can be installed in all roof types in a portrait or landscape format layout. The fixing modules can be fitted on to wooden or metal structures from 12 to 50 degrees pitch.

- RIS system: This system is from the British manufacturer GB-Sol and is a solution for mounting integrated PV panels within a roof surface and to stand all weather conditions. It is self-sufficient in sealing the roof, requires no additional membrane and can provide a flush installation to the surrounding tiles.

4. PV façade systems: These solar technologies are integrated into the building façade either as a second layer or as part of the building fabric.

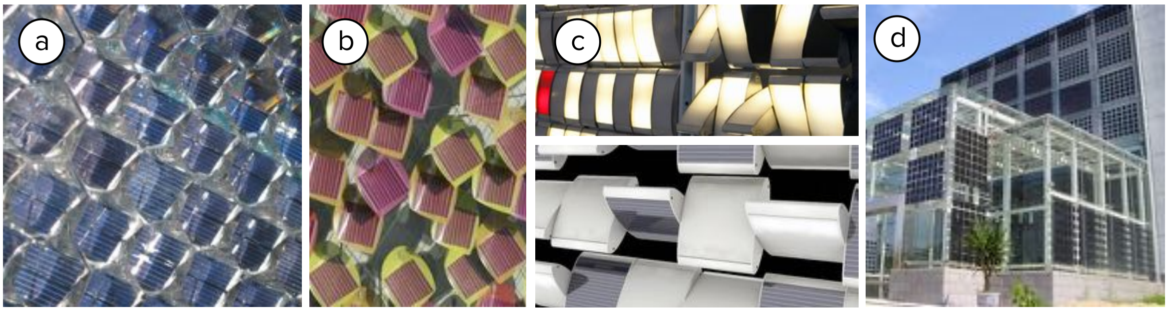


Figure 40 – PV façade systems: a) Solar Honeycomb, b) Solar Ivy, c) PV OLED Wall, d) In-wall PV panel.

- Solar Honeycomb – BeeHive PV: Solar panel that replaces the glass facades of a building providing insulation and clean energy generation. The BeeHive Panel is made up of a double-glazed glass sandwiching that looks like a honeycomb, hence the name. The honeycomb is made of acrylic, and inside each hexagonal cell there is a silicon cell. The hexagonal design concentrates the sunlight by 2.5 times onto each cell, as a result 1m^2 of this technology can generate up to 140W of electricity.
- Solar Ivy – Plant PV: Modular and customizable photovoltaic product with a wide range of applications. First a steel wire mesh is attached to the building, this can bend, curve or stretch to match any contour. The leaves' colour and shape can be customisable and positioned for varying densities depending on windows and exterior shading. This system provides renewable energy for the building using the sun and breezes while also serving as a shade screen that minimizes solar heat gains.
- PV OLED Wall – PV and OLED solar louvers: Gathered in lines, these PV&OLED tiles create a giant and bright blind that generates electricity during the day, which then is used at night to power OLED screens. During the day, a small electrical engine allows pivoting each PV tile to orientate the solar cells perpendicular to the sun, or to let natural light into the building. At night, OLED tiles can be faced towards inside the building illuminating indoor spaces or creating a giant TV screen in a house, or can be faced towards outside to become a giant screen.

- In-wall PV panels – Solar façade: This technology consists of PV modules, either monocrystalline or polycrystalline, made of double sided low iron tempered glass with solar cells laminated in between. It is ideal for roofs, skylights and facades, and is fully integrated as part of the building's façade while generating electricity.

5. PV windows systems: These solar technologies replace traditional windows glazing for solar glazing capable to generate electricity while letting the daylight going through.

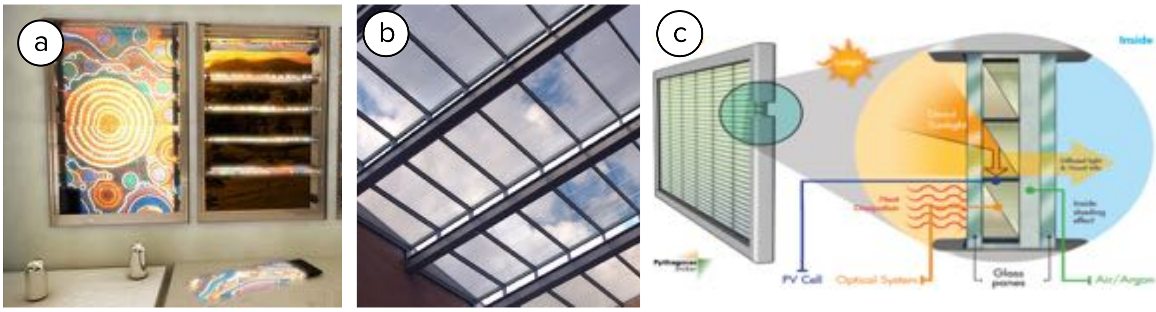


Figure 41 – PV windows systems: a) Lightwat louvers, b) PV glass, c) PVGU system.

- Lightway – Solar louver window: This is a prototype technology designed to bring the louver window back to the future. The louvers have integrated cutting-edge transparent solar cells that generate electricity during the day, which is then used for lighting at night by using OLED. The system is transparent, highly efficient and portable.
- PV Glass – Transparent coloured solar glass: From Onyx Solar, it allows the entrance of the sunlight, avoiding UV radiation and infrared radiation, and seeing through the glass at the same time. The glass is customisable in terms of colour and transparency from 10%, to 30% of transparency degree, depending on the luminosity required. This way, the PV glass can be integrated as an artistic coloured PV skylight, curtain wall, balcony or any other multifunctional constructive solution. Colourful solutions maintain the same efficiency rate as non-coloured.
- PVGU – Photovoltaic Glass Unit: This is a simple to install technology that offers many architectural design benefits. For example, it combines high density solar power generation with the energy benefits of an insulated glass unit, it improves building energy efficiency by better optimizing solar heat gains and day lighting than traditional glazing, it blocks direct sunlight from heating up the building saving on cooling costs, and it allows diffused light to illuminate the indoor space saving on lighting. The PVGU can be used to replace traditional glazing on existing windows with a U-value of 0.30 W/m^{2}K and a maximum power density of 120 W/m^2.

6. PV blind systems: These solar technologies replace traditional internal blinds for solar blinds capable to generate electricity and release it as needed at night.

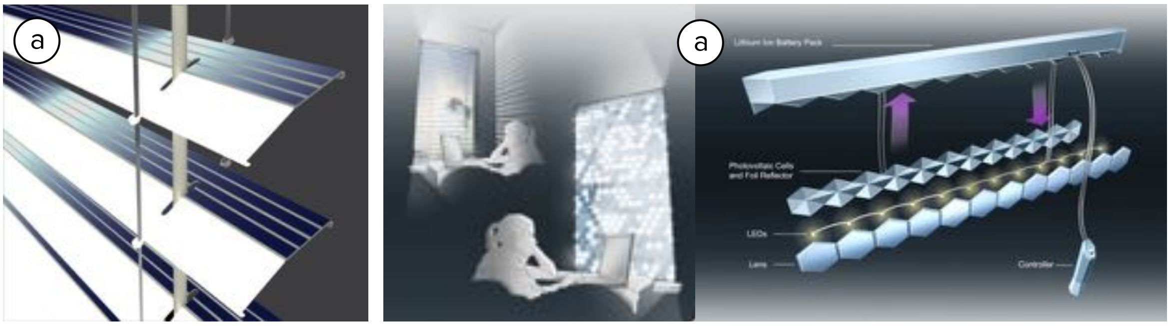


Figure 42 – PV blind systems: a) Lightwat louvers, b) PV glass, c) PVGU system.

- Blight – Venetian PV blind: This technology uses standard functions of a venetian blind with added flexible solar cells that generate electricity during the day and a battery that stores this energy so it can be used for lighting during the night. The blight is an optimal indoor efficient lighting solution that is able to replace current lamps without any need of electric supply. Also, with the revolving blades, it follows the course of the sun hence catches maximum of energy.
- Light in the dark – Louvre PV blind: This is a similar prototype of an active blind system that also collects energy from the sun by day and releases it as needed at night. These blinds aim to save energy by keeping building cool in summer and providing insulation during winter.

7. PV shading devices: These are passive and active solar technologies, which generate electricity while simultaneously shading the house from the sun.

Figure 43 – PV shading devices: a) Shadovoltaic system, b) Movable PV shutters.

- Shadovoltaic – PV glass louvers: Shadovoltaic is a fixed or controllable (following the sun's path) external glazed solar shading system that can be installed either vertically or horizontally in front of the façade. Mono-crystalline or poly-crystalline PV cells are integrated into the glass of the shading louvers, either by attaching them to the reverse side of the glass panels or by laminating them between two sheets of glass.

- Movable PV shutters – PV louvers: This technology combines both high-tech active solar and low-tech passive solar components into smart operable building envelope. It is made of wooden shutters covered with PV solar cells that generate electricity while they simultaneously shade the house from the sun.

As it can be seen, many BIPV technologies are present in the market and in the forefront of research due to the increasing concerns related to environment, energy independence and fossil fuels dependence. There are several research publications on the field. For example, comprehensive reviews of BIPV applications by Biyik et al. (2017) and Baljit et al. (2016) in terms of energy generation, nominal power, efficiency and performance assessment; several case studies of BIPV projects applied in office buildings (El Gindi, et al., 2017), retrofits (Samir & Ali, 2017) and facades (Piratheepan & Anderson, 2017); and technical, economic or performance assessments of different BIPV technologies by Sharples & Radhi (2013) Martellotta et al. (2017), Gautam & Andresen (2017), Akata et al. (2017) and Luo & He (2017).

2.3.2.1.2 Building Integrated Solar Thermal (BIST)

Solar thermal systems are mainly used for the production of low-temperature heat for sanitary hot water and space heating support. The typical BIST system normally comprises a group of BIST collectors that receive the solar irradiation and convert it into thermal energy, in which the heat is transferred to the air, liquid, or both. There are mainly three types of BIST technologies, depending on the medium of heat transfer. These are based on air, water or refrigerant, and are described as follows:

1. Air-based BIST collectors: These technologies use air as the working fluid for absorbing and transferring solar energy. The collected solar heat is usually used to pre-heat the intake air for the purpose of building ventilation and space heating. The main advantages of air-based collectors are: anti-freezing and anti-boiling operation, non-corrosive medium, low cost, simple structure, reliable and cost-effective solution even at low irradiation level. But air has relatively low thermal mass and heat capacity, resulting in lower efficiency, higher mass flows and bigger ducting and equipment compared to hydraulic-based systems.

   There are many types of air-based BIST collectors, but they are all built by incorporating an air gap between the back surface of the solar collector and the building fabric. The most popular technologies are:

- Transpired solar collectors (TSC): TSCs were invented in the 1980's as a method of using solar radiation to preheat ventilation air for buildings (Hollick, 1994; Kutscher, 1996). Since the first commercial installation of a TSC in 1986 on a Ford assembly plant in Canada (SolarWall, 2009), more than one thousand TSCs technologies have been installed in more than 35 countries, most of them by the American company SolarWall (2017), which claims to achieve an economic payback of between 2 and 10 years from their case studies. The first TSC system in the UK was installed in 2005 on the southeast façade of a single-storey industrial building and since then around twenty TSCs, totalling an area over 12,500m^2, have been installed and are now operating around the UK (Brown, et al., 2014). Industrial and warehouse/distribution buildings are the most popular case studies and generally comprise of the largest collector areas, but there are also a few case studies at the residential scale. For example, 335m^2 of TSCs were installed on a 24-story apartment building in Canada (Hollick, 1996) and 9m^2 were installed as a low carbon retrofit solution in an existing house in the UK (Brown, et al., 2014).

  Figure 44 illustrates the simple operating principle of TSCs, which consists of steel cladding panels with thousands of evenly spaced perforations. First, the metal cladding absorbs the solar radiation, which heats the boundary layer of air on its surface. Then, a fan assists drawing the air, which passes through the perforations absorbing the heat from the edges. Once warmed air is inside the cavity, 100 to 300mm wide (Kutscher, 1994), the internal face of the steel cladding further heats it. Warmer air moves upwards in the cavity and can then be distributed directly into the building as pre-heated ventilation or ducted to into the main heating system to reduce its energy consumption. 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).

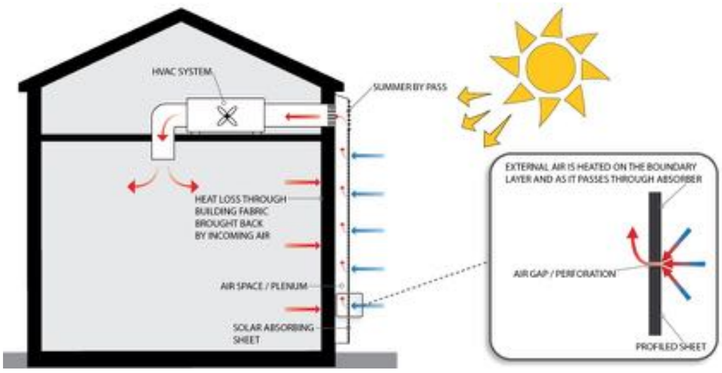


Figure 44 – Diagram illustrating the operating principles of a TSC (Brown, et al., 2014).

The main design guidelines for a TSC installation are as follows (Brown, et al., 2014):

- South facing orientation – Most of the TSC installations in the UK have an un-shaded orientation within 20 degrees of South.
- Vertical façade – In the UK TSCs are generally installed vertically on the façade and to date roof mounted systems do not exist commercially.
- Size – TSCs are usually sized to match the fresh ventilation rate of the building.
- Colour – The colour influences on the TSC ability to convert solar radiation to heat. As darker colours absorb more solar radiation, black is the best choice in terms of thermal performance. Despite this, lighter colours have been used in numerous case studies, since it is argued that a larger collector area can easily compensate the loss in performance associated with lighter colours (Salem, 2012).
- Cladding type – The metal cladding market offers mainly three different solutions: profiled metal sheeting, cassette panels and tongue and groove planks. There are no publications to date reporting if their difference in performance.

TSCs are a relatively new technology in the UK, so energy figures cannot be verified and there is a lack of independently tested monitoring data available to assess the efficacy of the installations. Only circumstantial information indicates that the TSC installations have been successful for the UK's climate, but there is evidence that TSCs have been successfully implemented in the US and Canada (Hollick, 1996). In America, its performance has been extensively tested and verified to deliver air temperature rise of 16 to 55oC above ambient depending on flow rate, to allow CO2 saving of 200kg/m2 of TSC, to reduce annual heating costs by around £50/m2 of TSC and to have an efficiency of up to 80% (SolarWall, 2017). Other benefits include their low maintenance and operation costs with a long-life span, they bring back the heat lost through building fabric and they provide an extra layer of insulation.

2. Water-based BIST collectors: These technologies use water as the working fluid for absorbing and transferring solar energy. The heat from the solar collector is suitable for direct domestic hot water production and indirect space heating. The main advantages of water-based collectors are: high thermal capacity and thermal conductivity, low viscosity, low cost, easy storage. But water is corrosive in nature, can cause freezing and scaling problems which pose challenges when designing

plumbing, which will need protection against water leakages. There are two water-based BIST technologies in the market:

- Roof integrated solar thermal: This roof integrated BIST panels replace the tiles or slates on the roof. Roofing works are completely separated from plumbing or electrical connection, which can occur later from inside the roof to give more flexible installation options. Viridian,
- Hybrid solar PV thermal panels (PV-T) for roof or wall application: This technology combines a PV module with a thermal collector, resulting in a better control of the temperature of the PV cells that increases the PV electrical efficiency by 4 to 12% during practical operation while uses the waste PV heat. DECC (2016) published a very detailed report which investigates the current state of the art of these technologies, reviews the market and the different types of products, describes the technical standards and certifications, analyses the performance and costs, identifies the barriers to deployment and presents different case studies. The report concludes that there is a limited product choice and experienced installers in the UK, with only 2 out of the total 13 manufacturers having market presence in the UK. Typical installed costs are around £2,250 to £3,000 per kWp, which is significantly higher compared with PV systems (£1,000/kWp) or TSC systems (£400/m^2). For this reason, to make the PV-T systems economically viable a large water cylinder and DHW demand is needed, hence good applications for PV-T are leisure centres or sports facilities. Instead, PV-T are less recommended for domestic scale, with only 500 PV-T installations in the UK.

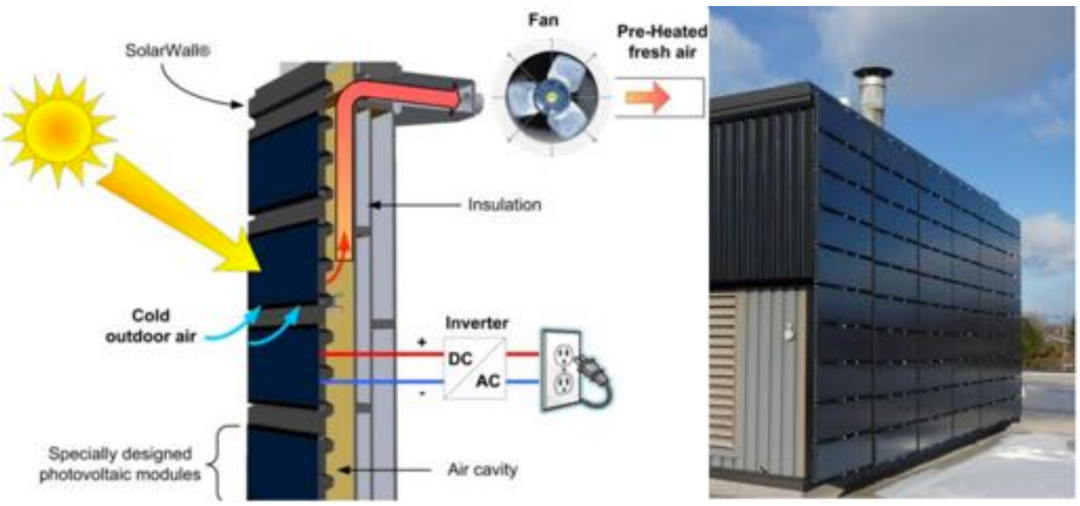


Figure 45 – Water-based BIST collectors: Façade mounted PV-T system (SolarWall, 2015).

3. Refrigerant-based BIST collectors: Compared to water, refrigerant has lower boiling/freezing, lower viscosity, and higher thermal capacity, which results in a more efficient transfer of a larger amount of heat with a smaller fluid volume. However, refrigerant-based technologies are more expensive, need to consider environmental behaviour and tend to need refrigerant recharging. The most popular technology is:

- Building integrated heat pipe: Compact and super highly efficient heat exchange technology that works with a constant refrigerant flow. Design is versatile, scalable and adaptable to many applications, and its small weight makes it easy to assemble and install. However, it is a fragile system, difficult to maintain and to replace.

Figure 46 – Refrigerant-based BIST collectors: Heat pipe solar collectors integrated into the building as shading systems or double-skin facades.

In conclusion, BIST systems offer flexible size and height ratios, are easy to integrate into the building envelope and can provide significant energy savings in both water and space heating. Many BIST technologies are present in the market and in the forefront of research due to the increasing concerns related to environment, energy independence and fossil fuels dependency. There are several research publications on the field. For example, comprehensive reviews of BIST applications by Buker & Riffat (2015) and Baljit et al. (2016); several case studies of BIST projects applied in retrofits (Giovanardi, et al., 2015) and facades (Garay Martinez & Astudillo Larraz, 2017; Visa, et al., 2017); and performance assessments of different BIST technologies by Li et al. (2016), Gautam & Andresen (2017), Beccali et al. (2016) and Hsieh et al. (2017).

2.3.2.2 Wind Energy Technologies

The call of integrating wind turbines into our buildings is interesting because rooftops are elevated above ground, where it's windier; and electricity is generated on site, where it's needed. However, despite some benefits, building integrated wind does not make much sense as a renewable energy strategy. This review examines both the pros and cons of this technology, considers some case studies and explains why it is usually a complex idea.

Building integrated wind turbines have to overcome several challenges to meet expected performance and to be cost-effective. The main challenges are:

- Turbulent airflow: Wind turbines work better when wind is strong and in a single direction. But in rooftops, as wind comes over the edge of a roof or around a corner it is separated into streams creating a lot of turbulence, which affects negatively turbine's performance. For this reason, it is usual to elevate wind turbines at least 9m above any object within 150m, including the building itself.
- Noise and vibration: Wind turbines emit noise and vibrations, which are huge challenges for their integration within the building itself. Many attempts have been made to integrated wind turbines in tall buildings, reinforcing the structure of the building and adding flexible materials to reduce harmonic resonance, but most of these attempts have failed and turbines have to remain switched off because of complaints from residents about noise.
- Safety: Although there is no evidence of injury or damage from building integrated wind turbines, building owners and insurance companies are very sceptical to accept the risk that blades might fly off and injure people or nearby properties.
- Poor measured performance: Manufacturers are reluctant to share measured performance data of their case studies, may be because the actual electricity output is much worse than expected. A few case studies have published results. For example, a Windside turbine in Wisconsin with a 6% of its rated output (Madison Gas and Electric, 2009), the Warwick Wind Trial Project in the UK that monitored 26 building-mounted wind turbines and found an average capacity factor of 0.85%, a field trial of 39 building mounted micro-wind turbines that found that only two sites had sufficient wind resource to make them economic (James, et al., 2010)and a report on 19 small wind turbines in Massachusetts that found a performance 60% lower than expected (Shaw, et al., 2008).
- Cost-effectiveness: While large freestanding wind turbines generate the cheapest renewable electricity today, small wind turbines are much less cost-effective, and when integrated in buildings, the cost goes up while the production drops.

Despite the challenges, quite a few manufacturers offer wind turbines for rooftop integration. The following is a small sampling of what products are available on the market:

- AeroVironment AVX1000: A 1kW horizontal-axis wind turbine manufactured by the world leader in rooftop wind technology. The turbines are designed to be installed in a building's parapet in a row. For example, it was installed at Logan Airport in Boston.

- Aerotecture helical rotor: This is a light-weight 1kW turbine designed for vertical mounting. It was unsuccessfully installed on a Mercy Housing Lakefront in Chicago.
- Windside: These are Savonius-style, vertical axis wind turbines made by forming two spiral vanes. They are specially designed to be virtually silent, less than 2dB at 2m.
- Quiet Revolution QR6: Only in the U.K, this is an elegant, helical-style 7.5kW wind turbine with blades and spokes made from carbon fibre. It is 5m tall, has a diameter of 3.1m, and is mounted on a mast installed either stand-alone or on top of a building. The company's website lists the price for the turbine and controls at around £30,000.

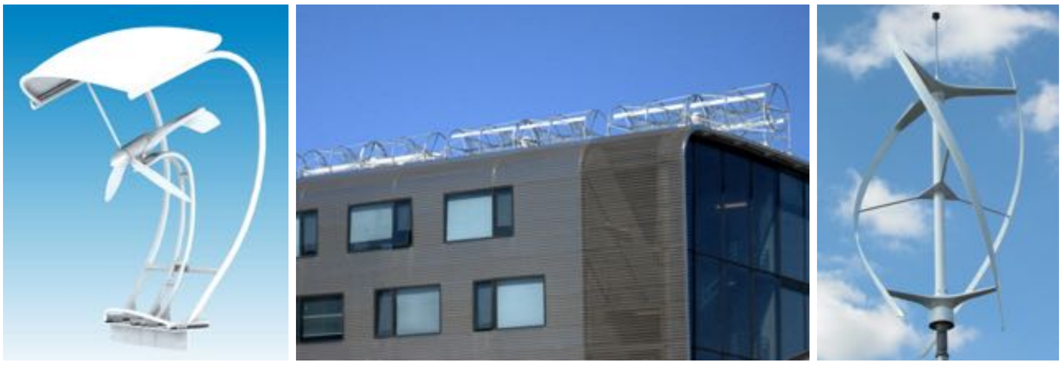


Figure 47 – Building mounted wind turbines: a) AeroVironmnet, b) Aerotecture, c) Quiet Revolution.

There are not many case studies with building integrated wind turbines, but those that have been built are very significant and relevant. For example, the Bahrain World Trade Centre (2008) was the first skyscraper in the world to integrate wind turbines into its design, with 3 horizontal-axis wind turbines siting across beams that connect the two towers of the building and generating 11 to 15% of the building's energy demand. The Pearl River Tower (2011) in China was designed with an unusual yet elegant shape to direct wind to inlets in the façade where vertical-axis turbines are located, ensuring maximum efficiency and maximising wind speeds. The Greenway Self-Park (2011) in Chicago was equipped with 12 vertical-axis wind turbines placed in two double-helical columns on the corner of the building, which can generate enough electricity to power the lighting of the building.

Figure 48 – Case studies of building integrated wind turbines: a) Bahrain World Trade Centre, b) Pearl River Tower, c) Greenway Self-park.

2.3.3 TECHNOLOGIES TO STORE ENERGY ON-SITE

Energy storage technologies are categorised in regard to the form of energy they use. This section provides brief outlines of each technology, using information from different sources presented to be comparable to each other. It is important to clarify that new technologies are continuously being developed, however this review covers only those that are for domestic scale, widely used, available in the market or close to deployment.

2.3.3.1 Electrical Energy Storage

An average household with renewable supply – i.e. solar PV panels or wind turbines – will sometimes not use all of the energy created by their PV panels for one day, which means that the energy excess will be fed back to the grid. Instead, electrical energy storage can take the excess solar power created by the panels and use it to charge the batteries during the day. These batteries can then supply energy to the household during the night and on cloudy days by using the excess supply.

The batteries market is rapidly growing as more manufacturers aim to innovate and overcome some of the challenges within the energy storage industry. Due to the relevance of electrical energy storage for future energy systems, numerous review studies have been published. Earlier reviews, for example by Ibrahim et al. (2008), Chen et al. (2009) and Huggins (2010), discussed the energy storage concept and aims including the whole range of uses, technologies and associated key technical features like durability, capacity and efficiency. Other authors reviewed a specific typology of the full variety of energy storage technologies, e.g. the review of phase change materials for building applications by Cabeza et al. (2011); the potential of phase change materials to reduce domestic cooling loads by Sajjadian & Sharples (2015); the review of energy storage for wind power applications by Díaz-González et al. (2012); the review of electricity storage applications by Brunet (2013); and the review of electricity storage for building applications by Chatzivasileiadi et al. (2013). Due to the constant attention on energy storage, recent reviews have become more focused on the latest progress of a particular technology, application, scale and/or country. For example, the evaluation on lithium-ion batteries for power and automotive applications by Stan et al. (2014); on hydrogen storage by Niaz et al. (2015); on storage demonstration projects in the UK's distribution networks by Lyons et al. (2015); a comparative life cycle cost analysis of different electricity storage systems by Zakeri & Syri (2015); an optimisation of time schedules of energy storage for renewable energy by Ho et al. (2016); and a review of energy storage for community scale by Parra et al. (2017).

The graph shown in Figure 49 shows the evolution on the number of research publications, in Elsevier database, related with the fields of residential energy storage and batteries typology. As it can be seen, hydrogen storage attracts most of the attention due to its huge potential for long-term storage, and this interest has grown rapidly since 2002. Although lead-acid and Li-Ion batteries are investigated less, an increase on its interest can be seen from 2008, but with the attention in lead-acid falling noticeably in 2014 when it was overcome by Li-Ion batteries.

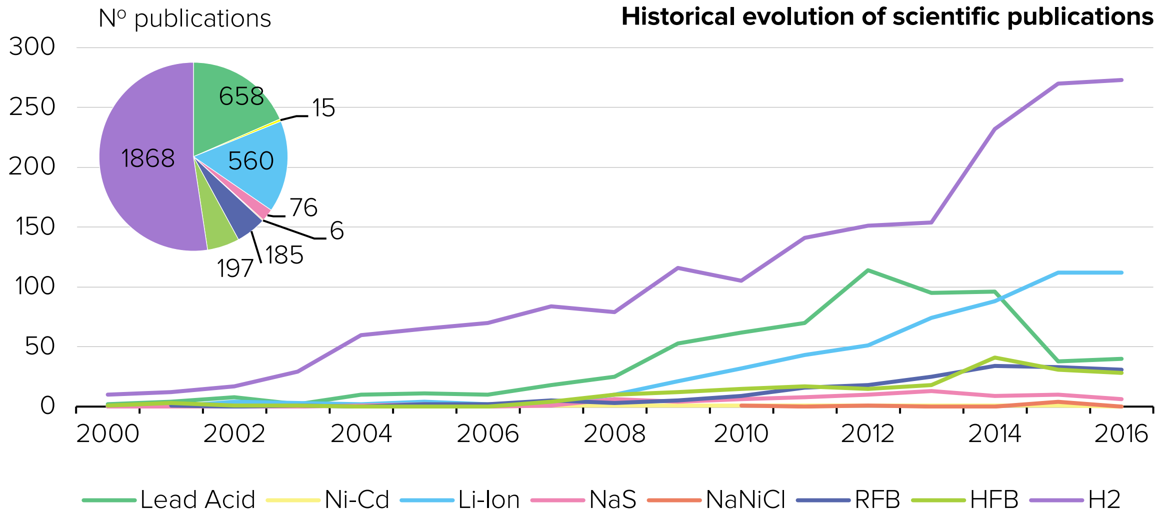


Figure 49 – Linear graph showing number of publications grouped by keywords – i.e. type of storage – from 2000 to 2016. Pie chart showing distribution of total published papers per type of storage. Data source: Elsevier

Electrical energy batteries offer an established form of energy storage as a standalone option. There are two types of connection between renewables systems and battery systems, these are DC and AC coupled systems (see Figure 50). In AC coupled systems the battery is connected to the PV system, which consists of the PV generator and inverter, via a charge regulator and a battery inverter. Oppositely, DC coupled batteries are connected to the DC link of the PV inverter.

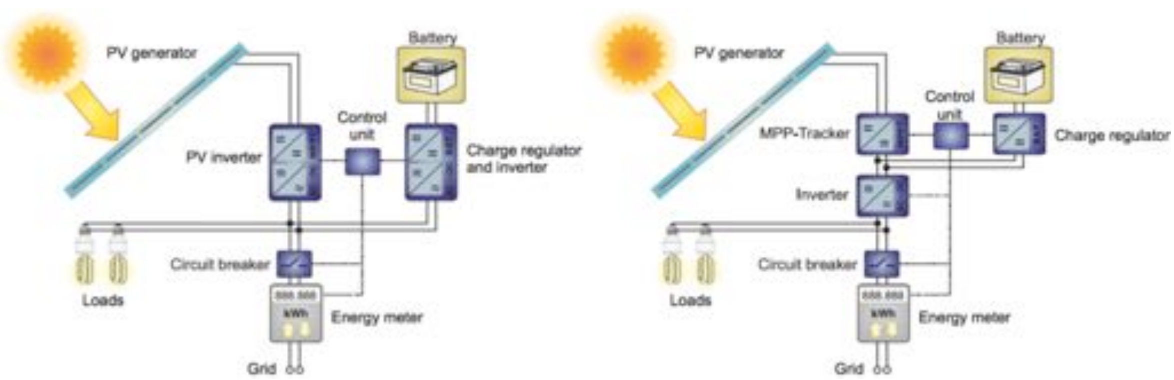


Figure 50 – Schematic layouts of two types of residential PV battery systems: AC coupled (left) and DC coupled (right) (Weniger et al., 2014).

There are numerous storage technologies and flexibility options to serve the balancing between demand and supply. Rand & Moseley (2015) agree that it is necessary to classify the different storage technologies and flexibility options into different categories, especially from an application's point of view, because not any storage technology can be applied in any application. Following Rand & Moseley (2015) classification, and to understand the various approaches currently being implemented around the world, this review focuses in ten main typologies of batteries:

- Lead-acid: This is the battery technology with the longest history, used commercially since the 1890's; hence it is the most mature of the technologies. Lead-acid batteries, despite their toxicity and environmental and health risks (Zhang, et al., 2016), are very popular due to low cost/performance ratio, short life cycle, simple charging technology and low maintenance requirements (REA, 2015). A description about the fundamentals of lead-acid batteries by Pavlov (2017) indicates that their main disadvantage is that as they discharge higher power their usable capacity decreases. Also, they suffer from various technical issues, mainly short cycle life, low depth of discharge (<20%), short lifetime (3 to 4 years), slow charging, maintenance requirements, relatively low energy density, and are bulky and heavy. However, they are widely used coupled with photovoltaic systems to increase electricity self-sufficiency in households (de Oliveira e Silva & Hendrick, 2016).
- Nickel-Cadmium (NiCd): A mature technology used since around 1915, NiCd batteries rapidly lost market share in the 1990's due to their higher cost and highly toxicity (REA, 2015). Among their advantages is their ability to deliver almost their full rated capacity at high discharge rates and to charge at fast speed. Also, they have high energy density and a long-life cycle, and can perform well at low temperatures ranging from -20°C to +40°C. However, they need very good care to attain longevity due to their memory effect that causes a loss of capacity if not given a periodic full discharge cycle (Cadex Electronics, 2017). This is a significant drawback for renewable energy applications, which tend to be unstable, unpredictable and no cyclical. Instead, they are mainly used for stationary purposes and for the airline industry (REA, 2015).
- Nickel-Zinc (NiZn): Compared with NiCd batteries, they have better environmental impact, higher energy density (+25%) and cheaper price; while compared to lead acid batteries, they have a higher energy to mass ration and a higher power to mass ration (Amrouche, et al., 2016). Due to these reasons, NiZn batteries have the potential to be used for renewable energy applications at the domestic scale and replace both lead-acid and NiCd technologies.

- Sodium Sulphur (NaS): This type of battery is still in the early stages of deployment, especially in Japan (IRENA, 2015). They have relatively high energy density, high discharge rate (<92%), long cycle life, and are fabricated from inexpensive materials. However, their market price is high and they require very high operating temperature (350 °C), hence they are not useful for domestic scale applications (Palizban & Kauhaniemi, 2016) but are the leading market technology for large power scale – i.e. grid scale (IRENA, 2015).
- Sodium Nickel Chloride (NaNiCl): The NaNiCl battery is a high operating temperature battery (270 °C to 350 °C) that has been commercially available since 1995. These batteries are suitable for bulk storage in large renewable energy power plants, due to their long discharge time, long cycle life and fast response (Amrouche, et al., 2016); but they are inadequate for the domestic scale not only because heat is required to keep its chemicals molten state temperature but also because molten Sodium reacts dangerously with water causing fire in reported incidents (GENI & Oberhofer, 2012).
- Lithium-Ion (Li-Ion): Li-Ion batteries are the most well-known and widely used form of storage in the world, representing 85.6% of deployed energy storage systems in 2015 (IRENA, 2015). Their high energy density, high flexibility in their discharge time, low standby losses and a tolerance to cycling, makes them suitable for many different applications, being electric vehicles and consumer electronics the most popular ones. Although these are the more expensive type of batteries, they have started to come down in price, and it is expected that this trend will continue in future years (REA, 2015). In fact, they are becoming more popular among the domestic scale renewable energy applications and have the lowest cost per cycle (IRENA, 2015).
- Lithium Iron Phosphate (LFP): They share many advantages with Li-Ion batteries, but on top of that LFP batteries have longer cycle life, a very constant discharge voltage that allows the cell to deliver almost full power until it is discharged, and lower discharge rates (Satyavani, et al., 2016).
- Salt water: Recently deployed in 2008, salt water batteries have much lower energy density compared to Li-Ion and LFP, but they have some important advantages in applications where size and weight are not a constraint. For example, they are made of non-toxic components and they can have full discharge rates (100%) with no damage to the batteries. Although they have been used in residential scale projects, their weight per kWh is about 15 times greater than Li-Ion (Aquion Energy, 2015), which makes them less convenient in terms of building integration.

- Flow Battery (FB): The electrochemical reactions of FB batteries are similar to conventional and high operating temperature batteries, but they differ in the way the electrolytes are stored in external tanks. The most common types are Redox Flow batteries (RFB), which are suitable for mobile applications thanks to their high levels of discharge but low energy density; and Hybrid Flow batteries (HFB), which use one of their electro active component deposited as a solid layer and are suitable for community and utility scale applications. Only a few FB batteries systems have seen deployment (Nguyen & Savinell, 2010), consequently the technology is relatively new and unfamiliar. However, in 2016, a unique hybrid zinc-bromide (ZB) flow battery for residential application was deployed into the Australian market, claiming a full discharge rate (100%), no capacity loss with age or uneven use – i.e. periods uncharged, exposition to extreme temperatures or overcharging – and made from reusable and recyclable components (ZCell, 2017). Research into the use of ZB batteries in the residential sector started back in 2005 and some case studies have been published (Nakatsuji-Mather & Saha, 2012).
- Hydrogen (H_2): This technology uses electric energy to create water electrolysis – i.e. water is split into hydrogen and oxygen – to generate the burning fuel. Therefore, it is a chemical energy storage technology that uses the resulting hydrogen fuel, which can either be burned directly in conventional power plants or it can be transformed to and synthetic natural gas. The efficiency of this technology is lower compared to Li-Ion batteries, but it is a promising technology because it allows large amounts of energy to be stored over longer periods of time. A comparative study of the use of Li-Ion batteries and hydrogen storage for residential use from Zhang et al (2016) shows that Li-Ion batteries are better in terms of self-sufficiency ratio and cost performance.

This review underlines that there is a wide range of storage technologies and that each type is suitable for specific applications. For example, batteries for residential scale renewable energy applications have to meet the requirements of unstable supply, heavy cycling (charging and discharging) and irregular full recharging; hence there is only a small range of battery types fitted for these unique requirements. These are lead-acid, NiZn, Li-Ion, LFP and ZB batteries. Considerations for choosing among these battery types include:

- Cost: A lower price is always attractive, but if this means less quality and battery life, the need for frequent battery replacements could increase the cost over time. Therefore, it is important to consider issues other than price when making the decision.

- Capacity: This is a measure of the amount of energy stored in the battery. A bigger battery capacity will offer more self-sufficiency and energy saving to the household. The balance between price increase and energy savings could be very important when deciding the ideal battery capacity for the household.
- Voltage: The battery bank voltage must be considered to ensure it matches the system requirements. It is often determined by the inverter specifications if installing a DC-to-AC system or by the voltage of the loads in a DC system. The most common battery voltage is 12V, 24V or 48V. In the early days, the cost of a PV-battery system was reduced by limiting its size, thus the 12V used to be a standard for extra low voltage power lights and appliances. In recent years, inverters and PV panels have become more efficient and a lot more affordable, while home users also need more power and dislike the limitation of using only low voltage appliances. Therefore, nowadays the most popular solution is a 24V or a 48V battery bank connected to a 230V AC inverter. This means the wiring of the house does not have to be different from any other grid-connected household and cabling cost is greatly reduced.
- Cycle Life: This is the most critical consideration because it provides the number of discharge/charge cycles the battery can offer before capacity drops to a specified percentage of rated capacity. Batteries from different manufacturers may have the same capacity, energy content and be similar in weight. But their design, materials, process and quality influence how long the battery will cycle.

In conclusion, advances in technology and materials have greatly increased the reliability and output of modern battery systems, and economies of scale have dramatically reduced the associated cost (REA, 2015). Continued innovation has created new technologies like electrochemical capacitors that can be charged and discharged simultaneously and instantly and provide an almost unlimited operational lifespan. Energy storage could offer important benefits to the UK in terms of energy security (Roaf, et al., 2005), the integration of renewables on the household's energy system, and growth of manufacturing and jobs (REA, 2015). Storage can be implemented at all scales, from large grid scale to residential batteries. For example, in a household with solar renewable supply, based on typical daily PV generation and electricity demand profiles, storage could potentially lower the electricity bills and increase self-consumption of solar energy, also reducing the grid imports and CO_2 emissions.

2.3.3.2 Thermal Energy

Section 2.1 has set out the current state of domestic heat supply and demand in the UK, with most of the heating needs currently met using the combustion of fossil fuels. This situation has to change drastically if the UK is to meet the challenging carbon targets of an 80% reduction in greenhouse gas emissions by 2050 (BERR, 2008). The domestic sector faces a range of challenges and the key issues are reducing the overall demand for heat and decarbonising the residual heat loads.

In low carbon built environment scenario, if the supply of electricity in the UK is progressively decarbonised through the implementation of renewable generation, then the electrification of heat using heat pumps would be an effective way to meet the low-carbon space and water heating demand (Flett & Kelly, 2017). However, the widespread adoption of heat pumps would significantly increase the power flows on the electricity network. Wilson et al. (2013) indicated that a shift of only 30% of domestic heating to heat pumps could result in an increase of 25% in the UK’s total electrical demand. To mitigate the potential negative impacts of heat pumps particularly on peak demand and to reduce or delay network upgrade costs, load shifting of household thermal demands by using thermal storage could become essential (Flett & Kelly, 2017).

Thermal storage would play a key role in facilitating both the integration of low-carbon heat sources and the electrification of heat. In a low carbon built environment scenario, the use of storage in tandem with electrical heating will be important to limit the grid and renewable generation challenges of supplying heat via electricity as well as to limit energy bills. At present, storage using hot water tanks is common in households with electric heating because it enables occupants to take advantage of off-peak tariffs (Energy Saving Trust, 2008). However, they can require significant space, hence can be difficult to accommodate in smaller households. This problem becomes more acute if heat needs to be stored over longer time periods than is done at present. Consequently, innovation in this area will be important and many research publications are being published on this field. For example, phase change materials (PCM) thermal stores could allow more compact storage of heat, while hydrogen store that can be converted to heat or electricity could provide a more versatile storage solution to complement heating systems.

All these types of thermal storage, together with other flexible solutions, such as demand side response, could play an important role in helping balance the future electricity system, and in doing so will contribute to the UK’s energy security (Roaf, et al., 2005).

2.3.4 LESSONS LEARNED

Technologies to reduce energy demand should always be the first step when designing green buildings with low energy consumption and CO_2 emissions. For example, maximizing energy efficiency of new buildings, improving energy efficiency in existing buildings, using energy efficient appliances and lighting or making behavioural changes in the use of a building.

The second step is then to implement renewable energy technologies capable to collect the energy flows that occur naturally in the environment and that are effectively inexhaustible and use them to generate thermal or electrical energy free of CO_2 emissions. Many technologies have been invented throughout time, but not all of them are appropriate for buildings in the UK. This review studied the latest technologies available in the market and that are appropriate for the UK's climate. Among these technologies, solar energy seems a better solution because is easier to integrate in buildings, has many products in the market with better and more reliable performance and is capable to generate both electrical energy and thermal energy.

The last step is energy storage. To improve energy security and deploy more renewable energy; governments, finance providers and industry must recognise that storage technologies are an essential part of the energy mix and must become mainstream. As the price of energy storage continues to fall, the case for storage becomes even more compelling; however, an initial push is necessary to overcome the current barriers.

2.4 Architecture design of low carbon housing

Architecture, the art of designing and constructing buildings, has always been closely linked with the history of art. Not only because many public buildings, especially religious, were designed with aesthetics in mind involving the services of a wide range of artists and decorative craftsmen, but also because in many of these buildings, exteriors and interiors became a showcase for fine art painting, friezes, mosaics, metalwork or sculpture. Therefore, most major art movements – e.g. Renaissance, Baroque, Rococo, Neoclassical or Modernism – influenced the fine arts as well as the architecture, giving also name to the architecture movements (Maziar, 2012).

Owning to the nature of this research, this review considers architectural history from another perspective. Therefore, instead of focusing on the art side of architecture, the aesthetics, it focuses on the performance side of architecture and its relationship with energy and technology. As a result, architecture is categorised in movements that do not follow the traditional art movements. Across history, concepts such as green, ecological, sustainable or environmental architecture are used interchangeably (Steele, 2005). However, sometimes these terms are used indistinctly or even wrongly, thus have become confusing. According to Julien de Smedt, from JDS Architects: “There is a definition problem: ‘Green’ and ‘Sustainability’, the terms used to name the answer to the most pressing problem of our time, have become dangerously afloat in ambiguity and indeterminacy. Sustainable architecture is everywhere and nowhere” (JDS Architects, 2010).

For the purpose of this thesis, ‘green architecture’ is used as an umbrella term to define the overall evolution of architecture towards a reduction of the negative environmental effects and unsustainable activities caused by the built environment. According to Tabb & Deviren (2013) “the greening of architecture became an emerging process that attempted to transform modern architecture into more benign, environmentally oriented buildings”.

The birth of the green architecture process in the 20th century is due to the return of environmental values within developed countries (Ragheb, et al., 2016). Throughout this process, different movements have arisen reflecting the concerns and awareness of the moment (Tabb & Deviren, 2013). Green architecture is an evolving phenomenon that has advanced from rationalists and performance-based measures responding to specific environmental concerns, to far more ecological and systemic measures aiming to have an impact across every day more demanding contemporary culture (Tabb & Deviren, 2013).

Although there has been a growing interest in reducing CO_2 emissions in recent years, in an attempt to fight against climate change, attention to reducing energy use in buildings is not new. According to Jones (2012), the UK's research into improving the energy efficiency of buildings is now in its fourth decade of activity. It was initiated in response to the oil crises of the mid 1970's, continued with passive design through the 1980's and into sustainable design and zero carbon design during the 1990's and 2000's. Based on similar historical events, but in the American context, Tabb & Deviren (2013) in their book *'Greening of Architecture'* propose different names to the categories proposed by Jones (2012). But what is clear is that there is an agreement with the timing of the events, thus the 1970's represents the beginning of green architecture as illustrated in Table 3.

Table 3 – Green Architecture periodization according to Jones (2012) and Tabb & Deviren (2013).

	Jones (UK)	**Tabb & Deviren (US)**
1970's	Low Energy Design	Solar Architecture
1980's	Passive Design	Post Modern Green
1990's	Sustainable Design	Eco-Technology
2000's	Zero Carbon Design	Sustainable Pluralism

Table 3, which compares two different approaches to the history and evolution of green architecture, provides a small sample of the multiple varieties of ways that architectural movements can be interpreted and named. It is understood that categorising architectural movements by naming the different time periods is not the ideal approach, especially in the field of green architecture, which has evolved greatly and quickly since the 1970's with lots of conceptual interactions between periods. Therefore, even though the following review classifies and names each architectural movement per period, it is important to understand that there are not definite points to separate time and concepts and that green architectural concepts, methods and technologies described as dominant in one period, can and have been implemented in earlier or later periods.

To summarise the most important dates and events that are presented in the next section, a timeline graph is presented in Figure 51. This locates, from the 1950's, the various periods of green design in relation to the growing awareness of environmental issues, the introduction of new building regulations and environmental policies, the launch of green housing events and the deployment of new low carbon technologies. It also shows how global CO_2 levels and average global temperatures have steadily increased over the same period.

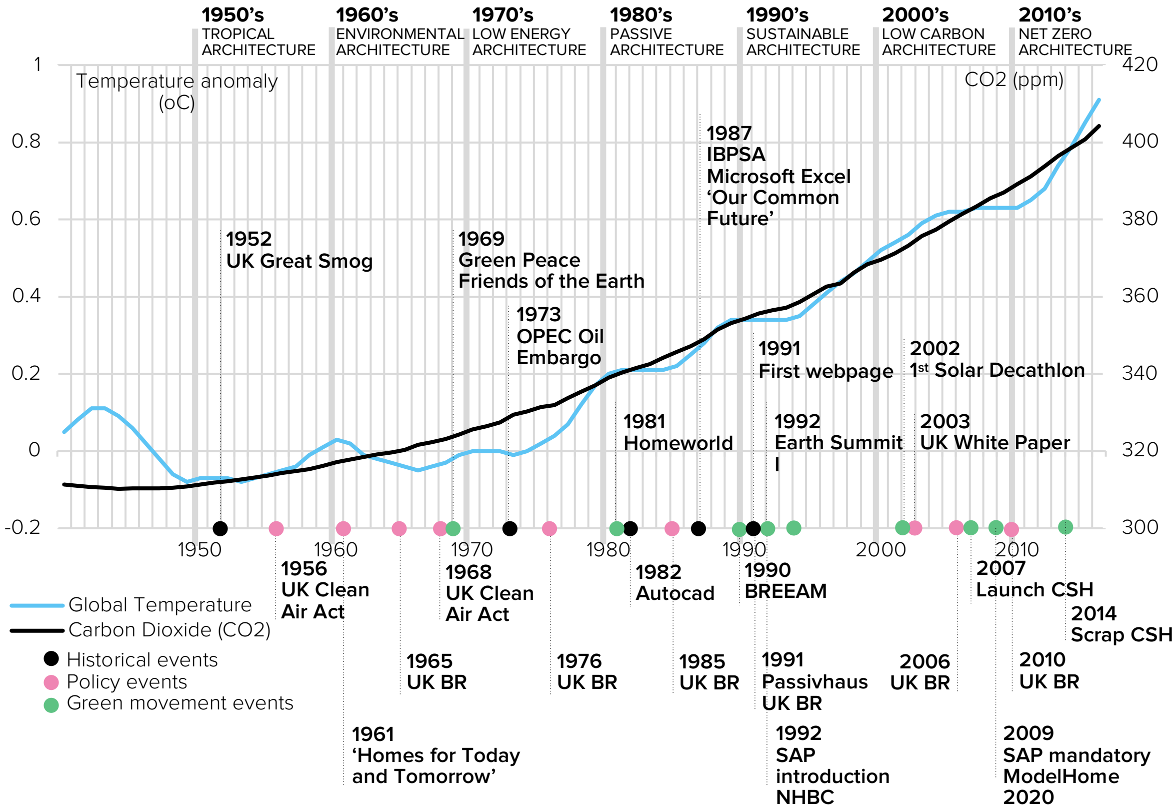


Figure 51 – Graph showing the historical evolution of green architecture from the 1940's to the 2010's.

Also, to illustrate the evolution of green architecture, Figure 52 shows the number of published research papers per year from 1970 until 2015 featuring concepts such as vernacular, low energy, passive, sustainable, low carbon or net zero across this time. For the search, the source base was Scopus, the keywords were 'architecture' and each of the terms listed in the graph, and the execution date was July 2016. The graph shows that although publications on the subject started to appear in 1970, it was not until the early 2000's that the subject became more popular among researchers.

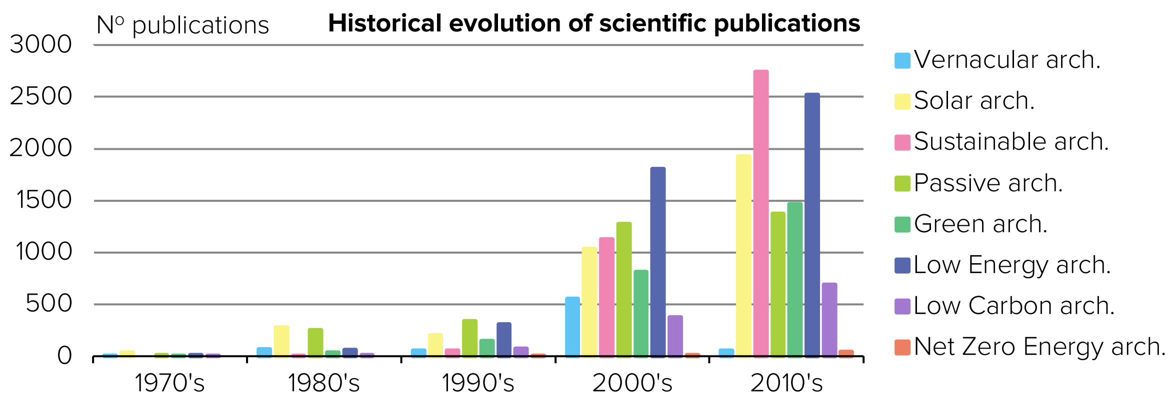


Figure 52 – Histogram showing number of publications grouped by keywords – i.e. architecture & vernacular, solar, sustainable, passive, green, low energy, low carbon, net zero energy – from the 1970's to the 2010's. Data source: Elsevier.

On the other hand, it must be highlighted that research shows that the green movement occurred worldwide (Ionescu, et al., 2015). This section focuses on the housing sector and thoroughly reviews more than 80 green house projects considering the integration of architecture, energy and technology. Regrettably, it would be too extensive to mention all the projects of green houses that have been built through history in every corner of the world, but it is expected that the selection of most relevant projects built in the UK, Europe, North-America, Asia or Australia inspire and demonstrate different sustainable solutions, materials and technologies in a broad range of climates and regions.

2.4.1 ORIGIN: VERNACULAR ARCHITECTURE

Across the world there is a long history of green construction; this is vernacular architecture. According to architectural historian Oliver (1997), these constructions were built to meet specific needs accommodating the values, economies and ways of life of the cultures that produced them. These early examples of green architecture were, by necessity, climate responsive, offering protection from inclement weather, but also responded to other environmental concerns like on-site water harvesting, sewage removal and fuel for heating. Vernacular buildings evolved over time to reflect changes on cultural identity (Oliver, 1997), to make the best use of local materials and conditions, and to provide appropriate shelter for populations inhabiting even the most extreme climates of the world (Roaf, et al., 2005).

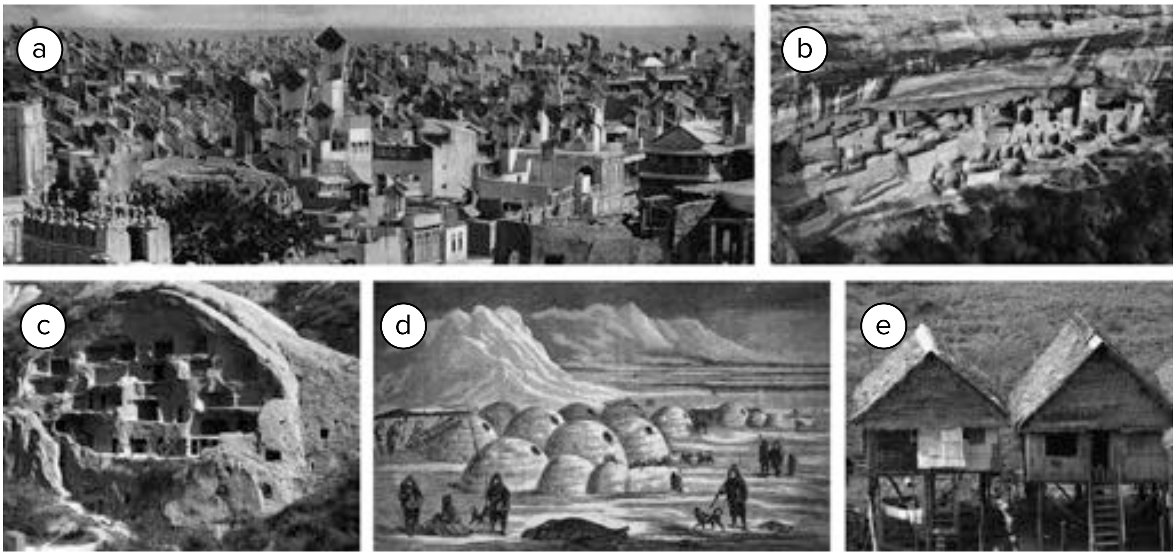


Figure 53 – Vernacular architecture: a) Wind-catchers in Hyderabad, Pakistan; b) Adobe houses in Mesa Verde, Colorado; c) Underground dwellings in Yanqing Guyaju, China; d) Igloos in Oopungnewing; e) Stilt house in Myanmar. Source: (Tabb & Deviren, 2013).

There are many ancient cities designed and built following the principles of vernacular design (Roaf, et al., 2005). For example, ancient Greece, Asia Minor or Hyderabad in Pakistan. Other locations worldwide indicate architectural design response to varying environmental conditions, such as Swiss alpine houses, Inuit igloos, Amazon raised platform dwellings, English cottages, North American adobe dwellings, Chinese underground dwellings, or Pakistanis wind towers. According to Oliver (1997), these buildings did not control climate, but rather modified climate by affecting internal conditions aiming at better levels of satisfactory comfort. Examples of typical climatic design strategies in colder climates use insulation, heat retaining materials and solar energy; or in tropical areas use stilts, platforms and extended roofs to capture breeze and shade.

Power from the sun, both in the form of direct solar radiation and in indirect forms – i.e. bioenergy, water or wind power – was the energy source upon which early human societies were based (Boyle, 2004). Renewable energy sources, derived mainly from the enormous power of the sun's radiation, are at the same time the most ancient and the most modern forms of energy used by humanity.

2.4.2 1850's: MODERN ARCHITECTURE

Strategies for collecting the sun's power developed slowly until the early years of the Industrial Revolution, but by then the advantages of coal, the first and most abundant of the fossil fuels had become evident (Murphy, 2014). The highly concentrated energy from fossil fuels soon displaced wood, wind and water as an energy source in industrialised countries.

The Industrial Revolution introduced the idea that humans, by using energy and technology, could overcome any limitation imposed by nature. Modernism proposed an abstract architecture, which had no reference to the place where it was built (Frampton, 2007), totally opposite to the vernacular construction that had been developed, improved and adapted through the centuries (Oliver, 1997).

Modern architecture broke from the eclectic traditions of the 18th century and focused on abstraction, standardisation and serial production pursuing a homogenous international identity (Tabb & Deviren, 2013). Modern building design evolved adding more complexity and reliance on technology, resulting in a vast architecture that tends to be energy inefficient. Buildings were designed to have shorter lives, were built with lighter mass, and were strongly reliant on HVAC systems demanding large quantities of fossil fuel energy (Frampton, 2007). Consequently, this increased the negative impact of buildings on the environment and their dependency on fossil fuels.

Fortunately, earlier climate responsive architectural works by Le Corbusier, Frank Lloyd Wright, Ralph Erskine, Constantinos Doxiadis, Louis Kahn and Alvar Aalto emerged as early modernist green precedents (Steele, 2005). The earliest modernist universal principles were reconsidered by environmental aware strategies leading to environmental designs. If modernism by then was contemplated as the origin of the existing environmental problems, then it also was responsible for many of the energy saving solutions available nowadays, such as HVAC systems, or the tendencies of economy and functionality.

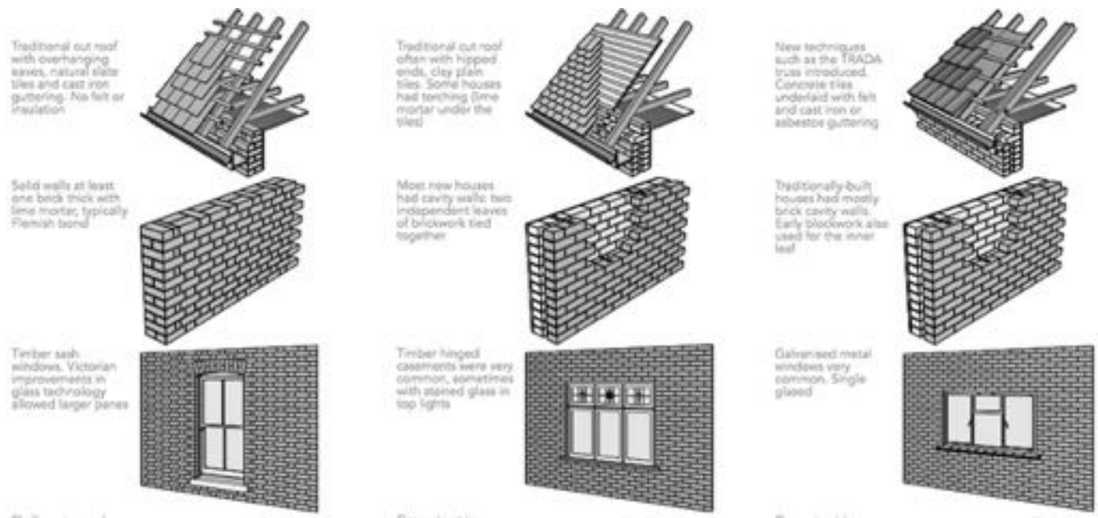


Figure 54 – Historical evolution of housing construction methods for roof, walls and windows (NHBC, 2015).

However, the modernism trend did not greatly influence the UK's housing. The houses kept the same aesthetic and layout than before as a response to the clients' conservative thinking, who did not push the housing industry to left behind traditional Victorian houses. In the UK, the main focus of effort and attention were methods of construction. Initially, walls were built with a solid single skin made with traditional materials such as stone or adobe. After World War II, cavity wall, with two masonry layers (brick or block) separated by an air cavity, was adopted as common method of construction (see Figure 54). Regarding the energy systems, there was no central heating; coal fires heated the downstairs rooms while Calor gas or paraffin stoves and electric fires provided the upstairs heating.

In 1952 Britain was hit by a terrible event known as the 'Great Smog'. By that time, smog had become frequent part of London life and Britain had long being affected by mists and fogs caused mainly by factories and homes. But on the 5th December 1952, meteorological conditions led to an air inversion that trapped pollutant particles and gases into the lower levels of the atmosphere. The impetus of the Great Smog almost brought the London city to a standstill and officially claimed the life of 4,000 people (Mett Office, 2015), although it could be up to 13,500 if influenza is considered (Bell, et al., 2004). This led the UK to create the Clean Air Act of 1956 and 1968, which banned emissions of black smoke and ordered operators of factories and residents of urban areas to switch to smokeless fuels. Pollution in the city was finally seen as a negative matter and was slowly being ended.

Figure 55 – Historical photos of the Great Smog (1952). Source: (Wagland, 2013).

It was the first time in history that financial incentives were offered to householders to substitute open coal fireplaces with alternative technologies such as gas fires or coke-fired furnaces, which produced minimal smoke. 'Smoke control areas' were established in some towns and cities guaranteeing that only smokeless fuels could be burnt. Power stations were also relocated outside the cities. The act represented an important momentum and triggered the modern environmentalism movements who began rethinking the hazards of environmental degradation to populations' quality of life.

2.4.3 1950's: TROPICAL ARCHITECTURE

Baweja (2008) in his thesis titled *'A Pre-history of Green Architecture: Otto Koenigsberger and Tropical Architecture, from Princely Mysore to Post-colonial London*' and Uduku (2006) locate 'Tropical Architecture' in Europe and 'Bio-Climatic Architecture' in the United States, in the pre-history of the environmentalism movement. Baweja focuses on Europe and challenges the typical 1970's to 1990's periodization of the history of green architecture. Instead, he states that one of the origins of green architecture lies in the tropical architecture developed by émigré European modernist architects, such as Otto Koeningsberger, Jane Drew, Maxwell Fry or Leo De Syllas; during their abroad experience in the colonies of the British Empire. According to Baweja's research, tropical architecture is a climate responsive and energy conservative design that was the pre-cursor to the environmentalism movement of the 1960's. He establishes continuities between tropical and green architectural practices and aims to demonstrate how architects trained in tropical architecture made their careers later in the field of green architecture.

Figure 56 – Tropical architecture: a) University College, Ibadan; b) Higher Secondary School, Sector 23, Chandigarh. c) Department of Marketing Exports, Ibadan. Source: RIBA.

2.4.4 1960's: ENVIRONMENTAL ARCHITECTURE

In the 1960's, there was a rapid expansion of the use of chemicals following World War II, which led to an increasing consciousness of the negative effects that contemporary life had on the planet. By then, nature writers started speaking more of environmental problems and the appreciation of natures' beauty. The first awakening ideas came in 1962 from the biologist Rachel Carson in her book *'Silent Spring'*, where she focused on the example of birds to document the damage caused by pesticides on the environment. It was the first time that environmental degradation and its impact on animals' health were emphasised while exposing a conspiracy between industry and governments in supporting and protecting the chemical industry to the detriment of humans' wellbeing.

The increasing awareness about the direct connection between environmental and social problems resulted on a growing call to governments to regulate industry more strictly. Nature writers and philosophers began to analyse the fundamental values of nature more in depth when criticising environmental problems and looked to radical political theories like anarchism, socialism and ecofeminism, as well as alternative social systems and other cultures like Buddhism and Native American. Their work coincided with the growth of ecological concerns and with the birth of environmentalism, and their pressure led to the formation in 1969 of organisations such as 'Green Peace' and 'Friends of the Earth'.

The rising consciousness of environmental issues had a small impact into the buildings of the time and there were only a few architectural responses. In US, during the 1960's, the powerful aspiration for accomplishment of the American Dream by the growing middle class diverted the attention. The majority of houses were designed to achieve this dream; a single-family detached housing typology, which doubled in size and was all-electric equipped with new technologies such as central heating, air conditioning, washing machines and dryers, larger refrigerators and freezers, TVs and telephones. Predominant modernism was still progressing without concern for environmental issues. The greening progress started to emerge only at the end of the decade, when the negative impacts of modern life upon the environment were exposed and made public.

Meanwhile in the UK, as a result of the Clean Air Act of 1956 and 1968, open fires were slowly being bricked up, removed or replaced by central heating in the majority of houses. In 1961 Parker Morris published *'Homes for Today & Tomorrow'*, an influential UK Government's report that recommended standards for all new homes, public and private, reflecting the new changed patterns of living with more informality in the way house space was used (University of the West of England, 2009). The main recommendations were for more living and circulation space, such as a bigger kitchen with electric appliances like washing machines and refrigerators, and for better heating throughout the house, with full or partial oil fired central heating system so that all spaces could be used freely. Comfort, convenience and efficiency, both in terms of space utilisation and energy consumption, were now established as the dominant factors determining the future of housing design. The initial impact of the report was widespread, the recommendations were made mandatory for public sector housing later in 1967 and briefly for local authority housing in 1969, but they were never made mandatory for private housing (NHBC, 2015).

The first UK national Building Regulations that addressed energy conservation came into place in 1965 (Palmer & Cooper, 2011), and introduced limits to the amount of energy that could be lost through elements of the building fabric of new housing. Although Part F, *'Thermal insulation'*, was only two pages in length, it introduced U-value limits for walls at 1.7W/m^{2}K and for roof at 1.4W/m^{2}K (HMSO, 1965) which created a precedent for improving building fabric.

2.4.5 1970's: LOW ENERGY ARCHITECTURE

In 1972, Sir Alexander Gordon, in his role as President of the Royal Institute of British Architects (RIBA), defined 'good architecture' as a building that exhibits the 3L Principles of "long life, loose fit and low energy" (Gordon, 1972). While the architects at the time did not immediately engage with this idea, over time it became a mantra that potentially defined good architecture and its role in modern society (Langston, 2014). However, during many years, architects following the green movement were mainly focused on achieving low energy buildings and gave much less consideration to durability and adaptability (Langston, 2014), ignoring the significant remark made by Jane Jacobs (1961) that "the greenest buildings are the ones we already have".

By this time, there were still few thermal insulation requirements for building fabric in the UK and many homes were still inadequately heated, with central heating being a relatively new concept for the majority of the housing stock. However, the OPEC Oil Embargo of 1973 increased the awareness of the dependence upon fossil fuels and security of supply (Fuller, et al., 1982). As a result, changes in construction methods arose: air cavities were filled with insulation materials and double masonry layers were built with lightweight aerated blocks reducing their weight (Hens, et al., 2007). Airtightness in buildings became a matter of concern with BSRIA developing the first computer program, named CRKFLO, capable of predicting natural ventilation rates (Jones, 2015) which were used in energy calculations.

To respond to the crisis, the UK Department of Environment set up a series of projects such as the Insulation Kits (IK) scheme, the Housing Development Directive (HDD) and the Better Insulated Housing (BIH) project. The IK scheme was introduced in 1976 to assist existing householders to buy simple insulation materials at half the normal prices – i.e. loft insulation, draught stripping and insulation jackets for hot water cylinders (Fuller, et al., 1982). The HDD project studied the energy performance benefits and impacts of better levels of insulation and increased airtightness in the housing stock. The BIH project focused in one case study, the Abertridwr Community (South Wales). Research consisted on the accurate and intense monitoring of the weather conditions and the energy and environmental performance of a total of 39 terraced houses over the period of one year. From these, 20 houses had higher levels of thermal insulation in walls, roof and floors, and a reduced heating system size, while the other 19 houses were left without improvements. Measured data included space heating energy use, internal temperatures, boiler efficiencies, thermography surveys, air infiltration and leakage, etc., which are fairly common nowadays but were very pioneering at the time. Also, the project was used to test new technologies such as the Titon trickle vents (Jones & O'Sullivan, 1986) and low emissivity glazing (Jones et al., 1988).

The results of these studies had a major influence at the time, helping to define the UK's housing energy performance, the technology components design and the building regulations (Jones, 2012). The objective was to inform the UK Government about the best measures to reduce domestic energy use, hence to influence and modify the building regulations at the time, which by 1976 reduced U-values for walls from 1.75 to 1 W/m^{2}K and for roofs from 1.4 to 0.6 W/m^{2}K (HMSO, 1975).

In the 1970's, the newly designed town of Milton Keynes became a focus of attraction for architects of the green movement, where innovative ideas for low energy homes were tested (Burrows, 1987). The Bradville Solar House (1972) was the first in the UK with an active solar system (Mansfield, et al., 2010), which combined solar roof collectors integrated in the roof, a huge storage tank, a gas boiler and a room convector heater (Everett, et al., 1985). This research project aimed to establish the design parameters of a system that could be developed for a mass market, to estimate the costs of such a system and to develop a computer simulation of its performance (Fuller, et al., 1982). Even though it reached its design performance and contributed 56% of the space and domestic hot water demand, the high cost of the system led to a payback of over 50 years (Everett, et al., 1985).

In the late 1970's concern about the energy crisis was at its peak and it was clear that a more cost-effective low energy house with a shorter payback was needed. The Bradville Solar

House had revealed the economic strains of active solar heating systems and lead to an increased interest in passive solar design, which were more affordable because they did not rely on mechanical or electrical components (Fuller, et al., 1982). For example, the construction of the Linford Solar Court (1979) had an extreme approach to passive solar design and increased the building fabric specifications to much higher standards, with double glazing and high levels of insulation (Mansfield, et al., 2010).

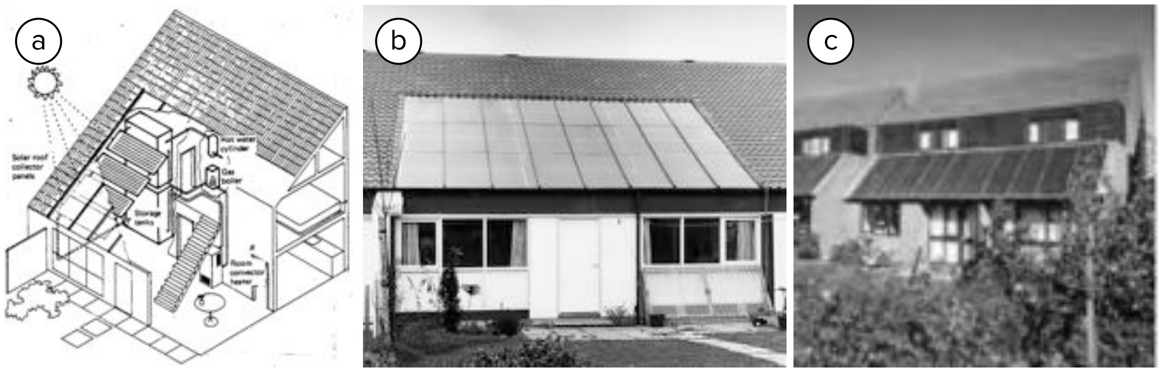


Figure 57 – Low energy arch.: a&b) Bradville Solar House. Source: RIBA c) Linford Solar Court. Source: NHBC.

While the UK was more focused on a 'climate rejecting' architecture with better insulation and airtightness to minimise energy exchange between buildings and their environment (Jones, 2012) (LaVine, 1992), the US and other European countries were leading another movement named 'solar architecture', that considered the integration of passive solar strategies and active solar technologies, hence focused on the benefits derived from solar energy (Tabb & Deviren, 2013). Many interesting examples of low energy houses with a systems-approach appeared at the time around the world.

In the US**,** the oil crisis even had a bigger impact stimulating policy reforms and research agendas, which resulted in a bigger interest in alternative energy sources, a growth in the green movement and an explosion of creative activity from both architectural and engineering disciplines. The term 'energy conservation' was originated to include a wide range of actions; for example, encouraging home occupants to turn down their thermostats in winter or to switch off their lights, installing photovoltaic panels in roofs and limiting driving speeds and car engine sizes (Owen, 1999).

This stimulation of the low energy architecture movement led to an increase on research focused on solar optics, thermal dynamics and high technology solutions (Tabb & Deviren, 2013). New research centres were created – i.e. Florida Solar Energy Centre (1974) and Solar Energy Research Institute in Colorado (1977) -, the world's first building heated and powered by solar and wind energy was built and the first amorphous silicon PV cells with an efficiency of 1.1% were created. In the later years of the decade, more architects were interested in low energy architecture and got involved in the development of solar architecture focusing on passive solar systems and active solar technologies. This growing interest resulted in some of the first off-grid unplugged buildings and solar communities, such as the Arcosanti housing development designed by Paolo Soleri and built in Arizona (Jenkins, 2011).

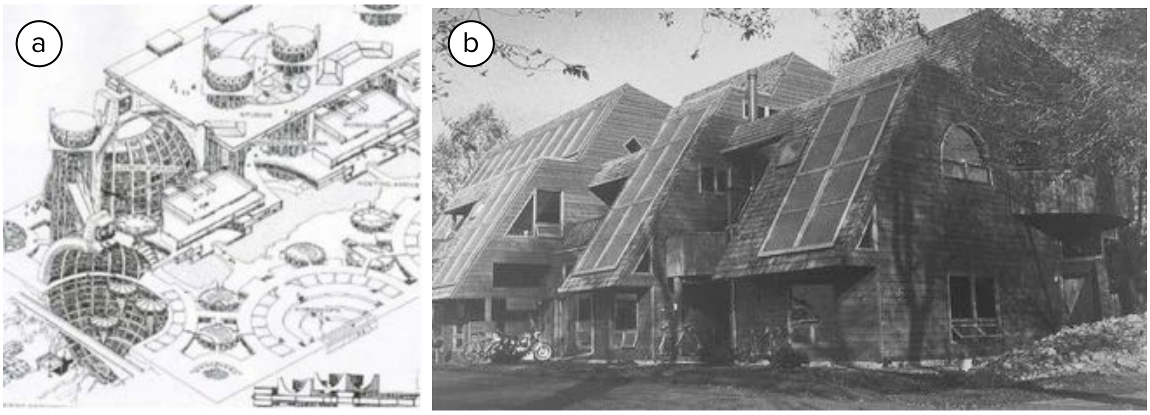


Figure 58 – Low energy architecture: a) Arcosanti plans. Source: (Jenkins, 2011). b) Student Housing project. Source: Tabb & Deviren, 2013.

In the first examples of active solar buildings, technologies were simply bolt into rooftops facing south to maximise generation. The main concern at the time was optimal efficiency, while quality of architectural integration, especially from formal and aesthetic point of view, were almost not considered. The majority of active solar buildings in the US tended to be commercial and institutional building types, however some examples of housing can be also found. For example, Joint Venture Architects designed the Student Housing project in Colorado (1975) with an active solar system of 75m^2 thermal solar collectors installed in the south facing roof that was capable of providing 70% of the energy demand for space and hot water heating. The project is a good example of how to deal with the compromise between the area needed for the opaque solar collectors and the area needed to guarantee enough daylight to the inside spaces.

The Zero-Energy House built in Denmark (1974) incorporated movable thermal insulation in front of windows, a device for the recovery of heat from exhaust air, a solar heating system consisting of 42m^2 of flat plate collectors and a 30,000l hot water storage tank (PHI, 2013). The Philips Experimental House built in Germany (1974), incorporated thorough thermal insulation of walls and windows, controlled air ventilation, heat recovery from exhaust air and waste water, utilization of heat pumps in various modes of operation, and utilization of solar energy by means of evacuated selective solar collectors (Bruno, et al., 1978). The Raven Run Solar House built in US (1974) designed as a cube sliced on the diagonal to maximise solar gains combined passive solar strategies, such as an attached greenhouse and louvered windows, with active technologies such as, solar air collectors for space heating connected to rock beds (bins of crushed stone) in the basement to store the heat for up to two weeks (Balies, 2014). While the design significantly reduced the need for main's electricity, it didn't eliminate it. But by 2009, the cost of PV panels so much affordable that a row of them was added on the garden shed to make the house net zero (Eblen, 2015). The Maison Solaire built in France (1979) for an Expo provided all the heating needs from solar energy by integrating PV and thermal collectors with a storage tank (Denzer, 2013).

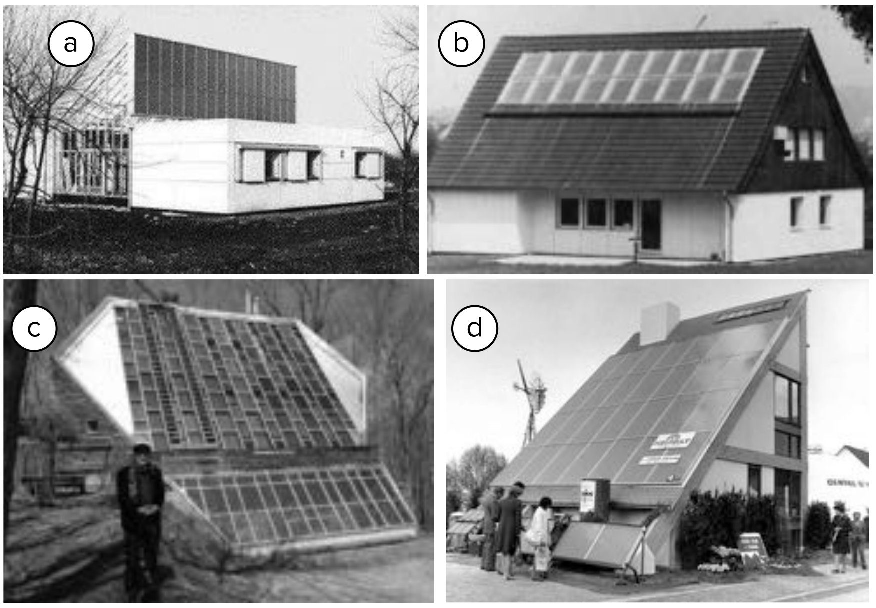


Figure 59 – Low energy architecture: a) Zero-Energy House, b) Philips Experimental House, c) Raven Run Solar House, d) Maison Solaire. Source: Passipedia.

Another house example worth to highlight is the House in Regensburg (1977) from Thomas Herzog. This elegant solar house built four decades ago is still today a unique and beautiful example of thoughtful, site-responsive architecture with integrated sustainable and passive principles to site, technologies and design. It has a glazed southern face, sloping roof for passive solar heat gains, natural limestone floor tiles for radiant heating, stilts to raise the house above the high ground water level and protect the beech trees and uses light-weight construction materials that blend with nature. Herzog's house, as his other projects, proofs the fact that creativity is not compromised by sustainability.

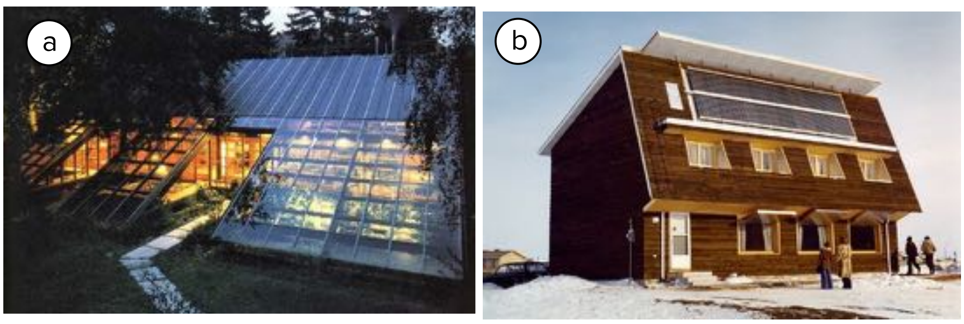


Figure 60 – Low energy architecture: a) House in Regensburg. Source: Thomas Herzog. b) Saskatchewan Conservation House. Source: greenbuildingadvisor.com.

Another big step forward in low energy architecture was the construction of the Saskatchewan Conservation House in Canada (1977) by the local Research Council (Besant, et al., 1979). This house, although forgotten for more than 30 years, attracted tens of thousands of people in the first couple of years (Huck, 2015) but was ignored by Canadian homebuilders and the Canadian public eventually forgot about it.

The Saskatchewan house is a two-storey house, rectangular in shape to expose a minimum amount of building fabric area, with a dark-brown cedar façade to increase the heat absorption from the sun and with very high standards of airtightness and insulation – i.e. 300mm of wall insulation instead of the typical 62mm at the time. In terms of energy systems, the house has a solar heating system that replaces the need for a boiler, energy-efficient kitchen appliances, a water-conserving toilet and also a heat recovery system for recycling hot water (Ralko, 2016). It represents one of the first examples of a house with a systems integrated approach to reduced energy demand, with higher levels of insulation and airtightness as well as energy-efficient appliances; renewable energy supply, with 17.9 m^2 of solar panels collecting and converting the radiation from the sun into heat and an air-to-air heat exchanger for ventilation; and integrated storage, with a large tank of 12,700l storing the heat in water for a later use to provide warm air and hot water as required by the occupants.

Thanks to this system approach (see Figure 61), the house was designed to provide 100% of its space-heating demand and achieved a remarkable 85% reduction on energy consumption (Besant, et al., 1979). Shurcliff (1981) presented the case study of the Saskatchewan House on his book *'Super Insulated Houses and Double Envelope Houses: A Survey of Principles and Practice'*, where he summarised the house's main cutting-edge design concepts as follows:

> 1. Truly superb insulation. Not just thick, but clever and thorough. (…)
> 2. Envelope of house is practically airtight. (…)
> 3. No provision of extra-large thermal mass. (..)
> 4. No provision of extra-large south windows. (…)
> 5. No conventional furnace. Merely steal a little heat, when and if needed, from the domestic hot water system. Or use a minuscule amount of electrical heating.
> 6. No conventional distribution system for such auxiliary heat. Inject the heat at one spot and let it diffuse throughout the house.
> 7. No weird shape of house, no weird architecture.
> 8. No big added expense. The costs of the extra insulation and extra care in construction are largely offset by the savings realized from not having huge areas of expensive Thermopane [windows], not having huge well-sealed insulating

shutters for huge south windows, and not having a furnace or a big heat distribution system.

9. The passive solar heating is very modest — almost incidental.

10. Room humidity remains near 50 per cent all winter. (...)

11. In summer the house stays cool automatically. (...)

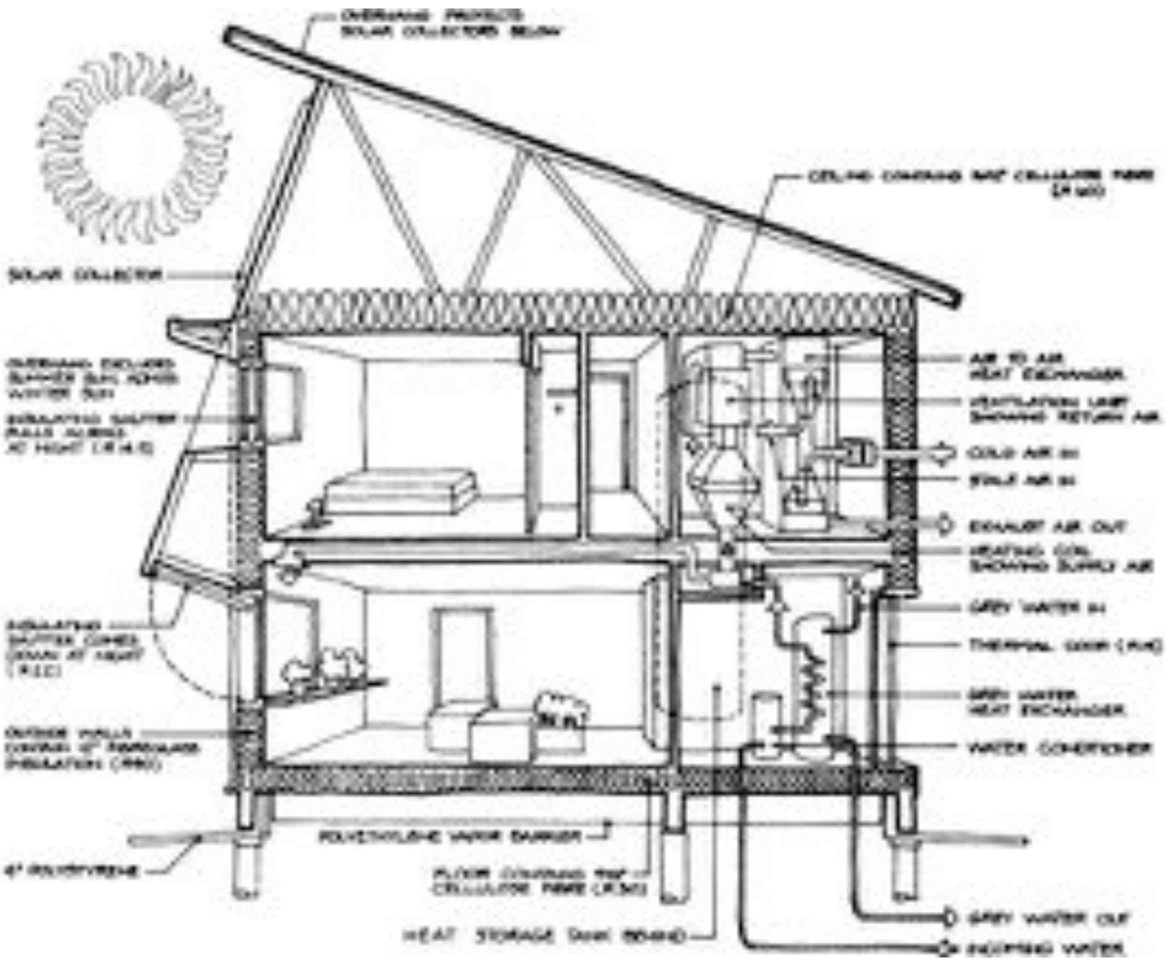


Figure 61 – Schematic showing the systems approach in Saskatchewan Conservation House. Source: Passipedia.

Although the world forgot the Saskatchewan house, eleven years later research by Wolfgan Feist, a German physicist who was interested in low energy architecture, created the Passivhaus programme that adopted many of the methods of energy conservation introduced in 1977 in the Saskatchewan house (Ionescu, et al., 2015). Feist adopted Shurcliff's list (1981), added a few more criteria and gave a name to the construction method, making it a successful 'fabric first approach' formula that has gone viral. Passivhaus is the fastest growing energy performance standard in the world with over 30,000 buildings having been built following its principles, the majority of those since 2000 with several projects completed in the UK (BRE, 2011).

A quotation from the architect and professor Piedmont-Palladino (1998) gives an indication of what was to follow after the 1970's low energy architecture movement:

> (…) The icons of the energy-conscious architecture of the 70's --- the single-slope roof with attached solar collectors, the Trombe wall, etc. --- became stigmas in the 80's as the reality of scarcity was obscured by the illusion of plenty.

2.4.6 1980's: PASSIVE ARCHITECTURE

In the 1980's, disposable income of British families improved and it was a period of economic boom and bust, entrepreneurship and innovation. There was also a big expansion in technical regulations associated with the construction sector, for example the vastly improved performance-based Building Regulations of 1985, which improved building fabric standards by reducing the U-values for walls from 1 to 0.6 W/m^2K and for roofs from 0.6 W/m^2K to 0.35 W/m^2K (HMSO, 1985). As national standards kept rising, owners of new homes were aware of the benefits of improved energy efficiency in construction methods and energy systems.

Although building energy modelling started back in the 1960's when ASHRAE published several papers from Mitalas & Stephenson examining heat transfer through walls (Haberl & Cho, 2004), it was not until the 1980's that CAD and energy modelling software became more popular and widely used by designers to test building's energy performance and to support the development of building energy standards (Tabb & Deviren, 2013). This decade witnessed the creation of the 'International Building Performance Simulation Association' (IBPSA) and the released of Autodesk AutoCAD (1982) and Microsoft Excel (1988), which is still used today as a modelling tool for custom situations (IBPSA, 2012).

The success of the post-modernism of the 1980's slowed down the momentum of the green architecture of the 1970's, which to a large extend utilised the language of modernism combined with the emergent renewable energy technologies of the time (Tabb & Deviren, 2013). Instead of solar exaggerated forms, which had become too predictable, rigid and inflexible, post-modern architecture looked back at the passive strategies of local vernacular forms and materials and found inspiration in historical references and the existing architecture of the place (Venturi, et al., 1972).

Although some may regard vernacular architecture as merely shelter in response to basic needs (Oliver, 1997), it could also be argued that vernacular architecture has also an empirical approach to construction that has allowed buildings to evolve through an intuitive, unconscious, absorbed and increasing knowledge acquired by trial and error of the making experience (Ionescu, et al., 2015). Moreover, vernacular architecture is also about the use of locally available resources and materials to address the occupants' needs, while allowing for a better integration of the building within its context and environment (Oliver, 1997).

According to Tabb & Deviren (2013), typical sustainable characteristics that describe well the post-modern vernacular domestic architecture of the 1980's include the following:

- Architectural forms and building elements that are climate responsive;
- Passive design strategies such as passive solar heating, good orientation, sun shading, spatial buffering or greenhouse effect;
- Optimised natural resources such as daylight, natural ventilation or solar radiation;
- Energy efficient technologies and appliances for heating, ventilation and control;
- Local, natural and low-embodied energy and materials;

In the UK, the concept of low energy architecture from the 1970's evolved including these newer strategies of passive design. Domestic buildings not only had good levels of insulation and airtightness driven by regulations, but also were designed to use solar energy as part of their heating and ventilation strategy, to optimise natural ventilation and daylight and to integrate thermal mass for heat storage and internal temperatures stability (Jones, 2012).

The UK Energy Technology Support Unit (ETSU), on behalf of the UK Department of Energy, sponsored from 1988 until 1994 a broad research project named 'Energy Performance Assessment' with the aim of first, accelerating the uptake of the design of low energy passive solar buildings through field trials on occupied buildings and second, to assessing the costs and benefits associated with incorporating passive solar principles within building design. The programme resulted in the energy analysis and evaluation reports of 30 case studies of different building typologies, which were all monitored to assess their energy saving potential, environmental performance and cost; for example, Jel's offices and factory building (Watkins, et al., 1990), Netley Abbey Infants' School (Baker & Steemers, 2000) or Spinney Gardens housing development (ETSU, 1990) to name a few.

The studies indicated that when considering solar heat gains, it was found that in winter the contribution from solar to heating load was between 10 to 30%, while in summer not all the contributions were useful and could even cause overheating discomfort. This revealed that as buildings incorporated more passive strategies, there was the need to respond quickly to heat gains from the sun and internal source with more responsive control of the heating systems, lower heating outputs during intermittent periods and more thermal mass of the building. Second, the additional cost of passive strategies ranged between 2% to 46% as a result of the redistribution of glazing or better thermal insulation to the design additions to glazing system and sunspaces. However, the analysis was undertaken with an additive approach only considering the cost of the passive strategies added to standard building costs. Future energy cost savings and the benefits of a holistic approach to design were not included in the analysis.

During the 1980’s a number of small and large-scale projects were developed based on passive solar design strategies. The new town of Milton Keynes, created as a way to address housing shortages in London in the 1960’s, hosted in 1981 the Homeworld 81 exhibition to attract investment from the private sector. This housing showcase brought together the best and latest ideas for domestic design in an exhibition village of full-scale homes (Stansell, 1981). Thirty-six houses were designed and built by international designers, architects and builders, who were invited to build houses that contained innovative features which could become common features in the next decade. Among the many innovations were homes with new shapes and styles; ideas to save energy and money; homes that could be built quickly; and homes that could reduce maintenance costs.

Figure 62 – Launch of the Homeworld 81 on the 30th April 1981. Source: (Stansell, 1981).

Four houses were of significant relevance within the 1980’s passive architecture movement because they showed that energy efficiency was a logical path (Fuller, et al., 1982). The Autarkic House (1981), a timber frame low energy house designed to be easy to build, extendable and self-sufficient with both passive and active energy systems (Littler, 1979). The Ideal Home (1981), a solar house with integrated solar thermal panels linked to a thermal storage system made of a chemical phase-change salt and a triple glazed south-facing wall forming a double height conservatory (Stansell, 1981). The Futurehome 2000, with active solar panels on the roof and an integrated solar conservatory space to warm the air that then was driven with fans inside the house. And the Greenwood House, a house with a pyramid shape, ventilation system, high levels of insulation and passive solar gains on its south-facing conservatory.

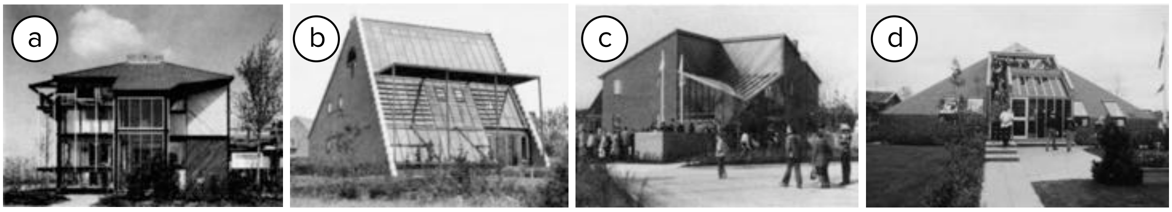


Figure 63 – Passive architecture: a) Autarkic House, b) Ideal Home and c) Future Home 2000. Source: (Fuller, et al., 1982). d) Greenwook House, source: Greenwood homes.

Also, in Milton Keynes, the Rainbow Housing Cooperative Conservatory (1980) retrofit involved the thermal upgrading of a Victorian home with a new active solar element. At a larger scale, the Great Linford Summerhayes Project (1980) consisted of eight houses built with high levels of insulation that were highly monitored to develop a better understanding of energy flows and occupancy houses; the Pennyland Project (1981)**,** an entire low energy development of 177 houses with passive solar low energy design aiming to raise awareness of the benefits of this type of construction within the mass-market; the Two Mile Ash Development (1983)**,** with four timber framed houses featuring extremely low space heating and with a financial revenue within just two years; and the Giffard Park Housing (1984)**,** a smaller development of 33 flats and houses with solar panels and 75% south facing glazing and conservatives that allowed for a 60% reduction of space heating demand. All these residential developments demonstrated that low energy homes were interesting for and could be sold to the private sector (Fuller, et al., 1982)

The growing activity of the 1980's green architecture movement resulted in many research publications, energy reports and design guidance handbooks being published. British publications included the design guidance *'Exploiting sunshine in house design'* published by BRE in 1988, which established the main design principles of solar passive architecture; and the report *'Low energy houses'* which published by ETSU in 1985, described in detail the Great Linford project and considered design, energy consumption and use, energy savings, cost effectiveness, marketability, thermal performance, fabric heat loss, infiltration and ventilation, solar gains, heat gains, energy balances, comfort conditions, heating systems and controls, and monitoring and data collection systems. Figure 64 shows the methodology used for the design of the Great Linford Project and the influence that early design decisions have on a systems-approach building. A new housing standard, the Milton Keynes Energy Cost Index (MKECI), was created in 1985 based on data gathered from the Pennyland and Great Linford housing projects. The MKECI was a single figure rating generated from a computer programme that took as input the size, aspect and occupancy of a house, together with full details of the building fabric – i.e. window areas and glazing, insulation (roof, walls and floor) – and the technologies – i.e. lighting and central-heating system (Milton Keynes Development Corporation, 1985).

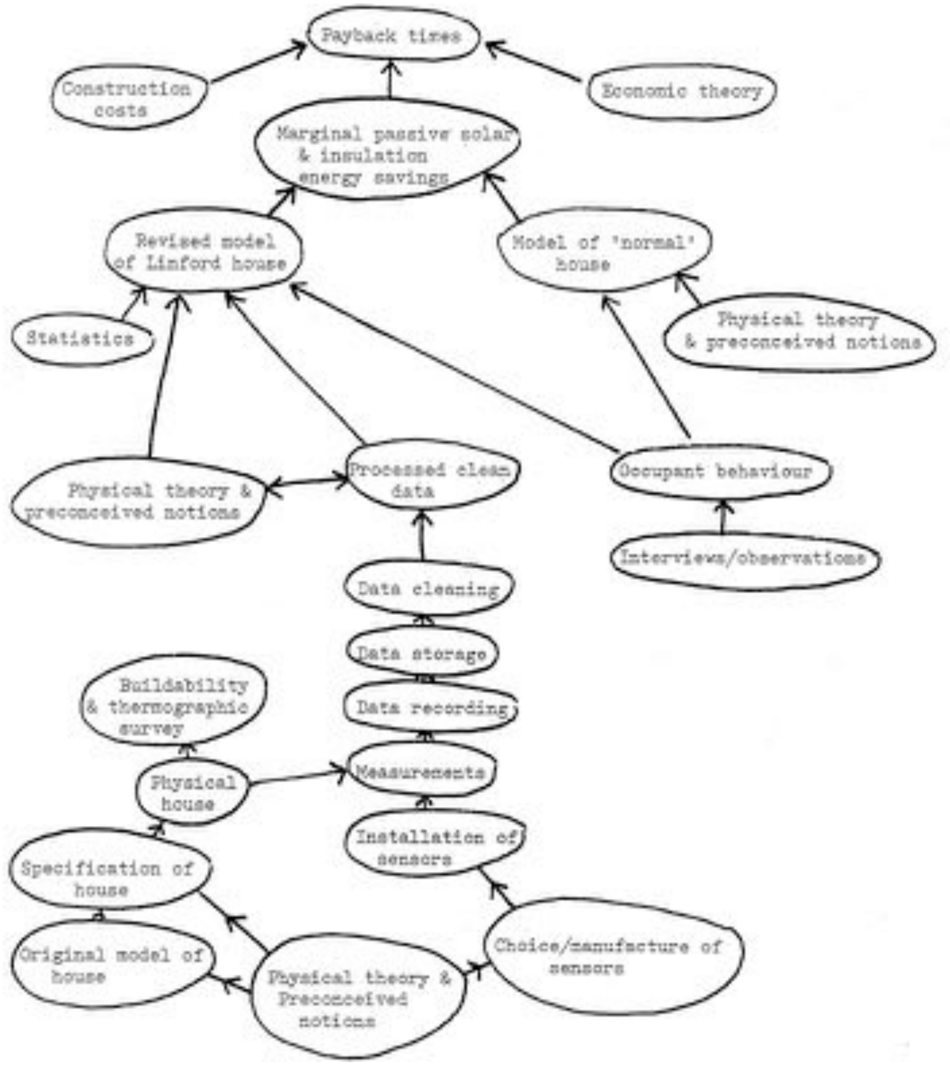


Figure 64 – Diagram showing the Great Linford Project methodology (Everett, et al., 1985).

Passive solar design was even more relevant outside the UK in regions where the climate was more favourable. In Australia, the Magney House (1984) was designed to adapt to the local hot-dry climate thanks to its vaulted butterfly roof that allowed for rainwater collection, solar protection and natural ventilation (Craven, 2017). In Washington, a more vernacular approach was used in the Hansen Residence (1980) with an earth-sheltered design and in the Bridge House (1987) with an integrated design to the site and a south orientation for passive solar (Cutler , 2008). At the end of the 1980's the awareness on passive design had increased and the main strategies of passive design were applied on a number of large scale projects. Sometimes referred as 'solar communities', these were urbanely designed to guarantee solar access at a whole-site scale (Jones, et al., 2009). For example the Pefki Solar Village (1984) in Greece with 465 dwellings intended to demonstrate that solar houses did not have to differ from conventional ones (Croxford & Kalogridis, 2006); the Linz Solar City (1989) in Austria introduced a policy of low energy social housing (Breuste & Riepel, 2005), and the Albertslund City in Denmark, which is an example of experimental urban and traffic planning (Vestergaard & Holt, 2010).

Figure 65 – Passive architecture: a) Magney House, source: Bellevarde Constructions. b) Bridge House, source: Cutler Anderson Architects; c) Pefki Solar Village, source: ellinotexniki.com.

Another trend that emerged during the 1980's was the re-use and recycling of existing buildings with new purposes and contemporary uses. The conservation trend included restoration, which focused on the preservation of the historic features while removing irrelevant materials from other periods; rehabilitation, which focused on repairing the most historic elements; and reconstruction, which considered upgrading existing buildings with newer materials and features to meet present construction standards and higher energy performance levels. Conservationists argued that by re-using and upgrading existing buildings, the amount of embodied energy and resources required was between 30 to 50% less than that used during new construction (Stein, 2010).

It is important to mention the publication of '*Our Common Future'* in 1987, which marked a breakpoint in thinking on environment, development a governance (Sneddon, et al., 2006) and included Brundtland's definition of sustainable development as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

2.4.7 1990's: SUSTAINABLE ARCHITECTURE

The holistic approach to environmental problems introduced by the Brundtland Commission led to an increase of interest in sustainability from society and governments. A direct result was the Earth Summit I held in 1992 in Rio, Brazil, which brought together an unprecedented number of countries to reach consensus about problems associated with the environment and development (Sneddon, et al., 2006). Many important international agreements emerged from the Summit, including the *'Agenda 21'* and the *'Framework Convention on*

Climate Change', the most directly related with architecture (Williamson, et al., 2003). The impact of the event was so big that sustainable development became the focus of attention of architects and the Union of International Architects (UIA) declared in their World Congress meeting in 1993 that all design professionals should commit to sustainable design, hence sustainable architecture should become standard practice (Kubba, 2016). Maxman and Majekodunmi, presidents of the American Institute of Architects and the UIA respectively, wrote in 1993: "Sustainable architecture isn't a prescription. It's an approach, an attitude. It shouldn't really even have a label. It should just be architecture" (Guy & Farmer, 2001).

The 1990's were also a period of technology evolution; advances in building technologies were not only apparent in the construction methods, but also in the designing process. For example, interest in construction materials led to the appearance of higher transparency levels, new lightweight materials or evolved glazing systems like low-emissivity glass; while at the same time the advancement of computer-aided design (CAD) software enabled architects and engineers to work together enhancing building modelling that reduced the risk with design and creating complex structures and forms that would have been unachievable in the past. As a result, architects' attention was now focusing on the detailed design of the building elements, such as materials, structure, mechanical systems, building services or joinery. On the other hand, it was also when Internet and Mobile Telephone Services were introduced which, among many other impacts, highly benefitted the share of research-based precedents of sustainable design and also the communication capabilities of off-grid building sites. Moreover, with the commercialisation of PV and wind turbines, renewable energy become widely available and affordable (IRENA, 2012), allowing for energy self-sufficiency to off-grid remote sites (Jenkins, 2011).

Sustainable technologies were less considered an ugly add-on fixed element of the building (Sütterlin & Siegrist, 2017), instead they were integrated as more dynamic elements part of a new sustainable system. It was a hybrid approach to design, in which energy technologies were used as active elements to generate energy but also as passive elements aiming at specific on-site resources, or new lightweight materials and glazing systems were combined with natural materials to provide more insulated and heavier building envelopes (Tabb & Deviren, 2013).

This type of high-tech sustainable architecture was more popular with large-scale building typologies, such as airports, train stations or sports stadiums (Tabb & Deviren, 2013); however, also some relevant examples of housing appeared at the time. For example, in Germany the Solar House (1992) was a complex and sculptural juxtaposition of architectural volumes, renewable energy components and passive sun shading elements (Weston, 2002).

In the US, the Casey Jacal Retreat (1997) was built with locally available materials – i.e. limestone and cedar wood – and designed to be off-grid with a PV system with battery storage used to provide electricity and heat water, a passive solar heating system, a fireplace, a composting toilet and a 20,000 litres rainwater cistern (Ryker, 2005).

Figure 66 – Sustainable architecture: a) Solar House, source: Abberville Press. b & c) Casey Jacal Retreat, source: Lake Flato Architects.

Engineers and architects were working together, and the critical interaction between architecture and technology enhanced the need to establish a more methodical approach to sustainable architecture where a holistic approach to materials, energy systems, human comfort, site response, etc. could be well evaluated. This prompted the introduction of methods of assessing, rating, and certifying the sustainability of buildings; such as the British 'Building Research Establishment Environmental Assessment Method' (BREEAM), the American 'Leadership in Energy and Environmental Design' (LEED), EarthCraft House, Energy Start and Green Building, and the German Passivhaus standard. Heincke & Olsson (2012) and Zhang et al. (2017) provide an overview and compare the key energy certification systems. Among all of them, the German Passivhaus standard became the most accepted and used energy performance standard at the time across the world (International Passive House Association, 2017). The success of the Passivhaus was a result of the simplicity of its concepts and methods, which are summarised as follows:

- Very high levels of insulation in walls, roofs and floors, and extremely high-performance windows with triple glazing.

Table 4 – Comparison of the Passivhaus (BRE, 2011) and UK Building Regulations (HMSO, 1995) standards in the period of the 1990's.

	Passivhaus	**UK Building Regulations (1995)**
Walls U-Value	0.08 - 0.15 W/m^2K	0.45 W/m^2K
Floors U-Value	0.10 - 0.15 W/m^2K	0.35 - 0.45 W/m^2K
Roofs U-Value	0.08 - 0.15 W/m^2K	0.20 - 0.25 W/m^2K
Windows U-Value	0.85 W/m^2K	3 - 3.3 W/m^2K

- Air tight building fabric, with values below 0.6 air changes / hour at n50. At the time, the UK's Building Regulations did not require that dwellings were testes for air tightness.
- Thermal bridge free construction details, which avoid the risk of increased heat loss, surface mould or even condensation.
- Mechanical ventilation system with at least 75% efficient heat recovery (MVHR) and with a fan power of less than 0.45Wh/$m^{3.}$
- Solar gains are managed and optimised to exploit the sun's energy for heating purposes in the heating season and to minimize overheating during the cooling season.

In the UK**,** the 1990's were a time of transition for the housing sector. The economic and housing bubble of the 1980's burst in 1991 resulting in negative equity for many families and in high levels of housing repossession. As a result of the housing crash of 1991, the British green architecture movement did not get very involved with the exciting sustainable tech architecture and the Passivhaus movement that were appearing in America and Europe. Local Authorities were replaced by Housing Associations as social housing providers due to the 'Right to Buy' scheme introduced in the 1980's (Disney & Luo, 2017). Technical information improving the design quality of housing continued, with new technical standards such as UK Building Regulations (1991) and NHBC Standards (1992); the publication of *'BRE housing design handbook: Energy and internal layout'* (BRE, 1993); the establishment of new institutions like the Commission for Architecture in the Built Environment (CABE) (1999); and the introduction of the **'**Standard Assessment Procedure' (SAP) (1992) as a new method to assess and compare the energy and environmental performance of dwellings;

2.4.8 2000's: LOW CARBON ARCHITECTURE

By 2000, the greening of architecture had proliferated globally with a broader and larger range of programmes and considerations. Sustainability, which now included buildings, communities and urbanism, considered greater levels of integration and complexity of renewable energy technologies and environmental design strategies. This is well explained in the book *'Green Architecture: the art of architecture in the age of ecology'* from James Wines (2000). By the time, a wide range of experience, knowledge and diversity had been accumulated regarding green architecture, and a huge amount of green technologies and materials, able to respond to the complex contextual and ecological integration of a residential building into a given place, had been developed. Vernacular, modern, tropical, environmental, low energy, passive, solar and sustainable approaches focus on a broad variety of green measures that every day become more integrated into the language of building design and more effective at increasing sustainability.

At the turn of the new century, the increased evidence of global warming, the wide scale of climatic incidents and the rising price of fossil fuels; together with evidence about a worsening environment, revitalised the interest in the green movement (Tabb & Deviren, 2013). The possible causes of global warming such as carbon emissions from the combustion of fossil fuels and methane emissions and the use of chemical fertilisers in large-scale agriculture became the main focus of attention and, as a consequence, green architecture incorporated newer and greater considerations on urbanism, ecology and scale. The scope for green architecture find solutions to this wide range of problems and concerns mostly related with carbon emissions, thus green architecture could now be named low carbon architecture aiming to reduce carbon emissions by incorporating sustainable measures and technologies on multiple levels and scales.

Increasing environmental concerns led to the creation of several energy conservation directives, policies and initiatives worldwide and nationally, especially in the energy and built environment sectors. In Europe, one of the main drivers on energy efficiency of buildings was the European Parliament Directive 2002/91/EC on Energy Performance of Buildings (EU, 2003), which required to establish calculations of buildings energy performance to comply with national targets. All member states needed to turn the directive into national law by 2006, but only by 2009 most of the countries had achieved it with many difficulties and variations in approach (Jones, et al., 2009). As a result of the European Directive, most countries started encouraging higher energy efficiency and reduced CO_2 emissions by raising their mandatory requirements through national building regulations (Bell, 2004). For example, in the UK the *'White Paper'* issued by the UK Government (2003) established that the UK should reduce CO_2 emissions by 60% from current levels by 2050 and by 80% by 2100. This was turned into changes on the *'UK Building Regulations 2000'* with a new Part L *'Conservation of fuel and power'* in the 2006 edition that set out the requirements of energy efficiency of different types of buildings, implemented the calculation methodology as a central part of demonstrating compliance (Anderson, 2006), and maintained the 2002's U-values levels to 0.35 W/m^{2}K for walls, 0.25 W/m^{2}K for roofs and 0.22 W/m^{2}K for floors (HMSO, 2006).

In December 2001, WWF-UK invited the UK Government to make a public commitment to develop one million sustainable homes, including new build and retrofit of existing houses (WWF-UK, 2002). This was an unprecedented approach of using policy as a main driver to reduce energy use from the residential sector. The first challenge was to agree on the definition of 'sustainable home'. In 2002, the EcoHomes standard was introduced as an environmental rating scheme for the UK's homes – i.e. new build and retrofit. The scheme, developed by the Building Research Establishment (BRE, 2006), considered 8 different areas – i.e. energy, transport, pollution, materials, water, land use and ecology, health and wellbeing, and management – and rated them to finally designate the home as 'Pass, Good, Very Good or Excellent' providing a mechanism of comparison and a benchmark.

Although the EcoHomes standard was improved on four occasions, in 2007 the '*Code for Sustainable Homes'* (CSH) was introduced to replace it, aiming to enhance the overall environmental performance of only new dwellings. The CSH measured the sustainability of a dwelling against 9 different design categories – i.e. energy, water, materials, surface water run-off, waste, pollution, health, management and ecology. (DECLG, 2010). Again, the CSH recognised environmental parameters other than energy use and CO_2 emissions, and each was awarded with points so the whole home was rated with a final score, from 1 to 6.

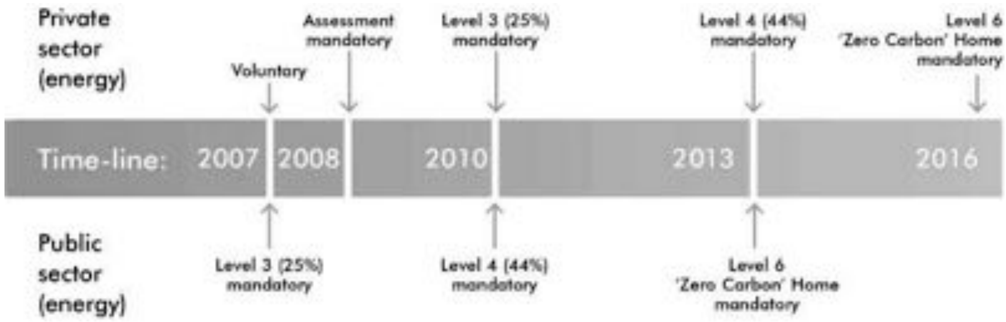


Figure 67 – Diagram showing the CSH Route Map (DECLG, 2006).

The CSH Route Map (see Figure 67) established that Level 6 would become mandatory by 2016, thus all new houses would have to be net zero carbon (DECLG, 2006). A net zero carbon house was defined as "one house whose net lifecycle CO_2 emissions are negative or equal to zero over one-year period" (DECLG, 2010). The emissions of CO_2 linked with buildings' lifecycle were evaluated in three phases: production, use and end of life. The majority of the UK's mitigation policies refer to the use stage only (Bows, et al., 2006) because it represents the majority of a buildings' carbon footprint (BERR, 2008). However, there are significant CO_2 emissions involved in the initial production of materials and construction of a building that should not be dismissed in a whole building assessment.

By 2009, SAP had become the UK Government's recommended method for measuring the energy rating of residential buildings (BRE, 2016), by complying with Part L (or equivalent) of the BR and also with the CSH. The SAP tool considered the energy associated with a dwelling's main characteristics – i.e. materials, ventilation, water and space heating and lighting – and assumed a standard typical occupancy use (BRE, 2016). Also, in 2009 the book *'A Handbook of Sustainable Building Design & Engineering'* (Mumovic & Santamouris, 2009) explained the principles behind low carbon design and offered a practical guidance through international case studies.

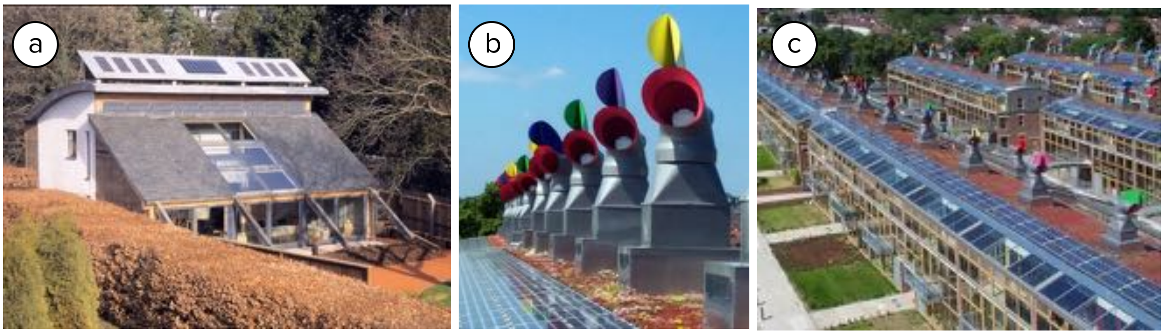


Figure 68 – Low carbon architecture: a) House for the Future. Source: Jestico+Whiles. b & c) BedZED project. Source: Inhabitat.

The increased attention on green benchmarks and standards from the UK's institutions and government bodies had a significant impact on the British housing projects of the 2000's. For example, in 2000 the House for the Future was built with the aim of showing the latest green technologies – i.e. earth block, green roof, sheep's wool and cellulose fibre insulation, ground source heat pump, biomass stove, roof-mounted solar thermal collectors, ridge-mounted wind turbine or a PV array – within a £120,000 budget, but finally the cost spiralled and users were not content with its smart computer control approach (Mourby, 2001). In 2001, the Beddington Zero Energy Development (BedZED) housing development was completed featuring 89 energy efficient dwellings and 2,500m^2 of mixed-use space for commercial, workspace and offices (Marsh, 2002). Low carbon design strategies at the building scale included solar PV, thermal mass, passive ventilation stacks with heat recovery, water saving and the use of ecological materials (Smith, 2005); while at the community scale other issues like green travel, food supply and community facilities were also included (Jones, 2012). Although the project was very high profile amongst the supporters of the green movement, it did not have a significant impact on the mass housing sector. Firstly, it was ignored by the housing industry who considered it as an "unnecessary inconvenient challenge" (Jones, 2012); and secondly, some of the systems were too new to the market, experienced some problems and did not perform according to their initial expectations (Tabb & Deviren, 2013).

Another important attempt to motivate the housing sector was the Renewable House Programme (RHP), a £6.7 million programme funded by the UK Government through DECC from 2007 until 2010. The programme investigated how natural renewable materials could be used in mainstream social housing projects. Woolley (2013) in his book *'Low impact* *building'* analyses in detail the 12 case studies of the programme, considering their construction, buildability, environmental assessment, design, performance, carbon-footprint and post-occupancy issues. The author describes the problems and obstacles that had to be overcome to gain wider acceptance of genuinely environmental construction methods.

Figure 69 – Low carbon architecture: a) Lammas Project, source: The Guardian, b) Hockerton Housing project, source: (Hockerton Housing Project, 2016) and c) Springhill Cohousing, source: (Architype, 2016).

At a bigger scale, the Lammas Project (2009) in Wales consisted of 9 traditional rural smallholdings built with the latest innovations in environmental design and permaculture, using a variety of low impact building methods and capable to be off-grid for most of the year. For example, electrical power is generated from a series of micro PV installations along with a 27kW hydro generator, heating is supplied from burning timber, domestic water comes from a private spring and other water needs are predominantly met from harvesting rainwater. Even though their energy consumption and environmental impact was very low (Lammas, 2016), the developers faced many difficulties with the authorities because some of the materials and methods used – i.e. natural earth and timber structure – did not comply with energy efficiency and building regulations (Woolley, 2013). Other relevant green community scale projects built during the 2000's include Hockerton Housing project (2002), with five earth-sheltered homes with renewable energy, water systems, food grown on site and green transport (Hockerton Housing Project, 2016; Smith, 2005); and Springhill Cohousing (2004), the first low carbon new-build cohousing scheme in the UK with 35 dwellings, shared outdoors, transportation and cooking facilities (Architype, 2016).

Meanwhile in Europe, one of the most relevant initiatives for low carbon architecture and housing was released in 2008, when the European Union Parliament developed a resolution entitled *'Action Plan for Energy Efficiency: Realising the Potential'* (European Parliament, 2008). This Action Plan joined various aims of the European Commission: "Calls on the Commission to propose a biding requirement that all new buildings needing to be heated and/or cooled be constructed to passive house or equivalent non-residential standards from 2011 onwards; and a requirement to use passive heating and cooling solutions from 2008" (European Parliament, 2008).

In the US, the Department of Energy organised the first Solar Decathlon in 2002, an international competition that takes place every two years and challenges twenty international university teams to design, construct and operate the most attractive, affordable, effective and energy efficient solar powered house.

Figure 70 – Solar Decathlon winning projects: a) Year 2002, source: (US Dept. of Energy, 2003), b) Year 2005, source: (US Dept. of Energy, 2005), c) Year 2007, source: Research for Energy Optimised Building, d) Year 2009, source: (US Dept. of Energy, 2010), e) Year 2011, source: Inhabitat, f) Year 2013, source: Inhabitat and g) Year 2015, source: (US Dept. of Energy, 2015).

The competition aims to stimulate the market by providing training to the supply chain, improving research on building science, fostering innovation in whole-building design, and educating and disseminating ideas to building professionals and the public sector (Farrar-Nagy, 2013). As a result of the success of the American event, Europe (since 2007) and China (since 2011) hold Solar Decathlons. Many interesting house designs have been built throughout the history of Solar Decathlon competition (see Figure 70), however only the winners are highlighted in the following list:

- Solar American House (2002) – By the University of Colorado, the team wanted to prove that solar energy could work and look good in any house. The main guiding principles were commercially availability of all the used technologies, mass-production of the house model and public acceptability rather than maximum solar energy generation. As a result, they designed a typical American home with a systems approach that integrated supply consisting of 7.68kWp PV system for electricity generation and 12 evacuated tube solar collector for hot water, storage consisting of a lead-acid battery bank and a 300l hot water tank, and reduced demand consisting of a highly insulated building fabric made of SIPs panels and an air source heat pump with energy recovery ventilation for space heating and cooling. (US Dept. of Energy, 2003).

- BioS(h)IP House (2005) – Designed by the University of Colorado, Denver and Boulder, the house was built using low to no petroleum natural materials, such as a new SIPs system named BioS(h)IP; and also featured an integrated systems approach with a radiant solar thermal system used for space and water heating and a 7KWp PV system connected to a battery storage which sustained the house and its electric loads even during the rainy season (US Dept. of Energy, 2005).
- Made in Germany House (2007) – Designed by Technische Universität Darmstadt, the house is all designed and built with German materials and technologies and combines both high-tech active solar i.e. – sliding PV shutters and integrated PV panels and solar thermal panels in the flat roof – and low-tech passive solar components into a smart operable building envelope (US Dept. of Energy, 2008).
- SurPLUShome (2009) – Designed by Technische Universität Darmstadt, the house is a two-storey cube that integrates an 11kWp PV system made of 40 mono-crystalline panels in the roof and 250 thin film panels on the facades capable of generating 200% of the energy needed in the house. To reduce energy demand, a boiler was integrated into the heat pump system providing hot water as well as heating and cooling, while the fabric's energy efficiency was improved with new technologies such as vacuum insulation structural panels, phase-change materials in both walls (paraffin) and ceilings (salt hydrate) and automated louver-covered windows to block undesirable solar gains. The cost of the house was on the range of $650,000 to $850,000 (US Dept. of Energy, 2010).
- WaterShed (2011) – Designed by the University of Maryland, the house features a holistic approach to water conservation, recycling and storm water management; an engineering system that collects excess energy generated by the solar thermal panels and an automation system that monitors and adjusts temperature, humidity and lighting parameters to guarantee comfort (US Dept. of Energy, 2012).
- Lisi House (2013) – Designed by the Vienna University of Technology, the house is for two people to live in communion with nature thanks to the two patios that organise the space, thus creating a balance between inside and outside. The house has two high-efficient air-water heat pumps that supply cold and hot water for space and cooling as well as domestic hot water, an energy recovery ventilation system, a subfloor system to

regulate indoor climate, and a heat-recovery shower tray; all of these systems are linked and controlled together through a tablet app and are powered by a rooftop solar PV system that generates more power than it uses over the course of a year. The design is guided by a vision for a healthy, sustainable future and a concept that could adapt to many lifestyles and climates (US Dept. of Energy, 2014).

- Sure House (2015) – Designed by the Stevens Institute of Technology, the house is both SUstainable and REsilient: hurricane-resistant with fibre composite shutters that allow it to be sealed up in an emergency, ultra-efficient building fabric exceeding Passivhaus standards with 90% demand reduction, open plan to let air and sunlight in, and solar-powered. The house is based on three principles: use less energy with smart design, generate all energy needed with renewable solar electricity, and be capable of providing power during electrical outages. As a result, it has an islanding PV array capable of producing energy even when the utility grid is damaged or disconnected, powering the house and its hybrid heat pump with hot water tank, and allowing neighbours to charge their electronic devices (US Dept. of Energy, 2015).

On the other hand, a good collection of more than 40 green housing case studies were published under *'Task 28: Sustainable Solar Housing'* as part of the Solar Heating and Cooling Programme by the International Energy Agency (2007). Each case study report includes information about the project, objectives, floor plans, building materials, building fabric specifications, technical systems schematics, energy performance, cost, etc. Table 5 summarises this information for the 22 projects that are relevant due to their integrated systems-based approach. The main highlights are:

- Around 64% of the case studies were located in Europe. However, Japan was the country with more examples, 6 out of the 22, followed by Germany with 5.
- In regions where heating was the major concern – i.e. UK, Austria, Germany, Holland and Switzerland – the average building fabric U-values were 0.15W/m^{2}k (walls), 1.08 W/m^{2}k (windows), 0.18W/m^{2}k (floors) and 0.13 W/m^{2}k (roofs); all within or very close to the Passivhaus standards criteria. Oppositely, Japan's case studies had much higher U-values and focused less on the demand reduction from the building fabric.
- The most popular technologies were MVHR systems and DHW thermal tanks, which were present in 82% of the projects, followed by thermal solar collectors (77%), and solar PV panels (50%).

- When considering heating systems, air source heat pumps (36%) were the most widely used followed by gas boilers (23%), ground source heat pumps (18%), wood fire stoves (18%), CHPs (4.5%) and biomass boilers (4.5%).
- Regarding the systems-based approach; the Vancak House (2003) and the Minergie-P House (2003) integrated 6 technologies within their respective energy systems, much more than the total average of 3.86 technologies per system.
- The case study with an overall better performance was the Plus Energy House (2001) in Austria, with a significantly low total energy demand of 12.8 KWh/m2 and only 5.9 kWh/m2 of heating and ventilation energy demand.

Table 5 – Summary of the case studies of the Sustainable Solar Housing Task 28 report that have an integrated systems-based approach. Data source: (International Energy Agency, 2007).

House Name	Location	U-Values (W/m²K)				Demand (kWh/m²)			Technologies									
		Walls	Windows	Floor	Roof	Total	Heating & ventilation	DHW	Them. Coll. (m²)	PV (kWp)	Ground source HP	Air source HP	MVHR	Gas boiler	Biomass boiler	Wood stove	Thermal tank	CHP
Integer (1998)	UK	0.2	2.16	0.35	0.2	-	-	-	3	✓	✓	x	x	x	x	x	✓	x
Zero-Heating (2000)	UK	0.12	1.1	0.14	0.12	-	-	-	✓	x	x	x	✓	x	x	✓	✓	x
Plus Energy (2001)	Austria	0.11	0.79	-	0.11	12,8	5.9	2.75	17	10	x	✓	✓	x	x	x	x	x
Passiv (2004)	Austria	0.11	0.78	-	-	-	14	2.5	22	3	x	x	✓	x	✓	x	✓	x
W (2002)	Czech Rep.	0.19	1.39	0.25	0.17	-	-	-	8	x	x	x	✓	x	x	7	✓	x
Vancak (2003)	Czech Rep.	0.12	1.1	0.27	0.11	29	12	34	5	x	✓	✓	✓	x	x	9	✓	x
Ultra-low energy (1996)	Germany	0.19	1.4	0.14	0.17	84.1	20	11.4	12	1	x	x	✓	✓	x	x	✓	x
Passive (2000)	Germany	0.13	-	-	0.10	-	15	-	✓	x	x	✓	✓	x	x	x	✓	✓
3-Litre Town (2001)	Germany	0.15	1.6	0.31	0.18	66.3	33.5	32.8	x	x	x	x	✓	✓	x	x	✓	x
3-Litre Twin (2003)	Germany	0.2	0.8	0.11	0.08	-	23	16	5	x	x	✓	✓	x	x	x	✓	x
3-Litre Urban (2003)	Germany	0.2	0.8	0.15	0.14	-	18.3	19.9	x	x	x	✓	✓	x	x	x	✓	x
Zonhuizen (2000)	Holland	0.11	0.68	0.11	0.12	119	25	15.1	4	x	✓	✓	✓	x	x	x	✓	x
Casco-zonnew. (2001)	Holland	0.2	-	0.14	0.17	73.2	51.9	4	x	✓	x	✓	x	✓	x	x	x	x
Archidome (2001)	Holland	0.12	-	0.14	0.12	117	15	21.9	✓	✓	x	x	✓	x	x	x	✓	x
Minergie-P (2003)	Switzerland	0.15	0.8	0.12	0.07	-	13.3	13.7	✓	x	✓	x	✓	x	x	✓	✓	x
Minergie-P (2003)	Switzerland	0.11	0.74	0.11	0.11	-	12.5	13.6	✓	✓	✓	✓	✓	x	x	x	✓	x
Daiwa (2002)	Japan	0.88	2.91	0.52	0.24	-	-	-	✓	3	x	x	✓	✓	x	x	✓	x
OM Solar (2002)	Japan	0.59	3.49	1.85	0.31	-	-	-	✓	✓	x	x	✓	x	x	x	✓	x
Okamoto Solar (2003)	Japan	0.27	1.5	0.29	0.13	70.9	12.1	8.9	✓	x	x	x	x	✓	x	x	✓	x
By the river (2003)	Japan	0.45	1.64	0.32	0.22	90	27.4	6.4	8	x	x	x	x	x	x	x	✓	x
Hybrid-Z (2004)	Japan	0.38	2.55	1.00	0.48	39	12.3	9.2	x	11	x	x	✓	x	x	x	x	x
Low energy (2004)	Japan	0.5	3.49	0.44	0.23	-	-	-	x	4	x	x	✓	x	x	x	x	x

Finally, the concept 'ecological footprint' originated in the 1990's derived into the concept of 'carbon footprint' to easily measure the use of carbon as an indicator of unsustainable energy use (US Environmental Protection Agency, 2016). The definition of the concept carbon footprint in 2007 as "a measure of the total amount of carbon dioxide (CO_2) and methane

(CH_4) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest" (Wright, et al., 2011) helped to strengthen and promote the idea of low carbon architecture as an architectural approach to design, construction and operation of buildings with a reduced carbon footprint.

2.4.9 2010's: NET ZERO ENERGY ARCHITECTURE

In previous decades, green architecture focused on renewable energy technologies and the design measures needed to add or integrate them into the building design. While this is still relevant nowadays, most recent green architects that have emerged during the last decade seem to be more ambitious and are not content with only having a low impact on the environment. Instead, targets are quantified by introducing the expression 'zero energy', which suggests independence, self-sufficiency or no cost (Voss & Musall, 2013).

In 2010, the European Commission introduced the term 'nearly zero energy building' and defined it as "a building that has a very high-energy performance (…). The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (European Commission, 2010). The directive also specified the time scale of the implementation of the nearly zero energy standards, with a deadline of 2018 for new-buildings occupied and owned by public authorities and 2020 for all other new buildings. However, the term was very ambiguous and lacked authority. "How close 'Nearly Zero' to 'Zero' should be?" was a question open to interpretation that still remains unanswered.

The question raised awareness on the subject and triggered the introduction of a greater variety of terminology aiming to define better the challenges and targets of green architecture for this decade. In the UK, the 'zero carbon' term was used to define buildings with zero CO_2 emissions to the atmosphere (Jones, 2012). In Germany, the terms 'zero emission' or 'climate neutrality' reflected the main focus on climate protection (Voss & Musall, 2013). In Switzerland, the term '2000-watt society' was introduced as a vision that aims to reduce overall average primary energy use per person to 2,000W to make the current high living standards of industrialised countries universally available to everyone in a sustainable way by addressing all aspects – i.e. consumer behaviour, mobility, recreation, construction and housing (Stulz, et al., 2011). In Austria, the term 'energy plus building' referred to a building that produces more energy from renewable energy sources, over the course of a year, than it imports from external sources (Stutterecker & Blümel, 2012). In the US, the definition of 'net zero energy' was established to reduce the energy demand of buildings up to the point that supply from renewable energy could meet this demand loads (Deng, et al., 2014). And in Canada, the government launched the EQuilibrium Housing initiative that integrated a broad range of products, technologies and strategies aiming to minimise housing's environmental impact (CMHC, 2017). Among all these terms, the most widely popular are 'net zero carbon', 'net zero energy' and 'plus-energy' (Voss & Musall, 2013).

2.4.9.1 Net Zero Carbon (NZC)

NZC architecture aims to design buildings with renewable energy supply systems capable to generate enough energy to meet their reduced energy demand, so the total annual CO_2 emissions are neutral. According to Jones (2012), neutral means that the building imports energy from the grid when there is no renewable supply available, but it feeds energy back into the grid when there is an excess of renewable energy generated. Therefore, the grid acts as energy storage.

There are many relevant examples of NZC housing projects around the UK. In Ebbw Vale (Wales), four detached houses were built at The Works as part of the Welsh Future Homes project in 2010. The aim was to showcase the best practice in low energy design and construction. The Larch House (2011) was the UK's first net zero carbon Passivhaus, built as a prototype for social housing with local materials and a great variety of low carbon technologies such as solar thermal, PV panels, triple glazing windows, closed timber frame panels or MVHR system (Waghorn, 2012). The Lime House (2011) built just after the Larch House by the same architects, implemented modifications and improvements into the design reducing the construction costs. The Ty Unnos Low Energy House (2011), designed by Cardiff University using local timber and materials to achieve Passivhaus certificate. Finally, the Lily House (2011) was built at an affordable cost within the normal benchmark of £950 to £1080 per m^2 and using a light steel framing (Steel Construction Institute, 2012).

2.4.9.2 Net Zero Energy (NZE)

NZE architecture aims to design buildings with net zero energy consumption and zero carbon emissions annually (Tabb & Deviren, 2013). This should be considered the logical continuation of a long evolution of green developments from the first solar houses towards the latest low carbon houses. Garde, et al. (2017) present convincing evidence that a careful re-thinking of conventional design towards NZE can achieve a far greater performance. Griffith et al. (2007) prepared a report that, although it is focused in commercial buildings, defines clearly the concept of NZE buildings as "a building designed with energy efficiency and on-site production to convert it from an energy consumer to an energy producer".

However, in their research they also concluded that if solar energy from PV rooftops was the only source to cover the total annual energy demand of a building, then a reduction of nearly 60% of the electricity demand was needed. Similarly, Voss & Musall (2013) in their book *'Net zero energy buildings'* concluded that a path towards NZE buildings is not achievable without a consistent efficient strategy. They also defined four alternatives to NZE buildings:

- Net zero site energy: Energy demand includes all building loads, while energy supply includes on-site energy as well as purchased energy from outside.
- Net zero source energy: Energy values are scaled considering the inefficiency of the energy grid and the power stations.
- Net zero emissions: Instead of energy balance, calculations include emission factors.
- Net zero site energy cost: The balance calculation considers energy cost, hence the cost of energy import from the grid is compared against the cost of energy fed into the grid.

These variations show that there are many different strategies to achieve a NZE building. For example, a building could be NZE by including the energy from an off-site wind farm into its energy balance calculations, or it could even achieve NZE standards by buying CO_2 credits from other buildings or projects. Therefore, it becomes clear that a correct definition of the methodology to achieve NZE buildings is essential, and that local zero balance (on-site) or network zero balance (off-site) are very different concepts.

An attempt to develop a common understanding and a consistent international definition and guidelines for NZE buildings was done by the International Energy Agency under '*Task 40: Towards Net Zero Energy Solar Buildings*' as part of the Solar Heating and Cooling Programme. As a result, 30 case studies of NZE buildings from all around the world were evaluated and monitored during at least one year to confirm their net zero output. One of the key findings was that occupant behaviour plays an important role in how energy is used in the house (Garde, et al., 2017). The more relevant case studies of NZE housing projects with an integrated systems approach were the Bosch Net Zero House (2010) and the ÉcoTerra Home (2006). In the US, the Bosch Net Zero House was built for $499,000 with a traditional design so it looked like the other houses of its neighbourhood. It had PV panels in the roof capable to generate more electricity than it used and store this into the grid, and a geothermal pump that guaranteed the heat and cooling needs all year around (Rhone, 2012). In Canada, the ÉcoTerra Home (2006) part of the EQuilibrium Initiative, included a hybrid solar system of PV and thermal collectors all integrated into the roof and linked to a ground water heat pump, a DHW tank and a MVHR system.

Figure 71 – NZE arch.: a) Bosch house, source: greenbuildingadvisor b&c) EcoTerra home, source: sabmagazine.

Other relevant NZE projects with a system approach have been built during the last decade. In Italy, the BioCasa_82 (2014) was the first house in Europe to be awarded the certificate LEED Platinium with 99% of recyclable materials, 100% of the rainwater collected and the 100% energy production from renewable sources thanks to an integrated PV system that generates about 14kWh of electricity and a high efficiency ground source heat pump for space heating, hot water and cooling (Archdaily, 2014). In Australia, the Illwarra Flame House (2013) included demand reduction with a rainwater harvesting and grey-water recycling systems, and energy-efficient LED lighting; renewable energy supply with a roof-based 9.4-KW solar panel system, which actually comprised two types of panels – i.e. a thin-film CIGS array on the north and south-facing sides of the roof to capture weaker sunlight, and a poly-crystalline PV array directly on top for maximum efficiency in optimal sunlight; and energy storage with a phase change material thermal store that provided cooling and heating (Fiorentini, et al., 2015). All the systems were linked through a building management system that offered control and information about all electrical appliances and stored energy.

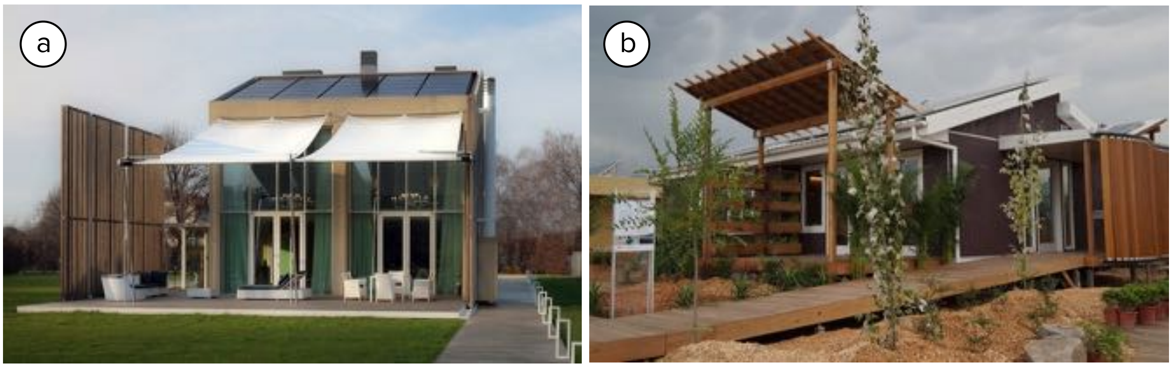


Figure 72 – NZE architecture: a) BioCasa_82 (2014); b) Illwarra Flame House (2013); Source: Archdaily.

2.4.9.3 Plus-energy Architecture

Plus-energy architecture, also known as Net Positive architecture, comprises buildings that produce an annual surplus of energy, hence with a net-positive impact on the environment. This is a challenging ambition because it means not just achieving sustainability but going beyond it by being fully self-sufficient. According to Tabb & Deviren (2013), designing for plus-energy buildings requires two key processes. First, to reduce energy demand and maximise the sustainable solutions more appropriate to the site to generate more energy than is needed, so the surplus can be fed into the grid. Second, to evaluate and validate the performance of all the systems and their positive impact on the environment.

A very interesting project that resulted in some good examples of plus-energy houses was the Model Home 2020 project, which started in 2009 involving the design, construction, testing and monitoring of six houses in five European countries. The project was led by the Active House Alliance, which developed a set of principles for an 'Active House' aiming for a plus-energy building that was also climate neutral with net zero carbon footprint and a high degree of liveability. The main idea was to achieve a balance between energy, indoor climate and environment (Active House Alliance, 2016). The Velux Group in collaboration with local governments, suppliers, architects, engineers and universities supported the Model Home 2020 project and has continued developing further case studies resulting in a total of 22 demonstration green buildings of different typology such as schools, houses, culture centres and childcare centres. The company has produced very informative reports of each case studies which can be found in their website (Velux, 2016). The main specifications of the 6 case studies that were part of the Model Home 2020 project are summarised as follows:

- Home for Life (2009) – In Denmark, this 190m^2 house incorporated a solar heat pump and 7m^2 of solar thermal collectors to cover hot water demand for the whole year, 50m^2 of PV panels to meet most of the electrical demand from appliances and lighting, thick concrete floors to store solar heat in the thermal mass and MVHR to meet ventilation and heating needs in winter. Monitoring results showed that the house produced more energy than it consumed over one-year period having an energy surplus of 9kWh/m^2/year (Velux, 2010).
- Green Lighthouse (2009) – In Denmark, this house's energy system consisted of a combination of district heating to power a heat pump that circulated solar heat, geothermal heat and cooling in the building; 76m^2 of solar cells on the roof to generate the electricity for lighting, ventilation and pump; solar heating and cooling, and seasonal storage in the ground (Velux, 2010).
- Sunlight House (2010) – In Austria, this 201m^2 house was located in a very challenging plot and included a highly efficient heat pump and MVHR for heating, 48m^2 of PV panels for electricity, 9m^2 of solar thermal collectors for DHW and highly insulated building fabric with ecologic materials. It optimised passive features such as daylight with a total windows area equivalent to 51% of the house floor area, and natural ventilation with automated windows during the warmer months of the year (Velux, 2011).

- LichtAktiv Haus (2010) – In Germany, this project transformed a traditional 1950's semi-detached house of 185m^2 into a modern house with automated roof windows to provide abundant natural light and controlled natural ventilation, shutters and screenings to protect from the sun, rainwater collection to supply water for toilets and garden, an air-to-water heat pump and 22.5m^2 of solar thermal collectors to provide free heating and hot water and 75m^2 of PV panels to generate electricity (Velux, 2011).
- Carbon Light home (2011) – In the UK, these two semi-detached houses used natural ventilation for cooling during the warmer seasons, a MVHR system for ventilation during the colder months, and thermal solar collectors linked with an air-to-water heat pump for water and space heating. The houses were designed to be net zero carbon with 70% reduction in CO_2 emissions and the remaining 30% being offset by improving the energy efficiency of the neighbouring houses, also known as an 'allowable solution' (Velux, 2012).
- Maison Air et Lumière (2011) – In France, this 130m^2 detached house had a very reduced heat demand thanks to higher levels of insulation on the building fabric, optimised solar gains through the windows and a MVHR system. It also had thermal solar collectors linked to a heat pump to provide for both water and space heating needs and 35m^2 of integrated PV panels that provided electricity for lighting and appliances. The roof had different angles to improve solar electric generation, making it a plus-energy house (Velux, 2013).

Figure 73 – Plus-energy architecture: a) Home for Life (2009); b) Green Lighthouse (2009); c) Sunlight house (2010); d) LichtAktiv Haus (2010); e) Carbon Light home (2011); f) Maison Air et Lumière (2011). Source: Velux.

More relevant plus-energy housing projects are collected in the previously mentioned book *'Net zero energy buildings'*, in which Voss & Musall (2013) consider different case studies of not only small residential buildings but also large housing developments, cities, office buildings, educational buildings or experimental buildings. Two of the house case studies are relevant because of their systems approach. The Lighthouse (2008) was the first NZC home built in the UK with an area of 79m^2 and a building cost of around £1,900 per m^2. Although its 4.7KWp PV system is capable to generate an annual energy surplus of 26kWh/m^2, the house also has a 10kW pellet boiler system to cover its heating demand, thus it is not completely plus-energy but it is net zero carbon because the electricity surplus offsets the pellets used (Voss & Musall, 2013). The second example is located in Riehen, Switzerland (2007) and is a plus-energy house that follows the Minergie Swiss energy standard, has a floor area of 302m^2 and a building cost of £1,700 per m^2. The house is all electric and is equipped with MVHR system, 84m^2 of not integrated PV panels to generate electricity, 7.5m^2 of thermal solar collectors that cover 60% of the annual hot water demand, a ground source heat pump that provides pre-chilled air in summer and pre-heated air in winter. Thanks to its huge PV system, the house has a positive annual energy balance, with about 30% of energy excess. However, because the house does not have any storage system, the design of the PV system was optimised to generate maximum electricity rather than prioritising self-consumption. Therefore, the 10º PV panels generate large quantity of energy excess between April and September, have a huge deficit of energy from November to February and cover the energy demand in March and October (Voss & Musall, 2013).

Figure 74 – Plus-energy architecture: a) Lighthouse (2008), source: e-architect; b) Riehen House (2007), source: architos; c) ZEB PilotHouse (2014), source: New Atlas.

Another relevant plus-energy house example is the ZEB Pilot House (2014) in Norway, an experimental project that claimed to generate from renewables three times of its energy demand. The house's systems combined many green technologies such as a 150m^2 PV array that was expected to generate 19,200kWh annually, 16m^2 solar thermal array, a rainwater collection system, a heat exchanger that recovers excess heat and redirects it to warm tap water and a swimming pool that is warmed using surplus heat.

2.4.10 LESSONS LEARNED

This review proves that during the past fifty years of sustainable development, green architecture has evolved significantly. It has been given different names depending on the interest or the concerns of the time, and it has also advanced at different speeds depending on the technological, economic, environmental and political barriers and drivers at the time. However, all these different approaches to green architecture have something in common; they respond to the same needs and to similar external limits and circumstances – i.e. conservation of energy and materials, response to climate, assurance of comfort, provision of shelter, reduction of CO_2 emissions and increase of self-sufficiency.

Figure 75 shows the number of case studies of green houses with a systems approach that were studied through this review and adds it to the graph presented at the start of this review (see Figure 51) that shows the evolution of the green architectural movement in relation to the growing awareness of environmental issues, the introduction of new building regulations and environmental policies, the launch of green housing events and the deployment of new low carbon technologies. It is clear that interest in green housing projects tends to respond to historical events and environmental concerns. For example, there was a significant rise in the number of green housing projects after the 1973 'OPEC oil embargo' and a massive increase at the beginning of this century in response to the dangerous rise of CO_2 emissions, with 60% of the case studies dating from 2000 onwards.

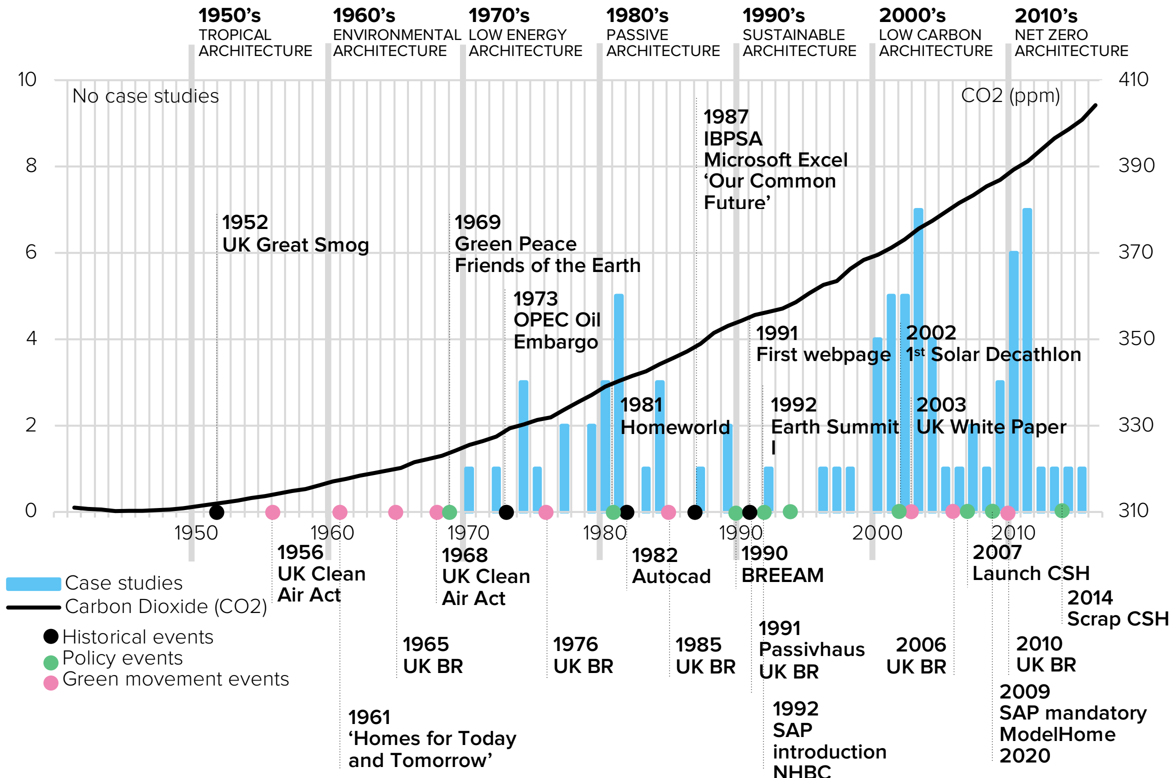


Figure 75 – Graph showing historical evolution of green architecture with the number of case studies reviewed.

This review proves that during the past fifty years of sustainable development, green architecture has evolved significantly. It has been given different names depending on the interest or the concerns of the time, and it has also advanced at different speeds depending on the technological, economic, environmental and political barriers and drivers at the time. However, all these different approaches to green architecture have something in common; they respond to the same needs and to similar external limits and circumstances – i.e. conservation of energy and materials, response to climate, assurance of comfort, provision of shelter, reduction of CO_2 emissions and increase of self-sufficiency.

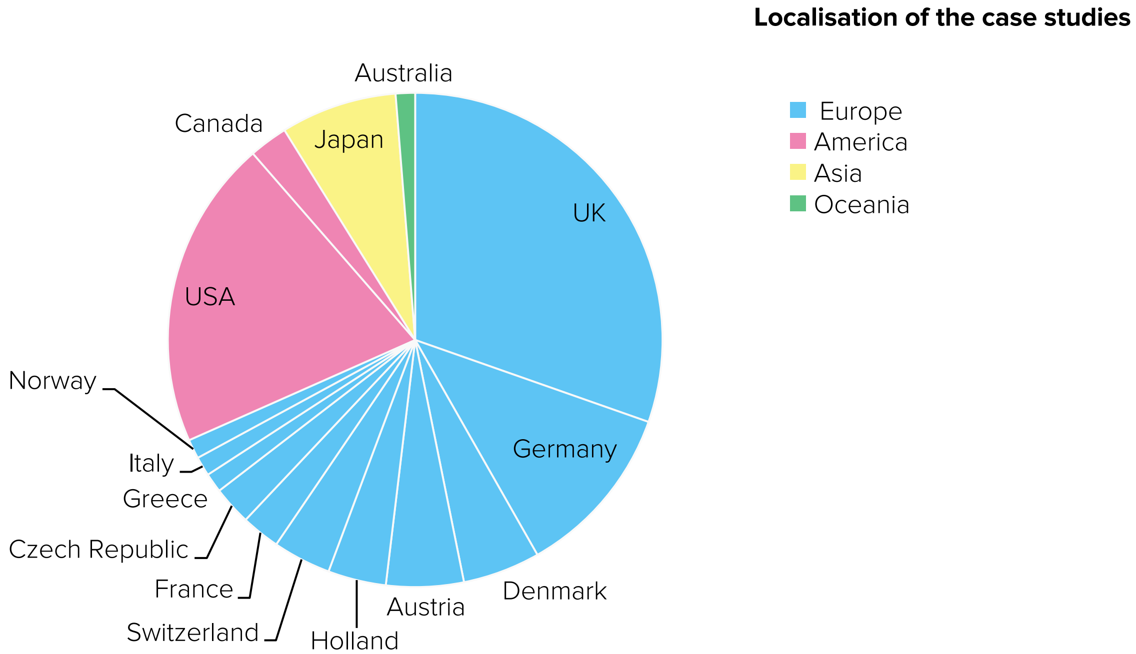


Figure 76 – Pie chart showing the distribution of the case studies by their location

A summary of all the case studies is presented in Table 6 In a chronological order considering the project's location, year of construction, the low carbon technologies used for reduced demand, renewable supply and storage and the final success a whole integrated energy systems approach.

Table 6 – Summary of all the green housing case studies presented in this review.

House Name	Location	Year	Reduced Demand Technologies					Renewables Supply Technologies								Storage Tech.			
			High Insulation	MVHR	Gas boiler	Eff. appliances	LED lighting	Solar Thermal Collectors	Solar PV	Ground Source Heat Pump	Air Heat Pump	Biomass boiler	Wood fire stove	Wind Turbine	CHP	Batteries	DHW tank	PCM or heat sink	Systems Approach
Arcosanti Housing Dev.	US	1970																	
Bradville Solar House	UK	1972																	
Zero-Energy House	Denmark	1974																	
Philips Exp. House	Germany	1974																	
Raven Run Solar House	US	1974																	
Student Housing Pr.	US	1975																	
Saskatchewan House	Canada	1977																	
House in Regensburg	Germany	1977																	
Linford Solar Court	UK	1979																	
Maison Solaire	France	1979																	
Rainbow Housing	UK	1980																	
Great Linford Summerh.	UK	1980																	
Hansen Residence	US	1980																	
Autarkic House	UK	1981																	
Ideal Home	UK	1981																	
Futurehome 2000	UK	1981																	
Greenwood House	UK	1981																	
Pennyland Housing	UK	1981																	
Two Mile Ash Develop.	UK	1983																	
Giffard Park Housing	UK	1984																	
Magney House	Australia	1984																	
Pefki Solar Village	Greece	1984																	
Bridge House	US	1987																	
Linz Solar City	Austria	1989																	
Albertslund City	Denmark	1989																	
Solar House	Germany	1992																	
UltraLow Energy House	Germany	1996																	
Casey Jacal Retreat	US	1997																	
Integer house	UK	1998																	
House for the future	UK	2000																	
Zero-Heating House	UK	2000																	
Passive House	Germany	2000																	
Zonhuizen House	Holland	2000																	
BedZED Development	UK	2001																	
Plus Energy House	Austria	2001																	
3-Litre Town	Germany	2001																	
Casco-zonnew. House	Holland	2001																	
Archidome House	Holland	2001																	
Hockerton Housing	UK	2002																	
Solar American House	US	2002																	

House Name	Location	Year	Reduced Demand Technologies					Renewables Supply Technologies								Storage Tech.			
			High Insulation	MVHR	Gas boiler	Eff. appliances	LED lighting	Solar Thermal Collectors	Solar PV	Ground Source Heat Pump	Air Heat Pump	Biomass boiler	Wood fire stove	Wind Turbine	CHP	Batteries	DHW tank	PCM or heat sink	Systems Approach
W House	Czech Rep.	2002	■	■				■					■				■		■
Daiwa House	Japan	2002		■	■			■	■								■		■
OM Solar House	Japan	2002		■				■	■								■		■
Vancak House	Czech Rep.	2003	■	■				■					■				■		■
3-Litre Twin House	Germany	2003	■	■				■									■		■
3-Litre Urban House	Germany	2003	■	■				■									■		■
Minergie-P House	Switzerland	2003	■	■				■					■				■		■
Minergie-P House	Switzerland	2003	■	■				■	■								■		■
Okamoto Solar House	Japan	2003			■	■		■									■		■
By the river House	Japan	2003				■		■									■		■
Springhill Cohousing	UK	2004	■			■			■										
Passiv House	Austria	2004	■	■				■	■	■	■	■					■		■
Hybrid-Z House	Japan	2004		■					■										
Low energy House	Japan	2004		■					■										
BioS(h)IP House	US	2005	■					■	■							■			■
ÉcoTerra Home	Canada	2006	■	■				■	■	■							■	■	
Made in Germany H.	US	2007	■	■		■	■	■	■		■					■	■		■
Plus-energy House	Switzerland	2007	■	■		■	■	■	■	■									
Lighthouse	UK	2008	■	■		■	■	■	■			■					■	■	■
Lammas Community	UK	2009	■						■										
SurPLUShome	US	2009	■	■	■	■	■		■		■					■		■	■
Home for Life	Denmark	2009	■	■		■	■	■	■		■							■	■
Green Lighthouse	Denmark	2010	■	■		■	■	■	■	■								■	■
Bosch Net Zero House	US	2010	■			■	■		■	■							■		■
Sunlight House	Austria	2010	■	■		■	■	■	■		■						■		■
LichtAktiv Haus	Germany	2010	■	■		■	■	■	■		■						■		■
BioCasa_82	Italy	2010	■	■		■	■	■	■				■				■		■
O-S House	US	2010	■			■	■	■	■	■							■		■
Larch House	UK	2011	■	■	■	■		■	■										
Lime House	UK	2011	■	■	■	■		■	■										
Ty Unnos	UK	2011	■	■			■	■	■		■								
Lilly House	UK	2011	■	■				■	■		■								
WaterShed	US	2011	■	■		■	■	■	■		■						■		■
Carbon Light Home	UK	2011	■	■		■		■			■						■		■
Maison Air et Lumière	France	2011	■	■		■	■	■	■		■						■	■	■
Green O.LA	US	2012	■	■		■	■	■	■	■						■	■		■
Lisi House	US	2013	■	■		■	■		■		■						■		■
ZEB Pilot House	Norway	2014	■	■		■	■	■	■	■							■	■	■
Sure House	US	2015	■	■		■	■		■		■					■	■		■

The main highlights from Table 6 are:

- Around 68% of the case studies were located in Europe. The UK was the country with more examples, 24 out of the 79, followed by the US with 16.
- The most popular strategy to achieve reduced energy demand is the fabric approach, with 89% of the case studies having high levels of insulation. The use of MVHR system is also very common (64%) and is present in almost any project from 2000 onwards. In the late 2000's, it became more common the use of energy efficient appliances (38%) and LED lighting (24%), coinciding with the implementation of the EU energy label and the phase-out of incandescent lights. Finally, it is certainly relevant that gas boilers, which are the prevalent heating system in the UK's traditional housing, are marginally used in green housing projects and only 19% of the case studies have one installed.
- When considering renewable strategies for the supply of thermal energy, solar thermal collectors (71%) are clearly the most common technology since the 1970's until today. In recent years, improvements in the air source heat pump market have pushed their acceptance, especially in Passivhaus projects, and are used in 19% of the case studies. They are closely followed by ground source heat pumps (14%), but only 2 of the case studies are located in the UK. Finally, the use of fuel burning systems is much less popular, with wood fire stoves used as complimentary heating in 9% of the cases and biomass boilers (2.5%) and CHP (2.5%) almost disregarded.
- Regarding renewable strategies for electrical energy supply, PV panels (58%) are the most popular technology since the 1990's until today. Wind turbines are not popular for the housing scale and are only used in 5% of the projects, almost all located in the UK.
- When considering storage systems, domestic hot water tanks (57%) are the most widely used since the 1970's, followed by PCM and heat sinks (24%) and electrical batteries (9%).

In conclusion, 67% of the analysed case studies have an energy systems-based approach with reduced demand, renewable supply and storage. Autarkic House (UK, 1981), Made in Germany House (USA, 2007), Lighthouse (UK, 2009), Maison Air et Lumière (France, 2011), Green.O.LA (USA, 2012) and ZEB Pilot House (Norway, 2014) are the projects that integrate more technologies; with 9 technologies running together in their energy system, much more than the total average of 5.2 technologies per house's system. However, most of these projects are pilot projects for housing exhibitions or technologies demonstration. This review has proved that houses with an integrated energy systems approach have been pursued from the early days of the green architectural movement, but cost, technologies reliability and public acceptance have been the main barriers to let green housing hit the mass market.

Accordingly, the EPH design developed in this research should be a turning point and have a more replicable, affordable and sustainable approach; so, it could hit the mass market and become the housing model of a future low carbon built environment. The lessons learnt from this historical review of green housing projects should be used to establish the main guidelines of the EPH design. The key features adopted in the revised case studies that make them low energy are as follows:

- Heating energy demand is reduced with a fabric-first approach using very high levels of insulation in walls, roofs, floors and windows; and minimising air leaks with good quality design and detailing to avoid unintended gaps and to achieve well sealed junctions.
- Electrical energy demand is reduced using A+ appliances, LED lighting and highly efficient low carbon technologies for ventilation, space and water heating.
- Passive solar gains are controlled, managed and optimised to exploit the sun's energy for heating purposes in the heating season and to minimize overheating during the cooling season.
- Energy generation from renewables is integrated and maximised using the building fabric, especially installing solar thermal collectors and PVs in south facing roofs and walls.
- Energy storage for thermal and electrical energy is installed to increase energy self-sufficiency and reduce dependency from the grid.

2.5 Summary

This chapter reviewed existing literature and provided background knowledge about the broad and relevant concept of energy, before focussing in the three topics that this thesis aims to integrate: modelling simulation, technologies performance and architecture design.

For energy, the topics of demand, supply and storage were analysed by considering the end-user and the fuel types. It was found that the main energy demand in a house is for space heating which normally uses gas as an energy source, while the rest of the demand comes from lighting, appliances and domestic hot water.

The modelling simulation review concluded that it is necessary a simple and easy to use model that can work with only limited information available. This is a practical approach to the modelling process because occupant's behaviour, location and weather variations can have a large impact on a household's energy demand.

The technology section reviewed low carbon technologies available in the market. First, it considered technologies that either reduce energy demand, or work using renewable energy sources. Then, it considered energy generation technologies that can be integrated into the building design, focusing on solar and wind energy. Finally, it analysed the quickly emerging energy storage market and the wide amount of literature that is written about this field in recent years.

Architecture was historically reviewed by considering the green movements that appeared since the 1970's until today and describing the most relevant housing projects that integrated a systems approach to reduced demand, renewable energy supply and energy storage. The focus of this section was the UK but including also housing examples across the world that were considered very relevant to this research.

In conclusion, this chapter gives a critical thinking to the subjects of energy, modelling, technology and architecture while highlighting and summarising the main findings and gaps in current research literature, so these can become the main design guidelines of the EPH design.

3 Methodology

Against the current background of dependence on fossil fuels, climate change, global population increase and finite resources; this thesis investigates a performance-driven design method in which three different research fields – i.e. modelling simulation, technologies performance and architecture design – are studied and integrated together with a systems approach to achieve an EPH design that could potentially decarbonise the new housing sector.

The performance-driven design method explored in this thesis proposes a holistic architectural research. However, this architectural research has many different aspects that are not easy to unify in a single framework. This chapter considers the complexity of the design framework to propose an architectural research method that considers the interactions and contingencies that occur in architecture. In a performance-driven design method, significant decisions should happen in the early stages of design. Performance modelling tools should enable the designer to make informed decisions based on energy simulation results, hence they should be interactive and provide visually comprehensible output.

Architectural research is often seen as lacking in scope, impact or rigour (Achten, 2015) because it does not use traditional research methods of science that tend to reduce the research question to a well-structured problem. Instead, architectural research embraces complexity and is often action-oriented, i.e. the findings have to be applicable in the everyday, complicated reality of architectural design (Achten, 2015). Due to this higher complexity, it is difficult to define how the ideal architectural research method should be. Among the few publications on the field, the architectural research models from Till (2007), Frayling (1993) and Jones (1992) are considered relevant because they allow interdisciplinary research into any of their proposed three stages and avoid the usual science/art or qualitative/quantitative classification. These three models break the limitations of traditional research methods and allow holistic thematic approaches; hence are used as a reference for the development of this thesis' methodological framework.

- Till (2007) identifies three myths that hold back the development of architectural research. Till also stated that architectural research has three stages of function that need to interact across traditionally separated intellectual fields using a tripartite approach:
    1. Architectural process: Considers the processes of design and construction of buildings; for example, theories of design or modelling of the environment.
    2. Architectural product: Studies buildings as completed objects; for example, issues of materials or construction techniques.
    3. Architectural performance: Considers the buildings once completed; for example, issues of occupation or environmental performance.
- Frayling (1993) was concerned about the specific relationship between design and research, and defined architectural research as:
    1. Research into: Takes architecture as its subject matter; for example, the studies of building performance.
    2. Research for: Is often driven by the needs of the sector and aims at future applications; for example, the development of new materials, typologies and technologies.
    3. Research through: Uses architectural design and production as a part of the research methodology itself.
- Jones (1992) proposes a 'systematic design method', defines the design process as a 'black box' and suggests that "one way to reduce the mystery of the 'black box' is to know as much as we can going into the project, and then evaluate the outcomes of the project after completion so that we can be more informed about the next design effort". His systematic design method has similarities with a scientific method of research (Groat & Wang, 2013) and consists of a three-step, potentially iterative, process:
    1. Analysis of the state of the art.
    2. Synthesis for a conceptual generation of the model.
    3. Evaluation of the model.

3.1 Research process

There are countless models of research processes, most of them planned to follow a series of stages or steps that are represented and simplified as a diagram. Braxler et al. (2001) classify research models in three categories:

- Linear models: They are often presented as fixed and linear series, with a clear start and end. For example, Johnson (1994) identifies eleven stages of activity that must be worked through in carrying out and completing an investigation: establishing the focus of the study, identifying the specific objectives of the study, selecting the research method, arranging research access, developing the research instrument, collecting the data, pulling out of the investigative phase, ordering the data, analysing the data and writing up.
- Circular models: They are analogous to the more general process of learning and although much the same set of stages is included, the experience of later stages might lead to a reinterpretation or revisiting of earlier stages. For example, Flick (1995) presents a circular process that includes investigation, analysis, comparison and sampling steps.
- Spiral or cyclical models: They can be entered at almost any point, these are a never-ending process which will cause the researchers to reconsider their practice and will return them to a different starting place.

For the purpose of this research, a linear process with a clear start and end seems the most appropriate; although it is known that this is a "simplification and idealisation of the research process" and that research is "anything but linear" (Braxler, et al., 2001). Figure 77 in the next page, shows how Johnson's linear stages are altered with a few additions and used to guide this particular research method. It also shows how Till's 'tripartite approach' – i.e. process, product, performance – and Jones' systematic design method – i.e. analysis, synthesis, evaluation – are integrated into the performance-driven design methodology of this research. Each research process shown in Figure 77 is then explained and described in more detail in sections 3.1.1 to 3.1.11.

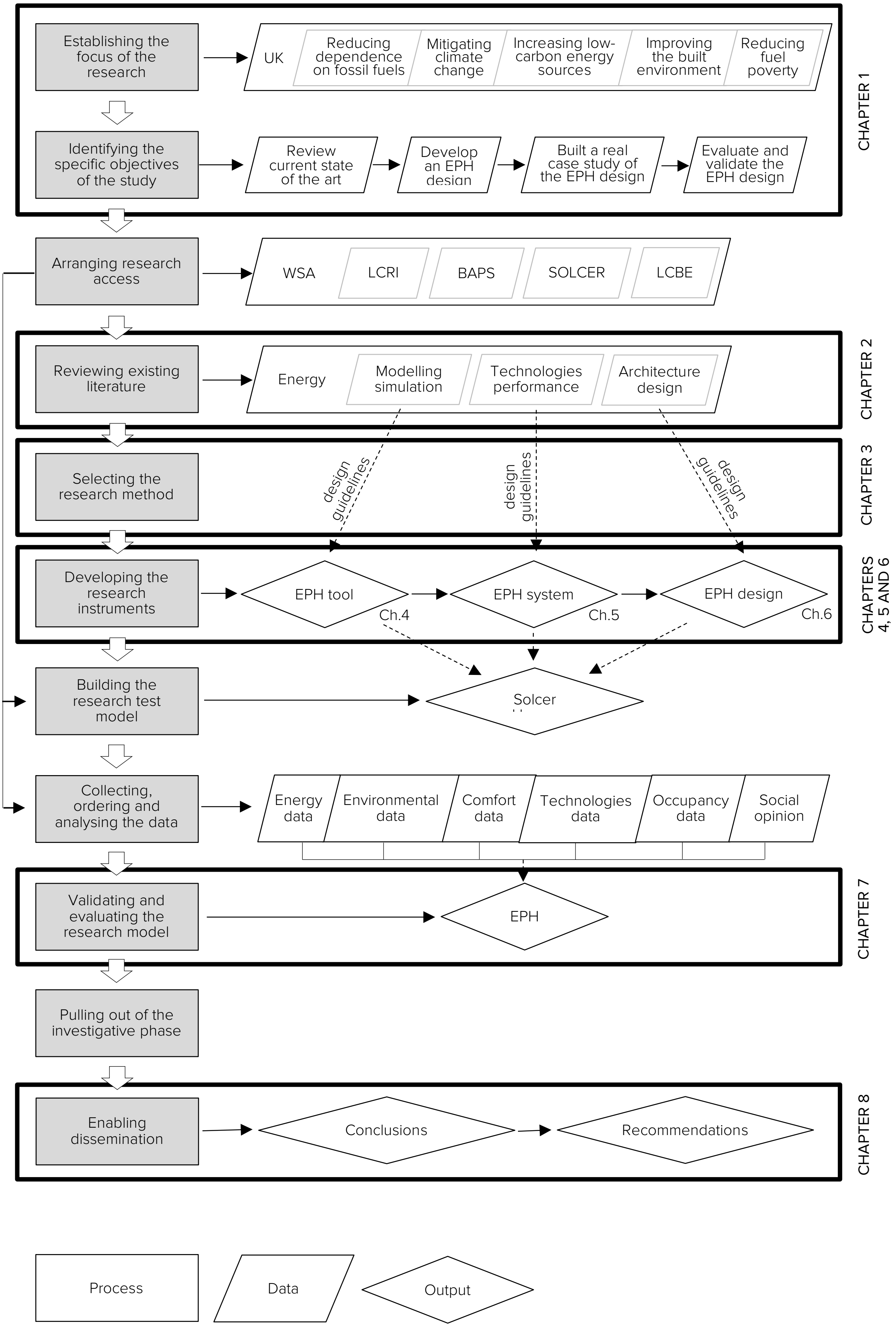


Figure 77 – Schematic of the methodology followed to develop this thesis research.

3.1.1 ESTABLISHING THE FOCUS OF THE RESEARCH

The selection of the topic and focus of this research is relatively straightforward because this thesis follows up the work done by the author as a researcher for the Welsh School of Architecture (WSA), Cardiff University. According to Blaxter et al. (2001) research is "powerfully affected by the researchers own motivations and values", which are essential to maintain interest over the duration of the PhD studies. It is also important to exploit strengths and prior knowledge. In this case the author uses the previous background as an architect for an architectural practice to make sure that the research is useful for academics as well as practitioners.

3.1.2 IDENTIFYING THE SPECIFIC OBJECTIVES OF THE STUDY

According to Johnson (1994), it is important to "attempt to define specific objectives in advance" to help with "choosing the research method and deciding on the forms of access needed". In this case, background reading and the on-going literature review influence the definition of research objectives.

3.1.3 ARRANGING RESEARCH ACCESS

Through the work as a researcher in the WSA, the author is "totally enmeshed in the subject" of the research and "an active participant" (Braxler, et al., 2001). Doing this PhD while having a full-time research position helps making progress on the research and in publishing the outcomes related to this work. Since April 2014, the author has collaborated with the Low Carbon Research Institute (LCRI) in the following projects:

- Buildings as Power Stations (BAPS), October 2013 to 2014: A collaborative research project with SPECIFIC Research Centre. The author initially developed a review of the market of integrated low carbon technologies.
- Smart Operation of Low Carbon Energy Regions (SOLCER), October 2014 to February 2015: SOLCER aimed to implement combinations of existing and emerging low carbon technologies through a system-based approach to optimise the use of energy at the point of generation. As part of this project, the author was involved with the Solcer House as architect and researcher. This allows to develop the thesis from a more theoretical approach, in terms of design and modelling of the building and its systems, and also from a more practice-based research implementing the EPH tool to size the energy system for a house in the real world.

- SPECIFIC 2 LCBE, June 2016 to June 2019: A collaborative research project with SPECIFIC Research Centre. The energy systems designed and implemented developed as part of this project are fully modelled and monitored to provide evidence of the ability for buildings to act as power stations maximising the combination of renewable energy supply, energy storage and energy demand reduction.

The work done for LCRI projects is only used as a seed for the proposal; it is clearly referenced and is fully developed on this PhD.

3.1.4 REVIEWING EXISTING LITERATURE

The literature review is considered an essential part of this research because it covers all previous research done on the topics of energy demand, supply and storage; modelling simulation, low carbon technologies and green architecture. There are many topics to review due to the holistic approach of this research. Therefore, the review stage is one of the longest and more time consuming, but in exchange allows to set the platform on which this thesis is based and helps to synthetize the ideas and guidelines to achieve the design of the EPH design. According to Duerke (1993) "the line between analysis and synthesis is not solid. This is to emphasize that good design ideas do not automatically follow analysis".

3.1.5 SELECTING THE RESEARCH METHOD

This research proposes a dynamic methodological framework for the design of performance-driven architecture in which many different techniques are used. This methodological framework is fully developed and described in this chapter.

3.1.6 DEVELOPING THE RESEARCH INSTRUMENTS

When reviewing architectural research methods, Groat & Wang (2013) define the research styles as research strategies and the research methods as tactics. They identify seven different strategies i.e. historical, qualitative, correlational, experimental and quasi-experimental, simulation, logical argumentation, and case studies and combined strategies. After evaluating different examples of each strategy, the most appropriate research strategy for this thesis is considered to be a combination of simulation, case study, experimental and survey research. "An increasingly common strategy in experimental research is to augment it, either iteratively or in distinct phases, with simulation modelling" (Groat & Wang, 2013). Figure 77 shows how the combined simulation, case study, experimental and survey strategies are "used to provide greater depth and/or validity concerning a particular aspect of the study" (Groat & Wang, 2013).

This thesis' combined research instruments are:

- Simulation – This thesis proposes a performance-driven architectural design, which takes a holistic approach towards energy and thermal performance of buildings while ensuring that the use and aesthetic of the design are not dismissed. In recent years, mathematical models, energy performance simulation techniques, as well as computer-aided design and drafting systems have been used. However, architects often find them impractical and incompatible with their knowledge base and design approach (Shi & Yang, 2013). Therefore, it is necessary to develop an effective instrument to conduct performance-driven design and simulation research from the perspective of architects. Therefore, the EPH tool is developed as a quick and easy to understand simulation tool, which can be used in the early stages of the project, to optimise and integrate EPH systems and EPH designs through a legible performance-driven simulation strategy. This involves "control and manipulation of the simulated elements, but it can reduce the need for empirical testing characteristic of experimental research" (Groat & Wang, 2013).
- Case study – The design of the EPH design is built as a prototype south-facing building, namely Solcer House, in South Wales. For the purpose of this study, the several systems and technologies are monitored over two years across different seasons; measurements are taken of the thermal behaviour of the systems and technologies, indoor thermal comfort conditions and energy consumption. The main purpose is to investigate how the design of an EPH design might be achieved for the UK scenario and to evaluate the performance of the specific design through a combination of experimental testing of a real case study, and subsequent simulation modelling to extend the results by changing the model design. The use of a case study strategy allows to combine the theoretical approach to the design and optimisation with the EPH design, with more practice-based research of using the EPH tool to size the EPH system for an EPH design in the real world.
- Experimental – Once an extensive set of data from the case study experiment is collected, numerical simulations are performed using the EPH tool, which is used from early design stages. Considering other modifications and calculations, the values obtained from the simulation model are compared with the experimental data "to verify the reliability of the simulation tools in reproducing real situations. Once the model has been calibrated, it is possible to generalise the results running the calculation for the whole year" (Groat & Wang, 2013). Both experimental data and numerical simulations are used in concert to assess the validity of the designed EPH design (tool, system and house).
- Survey – This part of the research is funded by EPSRC IAA as part of the research project named *'Solcer House – from demonstrator to real world'*. Following the receipt of Cardiff

University's ethics approval, an online survey is prepared with 'BOS online survey tool' (University of Bristol, 2017) and send to the visitors of the Solcer House, with anonymity and confidentiality assured. The aim is to investigate the potential impact of the systems-based approach implemented in the Solcer House and to know what people like or dislike about it. In total, 88 people answer over one-month period with a response rate of 17%. A sample of the questionnaire can be found in Annex 1.

3.1.7 BUILDING THE RESEARCH TEST MODEL

For evaluation purpose, the EPH design model is used in a real case study, named the Solcer House. The construction of the Solcer House was completed in March 2015 and the author was involved since the beginning being the architect and building site manager. The Solcer House project was built as part of the LCRI's SOLCER project, who secured funding from the Welsh European Funding Office (WEFO) to enable Wales and its industry partners to lead the way in research to cut carbon emissions, as part of the European Research Development Fund's Convergence, Regional Competitiveness and Employment programmes. The funding body conditions the use of the building to the public use only; hence the Solcer House is occupied as a test facility with daily office-type user profiles.

Figure 78 – Image of the Solcer House used as this thesis case study.

The Solcer House is located at the Cenin Renewables' site in Stormy Down in Bridgend, South Wales (see Figure 79). Due to the availability of land, the house is constructed as a detached property as shown in the site layout plan in Figure 80. However, Chapter 4 explains how during the design stage, the potential for the EPH design model to be constructed as a semi-detached or terraced is a key consideration which would be more in-line with requirements of developers of such a house design.

Figure 79. Map showing the location of the Solcer House near Bridgend, South Wales.

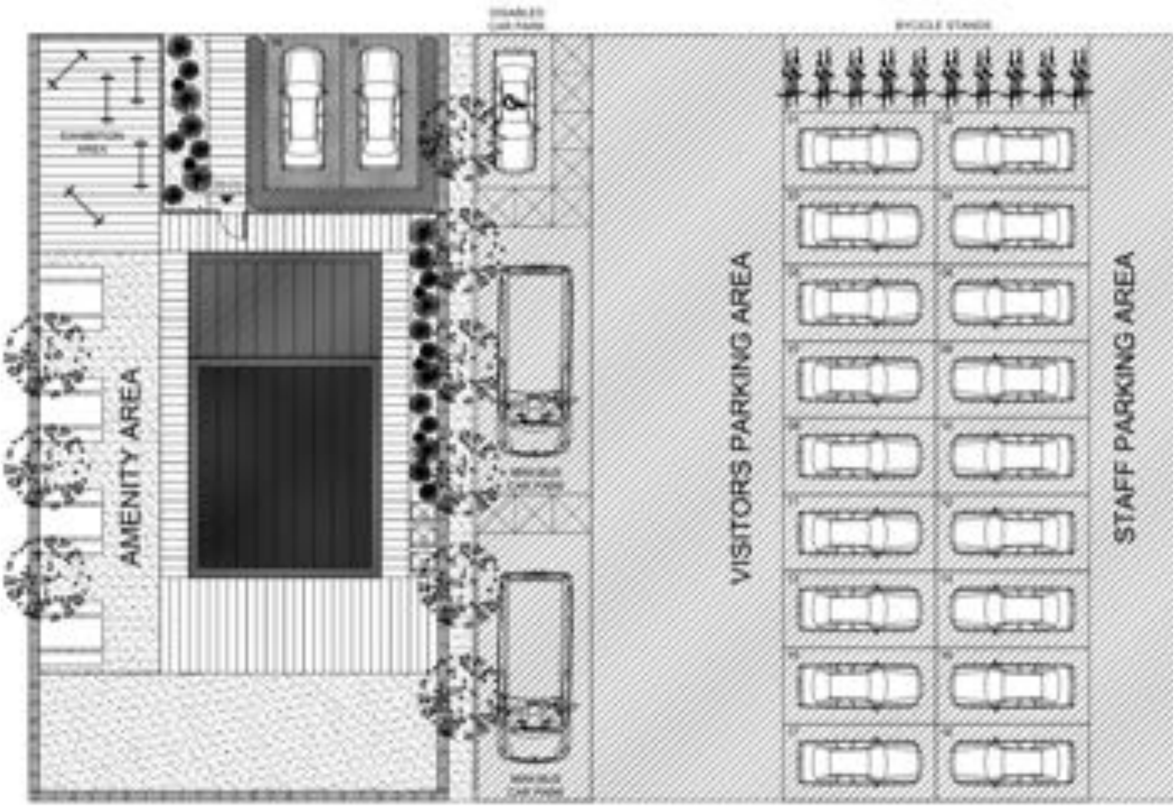


Figure 80. Proposed site layout of the Solcer House project.

3.1.8 COLLECTING, ORDERING AND ANALYSING DATA

To produce high-quality data, an extensive monitoring system is installed in the Solcer House as part of the SOLCER project. The aim of the monitoring system is to investigate the performance of the building and energy system post-occupancy. The monitoring includes:

1. Mains water consumption: Jet pulsed BSP cold water meter 25mm.
2. Heat for domestic hot water: Sontex Supercal 739 compact heat meter with a temperature resolution of 0.1ºC and 10 sec. of measurement cycle at nominal flow.
3. Mains grid electricity import and export: Elster A100C single phase meter with pulsed output and configured with reverse energy flow for import/export.
4. Sub-metering of electricity demand: YTL DDS353 45Amp single phase meter with a single pulse output and LCD screen.
5. Indoor air temperature, CO_2 and relative humidity in all rooms: Eltek GD47 transmitters with temperature resolution of 0.1ºC (±0.4ºC at -5 to 40°C), relative humidity resolution of 0.1% (±2% at 10 to 90%) and CO_2 range from 0 to 5000ppm ± (50ppm + 3% of measured value). All the GD47 transmitters are connected to an Eltek SRV250 receiver logger with 3G connectivity.
6. Energy generated with the PV system: Hobut M850-LDD DC meter with pulse output and with an accuracy of ±0.5% for voltage and current and ±1% for power.
7. Comprehensive monitoring of the thermal system: See section 7.2.2.

A Vaisala WXT520 Weather Transmitter is also located in the roof, not accessible from the ground and totally exposed, measuring:

1. Wind speed from 0 to 60m/s (±3% @ 10m/s) and wind direction from 0 to 360° (±3%, response time <250ms).
2. Rainfall accumulation with a resolution of 0.01mm (±5% uncertainty), rainfall duration counting each ten-second increment when droplet detected and rainfall intensity from 0 to 200mm/hr (one-minute running average in ten-second steps).
3. Barometric pressure from 600 to 1,100hPa (±0.5hPa at 0 to 30°C).
4. Air temperature from -52 to +60°C (±0.3°C at 20°C).
5. Relative humidity from 0 to 100% (±3% within 0 to 90%).
6. Additionally, the global solar irradiation on the horizontal plane is measured with a Kipp&Zonen CM3 pyranometer with a maximum irradiance of 2000W/m^2 and a sensitivity of 10 to 35μV/W/m^2.

To ensure good quality of construction works and indoor environment, the following site investigations are also done:

1. Thermography survey in heating season with a FLIR B400 infrared camera, which has a thermal sensitivity of up to 0.05°C @ 25°C;
2. Pressurisation tests to find the level of airtightness;
3. Indoor lighting quality considering correlated colour temperature and illuminance;
4. Fabric heat loss.

The monitoring data is collected every five minutes, stored in a Campbell Scientific CR1000 data logger and automatically transferred to the SOLCER server, managed by the SOLCER team. The collected data belongs to the research output of the WSA. Owning to the fact that "research needs to fit into the time and other resources available for the studies" (Braxler, et al., 2001) , the collected data is analysed for a period of only two years since the launch of the Solcer House. However, data is being collected and analysed over a five years period by the SPECIFIC 2 LCBE project team.

Regarding the online survey, this is prepared with 'BOS online survey tool' (University of Bristol, 2017). This is an easy to use tool that allows developing, deploying and analysing surveys via the web. As soon as respondents start completing the survey, their responses can be viewed as they come in and the user can customise how the data is displayed. All the visits to the Solcer House are recorded, numbered, kept for analysis and held on file even after the research is complete so that the researcher is "prepared to be accountable for the investigations" (Johnson, 1994). Visitors contact details are kept confidentially and data from the online survey sorting exercise is held securely in readiness for analysis.

3.1.9 VALIDATING AND EVALUATING THE RESEARCH INSTRUMENT

The monitored data collected from the Solcer House and the statistics from the online survey form much of the content of Chapter 7. This chapter evaluates the specific performance of the Solcer House case study and intends allowing to make generalisations about the performance-driven design approach to achieve an EPH design model. The tension between the study of a unique case study and the need to generalise is needed "to reveal both the unique and the universal and the unity of that understanding" (Jameson & Hillier, 2003).

The findings from this research are compared against the findings from previous background reading and those from similar case studies, to diminish the weakness noted by Johnson that in many thesis "little use is made of the data collected in the eventual discussion of the thesis topic" (Johnson, 1994). The monitoring data is evaluated using a discursive, as well as a graphical approach. The online survey's answers are statistically analysed, and the data is presented as a discussion supported through the use of quotations from the responders.

3.1.10 PULLING OUT OF THE INVESTIGATIVE PERIOD

The practical research stage is undoubtedly the most interesting and rewarding and the Solcer House builders, occupants and visitors appear to enjoy having a voice and taking part in the research project. Extracts from the occupants and visitors' voices, based upon their perceptions after testing and/or visiting the Solcer House are used to support the validity of findings and conclusions.

Whilst the research is for a small-scale building, it is time-consuming and requires a significant degree of flexibility on the researcher's part, especially during the construction of the Solcer House or when guided tours and visits to the Solcer House occur on a weekly basis. There is also the need to liaise carefully with building sub-contractors to ensure that the systems, technologies and materials are properly installed at the Solcer House as specified in the drawing details. The early decision on this research objectives ensure that interim research aims are met and adhered to.

3.1.11 ENABLING DISSEMINATION

The findings from the data analysis are used to extract conclusions, propose improvements to the EPH performance-driven design approach and make recommendations. These can be found in the final chapter of conclusions.

The efforts to promote a more systematic, comprehensive and clearly sequenced process of performance-driven design aim to provide the design professionals with a conceptual foundation more analogous to that supporting scientific research. Hillier et al. (1972) summarise the prevalent views about design as "the solving of problems" and state that research should bring "as many factors as possible within the domain of the quantifiable" with the goal of replacing "intuition and rules of thumb with knowledge and methods of measurement". Likewise, this thesis aims to develop a performance-driven design approach to achieve the challenge of an EPH design by proposing an in-depth research of the topic to reduce intuition and rules of thumb and provide as many quantifiable factors as possible.

The aim of the dissemination stage is to summarise the overall conclusions or message of the research in an assimilable and memorable form and to communicate the researcher's empirical experience to a wider audience (Johnson, 1994). Although sharing the whole research experience with readers is key to achieve the pursued Doctorate degree, there is also a prevailing desire to make sure that the research and the proposed performance-driven design method is useful and of interest for academics as well as practitioners. For this reason, a more traditional and formal stance of writing in the third person is adopted.

3.2 Summary

The aim of this thesis is to test whether energy positive houses with building integrated energy technologies could become the housing model of a future low carbon built environment scenario and lead to solve the UK's energy trilemma. The topic of energy positive housing is considered relevant to help solving the UK's current energy trilemma challenge.

In particular, this thesis aims to investigate the development of a performance-driven design method that leads to a replicable model of an EPH design suitable for the UK's climate. First, this model is built as a real case study, the Solcer House, and monitored for several years and over different seasons; measurements are taken of the thermal behaviour of the systems, indoor thermal comfort conditions and energy consumption of the technologies and systems. Once an extensive set of data is collected from the case study experiment, numerical simulations are performed using the proposed EPH tool. Then, the values obtained from the simulation model are compared with the experimental data from the real case study of the Solcer House to verify the reliability of the EPH tool in simulating and reproducing real situations of energy positive houses. Once the model and the tool are calibrated, it is possible to generalise the results and calculate and estimate the performance of any EPH design based in the UK for the whole year.

This thesis' findings, and particularly the recommendations, have been and will be presented in conferences and workshops to raise general public, builders and government's awareness of new ways to build affordable, sustainable and secure housing using a performance-driven design approach and to consider ways in which this information can be used to address the issues of fuel poverty, climate change and energy security. This piece of research may not give set answers to questions surrounding the best housing solution for the future, but it is anticipated that it could contribute to the understanding and examination of this issue. Findings aim to develop a better awareness of the importance of performance during the process of design of housing, examine architects' practices in the light of the findings, and consider how the design experience can be enriched with the proposed performance-driven design approach for all design professions.

4 Modelling simulation: EPH tool

The EPH goal presents a challenge for architects, who now have a decisive role to move forward the low carbon housing agenda if they want to play a leadership role on a building project team (Davies & Osmani, 2011; Roaf, et al., 2005). Traditionally architects used sketches, renderings and pattern books supplemented with axonometric and perspective drawings, written and diagrammatic specifications, photographs and small-scale models. This was a conventional architectural design methodology, which focused on building's space and form.

Contrarily, this thesis proposes a performance-driven architectural design, which takes a holistic approach towards energy and thermal performances of buildings while ensuring that the use and aesthetic of the design are not dismissed. In recent years mathematical models, energy performance simulation techniques and CAD drafting systems have been used. However, architects often find them impractical and incompatible with their knowledge base and design approach (Shi & Yang, 2013). Therefore, it is necessary to develop an effective method to conduct performance-driven architectural design and energy systems optimization from a designer's perspective. Hence, the EPH tool is developed as a quick and easy to understand tool, which can be used in the early stages of the project, to guide EPH designs with integrated EPH systems through a legible performance-driven design approach. Figure 81 shows the schematic of the design process of the EPH tool.

This chapter starts with an analysis of the topics of energy and modelling simulation tools reviewed in Chapter 2, sections 2.1 and 2.2, to learn the best of them, identify their limitations and establish the main design guidelines of the EPH tool. The findings of the analysis of the review are then synthesised into the design of the proposed EPH tool, which aims to integrate energy demand, supply and storage into the housing-scale modelling.

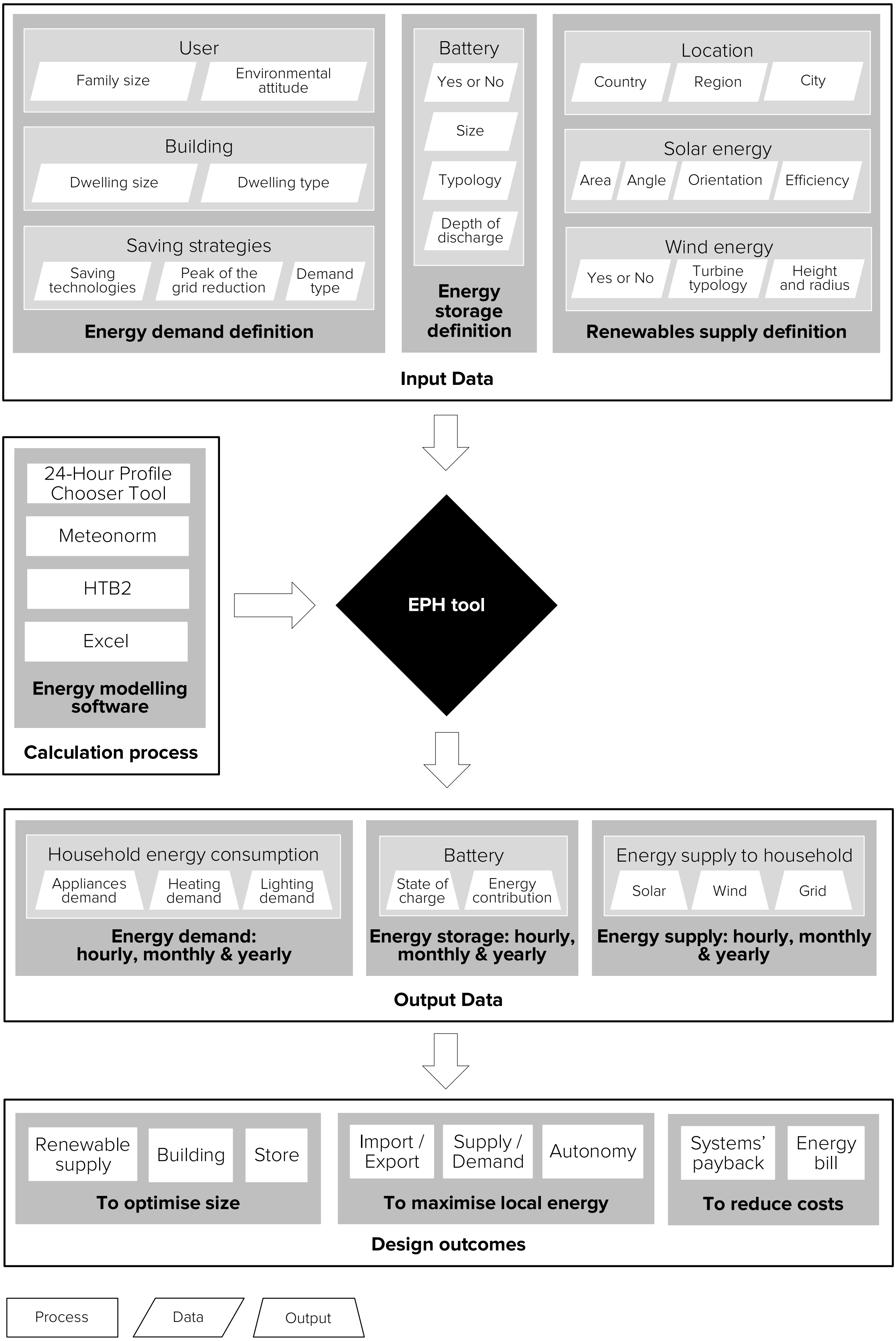


Figure 81 – Schematic of the methodology followed to develop the EPH tool.

4.1 Analysis: Guidelines for the EPH tool

This thesis aims to optimise the design of the UK's new households, so they can be energy positive, hence to be active energy generators rather than passive energy consumers. To achieve this proposed performance-driven design approach, the EPH tool is developed for simulating any domestic-scale energy system by combining energy supply, storage and demand (see Figure 82).

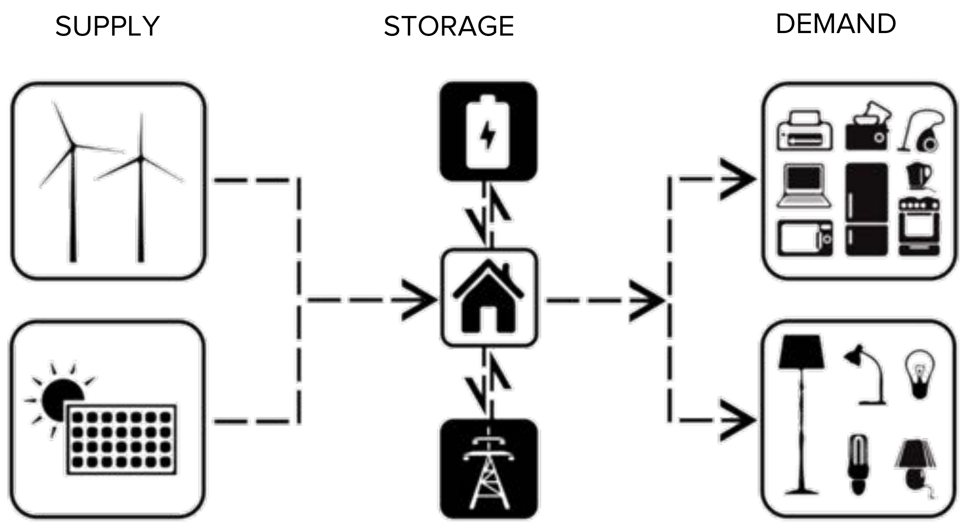


Figure 82 – Diagram showing the energy flow paths of the EPH system.

Initially, energy from renewable energy systems is used directly to cover the demand. Using the renewable energy directly in the building, rather than exporting and importing it to the grid, can avoid grid overvoltage, reduce capital cost, increase reliability and improve system's efficiency. When there is an excess of renewable energy generation, this is stored in the building's energy storage system for later use, which in this case is a battery system. Oppositely, when generation and storage cannot cover the demand, electricity is imported from the grid.

The EPH tool, with its user-friendly interface, aims to turn the UK's new households into power generator by calculating the appropriate size of the supply and storage systems that leads to maximize the use of renewable energy and minimize the amount and cost of electricity purchased from the grid. The intention is to reduce the UK dwellings' dependence on the grid; which could not only reduce demand peaks of the grid but also contribute to reducing potential overload on the grid. The extent to which such energy systems act, either reducing grid's demand peaks or achieving almost energy self-sufficiency with the grid only used as a back-up, could be determined by the size of renewable energy system and the storage capacity, in the context of the building's reduced energy demand.

First, a 'customised energy demand model' is developed to predict the energy consumed within the household in an hourly, daily, monthly and annual basis. Then, PV and wind energy generation models are developed to simulate the hourly, daily, monthly and annual generation from renewables. Finally, demand and generation models are linked to further create an energy balance and storage prediction model. In the three cases, a combination of HTB2 (WSA, 2017) and MS Excel is used.

The EPH designing tool has been developed with MS Excel using simulated hourly data from Meteonorm (Meteotest, 2009) for the weather data. For the modelling of energy demand, the average hourly profile data from the '*24-Hour Profile Chooser Tool'* (CAR, 2013), reviewed in section 2.2.2.1, is normalised and used as a basis for the simulation of the electric energy loads of appliances, lighting and DHW; while the thermal performance and the heating loads are simulated with the energy simulation software HTB2, reviewed in section 2.2.2.2. On the other hand, the modelling of energy supply is based on mathematical calculations that use basic solar radiation and building physics concepts. All the software needed for the modelling and simulation of energy demand, supply and storage is available in the WSA for educational use.

4.1.1 VERSIONS

The EPH tool evolved significantly throughout the development of this thesis, since its conception back in 2014 until its final version. Initially, it was a simple tool created to simulate the performance of a simple house with an energy systems approach. But later, it evolved so it could be used to model almost any house in the UK with an integrated systems approach to reduced demand, renewables supply and electric storage. Finally, after testing it in real case studies, getting feedback from workshops and conferences, and presenting it to colleagues and users, the tool takes its final shape. Although a final version is presented on this thesis, the EPH tool should be an ever-evolving model capable to adapt to new technologies and requirements.

Figure 83 shows the first version of the tool, named BAPS tool that was presented in Italy in October 2014 in the conference '9th Energy Forum'. The conference paper is titled *'New residential scale 'Buildings as Power Stations assessment tool'* (Coma, et al., 2014).

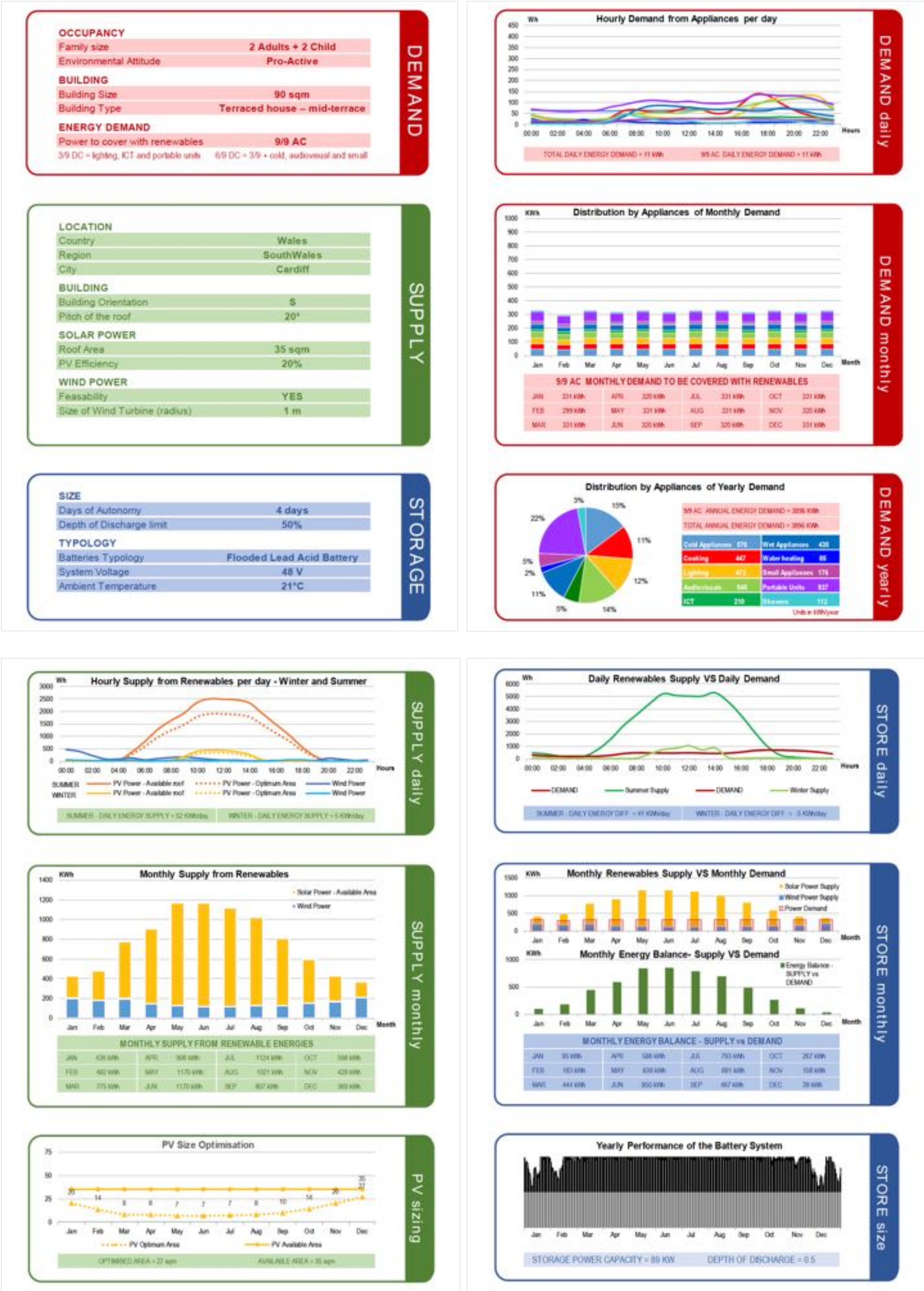


Figure 83 – Screenshot of the EPH tool, Version 1.0 presented in the conference *9th Energy Forum, 2014* (Coma, et al., 2014).

Figure 84 shows the second version of the tool, still named BAPS tool, which was presented in Chicago (US) in May 2015 in the conference 'International Conference on Sustainable Design, Engineering and Construction'. The conference paper was then published in the journal *'Procedia Engineering'* with the title *'Buildings as power stations: an energy simulation tool for housing'* (Coma & Jones, 2015).

Figure 84 – Screenshot of the EPH tool, version 2.0 presented in Chicago, in May 2015 in the conference *International Conference on Sustainable Design, Engineering and Construction* (Coma & Jones, 2015).

4.2 Synthesis: Design of the EPH tool

4.2.1 INPUTS

The EPH tool aims to include flexibility in the modelling process to simulate almost any household energy performance in the UK. For this reason, the calculation process starts in 'Page 1' by defining the variations on different characteristics of energy demand, supply and storage. Figure 85 shows a screenshot of the first page of the tool.

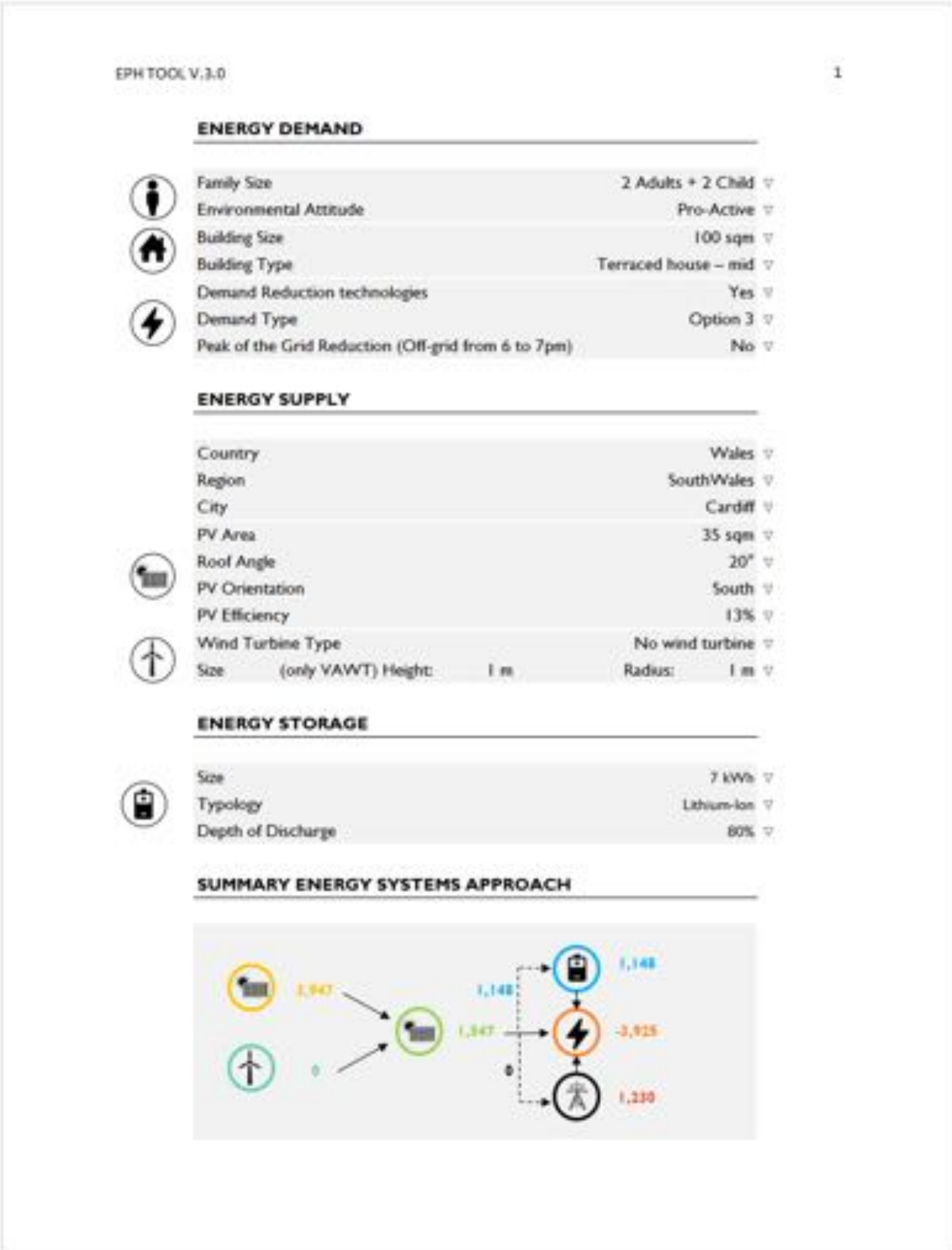


Figure 85 – Screenshot of the EPH tool v.3.0., page 1, showing Solcer House case study.

4.2.1.1 Demand

The energy use in dwellings is driven by occupants' needs; therefore, it depends on the level of services required in relation to the type of home and its heating system, lighting and appliances. Moreover, the energy use in the UK's households is highly influenced by both the size of the dwelling and the number of people living in it (Palmer & Cooper, 2013). Accordingly, the following factors in Table 7 are considered for the modelling of the energy demand of a home using the EPH tool.

Table 7 – Demand variation parameters used as input of the EPH tool.

1. Occupancy		
	Variations	**Multiplying factor**
$F1_{FS}$ = Family size (Energy Saving Trust, 2012)	1 Adult 1 Adult + 1 Child 1 Adult + 2 Child 2 Adults 2 Adults + 1 Child 2 Adults + 2 Child 2 Adults + 3 Child 2 Adults + 4 Child	1.00 1.75 2.50 2.00 2.75 3.50 4.25 5.00
$F1_{EA}$ = Environmental Attitude (DECC, Jan 2014)	Pro-Active Non-active	0.87 1.00
2. Building		
	Variations	**Multiplying factor**
$F2_{BS}$ = Building Size	50 m^2 60 m^2 70 m^2 80 m^2 90 m^2 100 m^2 110 m^2 120 m^2	50 60 70 80 90 100 110 120
$F2_{BT}$ = Building Type (DECC, Jan 2014)	Mid-terrace house End-terrace house Semi-detached house Detached house Bungalow Flat	0.725 0.898 1.004 1.083 1.008 0.738
3. Electric Demand		
	Variations	**Appliances included**
$F3_{DT}$ = Demand Type i.e. Appliances linked to the supply and storage systems	Option 1	Lighting ICT appliances Portable Units
	Option 2 = Opt. 1 &	Cold appliances Media appliances Kitchen appliances Washing
	Option 3 = Opt. 2 &	Space & Water Heating Cooking

4.2.1.2 Renewables Supply

The selection of building integrated renewable technologies is restricted to what energy sources are available on site and what can be fitted in, on, or around the building. Hence it is important to minimize the building's energy demand before considering or designing a renewable energy system. Although solar and wind energy are freely available everywhere and environmentally friendly, renewable energy systems are often perceived to be expensive, thus it is important to optimize their size and integrate them into the building construction to reduce construction costs. The factors in Table 8 are considered for the modelling of renewable energy supply with the EPH tool.

Table 8 – Supply variation parameters used as input of the EPH tool.

1. Location		
	Region	**Cities**
England	North East	Newcastle upon Tyne, Sunderland
	North West	Blackburn, Blackpool, Liverpool, Manchester
	Yorkshire	Bradford, Leeds, Sheffield, York
	East Midlands	Derby, Leicester, Northampton, Nottingham,
	West Midlands	Birmingham, Coventry, Stoke-on-Trent, Wolver Hampton
	East England	Cambridge, Ipswich, Luton, Norwich, Southend-On-Sea
	South East	Brighton, Milton Keynes, Oxford, Portsmouth, Reading
	South West	Bournemouth, Bristol, Exeter, Gloucester, Plymouth
	London	London, Sutton
Wales	South Wales	Cardiff, Swansea, Newport
	North Wales	Wrexham
Scotland	Lothian	Edinburgh
	Strathclyde	Glasgow
	Grampian	Aberdeen
	Central	Dundee
Ireland	North Ireland	Belfast

2. Building		
	Variation	**Multiplying factor**
Roof Area	10 to 75 m^2	10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75
Roof Angle	10° to 45°	10, 15, 20, 25, 30, 35, 40, 45

3. PV panels		
	Variation	**Multiplying factor**
Orientation	W to E	W, SW, S, SE, E
Efficiency	8 to 23%	8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23

4. Wind turbine		
	Variation	**Multiplying factor**
Feasibility	Yes or No	1 or 0
Size (radius)	1.5 to 4.5 m	1.5, 2, 2.5, 3, 3.5, 4, 4.5

4.2.1.3 Storage

The EPH approach is linked to energy storage. Therefore, the EPH tool needs to incorporate energy storage systems to ensure the use of electricity at times when the renewable energy systems are not generating.

The review on energy technologies in Chapter 2, section 0, shows that lead-acid batteries and lithium-ion batteries are the most commonly used storage systems at the moment. Therefore, correctly sizing them is important to achieve a well-designed energy system. There are many factors affecting battery sizing, and they are all considered in the calculation process used by the EPH tool as shown in Table 9.

One of the conditions for sizing batteries are the days of autonomy, i.e., the number of days of battery back-up that the storage system can provide. Another important factor is the depth of discharge (DoD), which is the limit of energy consumed from the battery, expressed as a percentage of the total capacity. Fully discharging batteries can reduce their operation lifetime considerably. For example, the DoD for lead-acid batteries cannot be no greater than 50%, while for li-ion or nickel batteries it can be up to 80% (Chatzivasileiadi, et al., 2013). The third aspect to consider is the ambient temperature, since low temperatures reduce battery capacity, while high temperatures shorten battery life. Finally, the voltage of the whole energy supply system needs to be determined; this is usually 230V in the UK.

Table 9 – Storage variation parameters used as input of the EPH tool.

1. Building		
	Variation	**Multiplying factor**
Size of batteries	No = 0 KWh	0
	Yes = 1 to 15 KWh	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
Ambient Temperature	-10ºC to +35ºC	-10, -5, 0, 5, 10, 15, 20, 25, 30, 35
2. Batteries		
	Typology	**Depth of discharge**
Typology vs DoD	Lead Acid	up to 50%
	Lithium-Ion	up to 80%
	Nickel	up to 80%

4.2.2 CALCULATIONS

The EPH tool assesses the energy generated from renewable energy systems, the effect of using battery storage systems, and the impact of demand reduction technologies. The EPH tool's calculation process updates automatically, hence any change on the household or systems' characteristics chosen in 'Page 1' has an instant impact on the results, which are immediately shown in parallel screens. The calculations are described in the next sections.

4.2.2.1 Demand loads

Following the same approach than the '*HES Survey'* (Zimmermann, et al., 2012) and the *'24-Hour Profile Chooser Tool'* (CAR, 2013), the energy consumed by households falls into one of these nine categories:

- Lighting: LED lighting.
- Portable units: mobile phones, chargers, cameras, etc.
- ICT appliances: laptops, desktops, printers, etc.
- Media: TV, audio-visual, router, etc.
- Cold: fridge-freezer.
- Kitchen: kettle, toaster, blender, etc.
- Washing / drying: washing machine, tumble dryer and dishwasher.
- Cooking: electric hob and oven.
- Heating: space and domestic hot water heating.

4.2.2.1.1 Appliances and lighting loads

The *'HES survey'*, used as a reference database, considers the specifications of the building and the energy systems, geographic location and occupant's behaviour. Considering all of them, the EPH tool calculates the eight types of energy demand loads (excluding heating) on an hourly basis for every day of the year, and then totals the hourly calculations to obtain daily, monthly and annual values. The followed method is described as follows.

First, the EPH tool uses the energy profile from the *'HES survey'* considering the following parameters: all types of households, any size of dwelling, whole year around, all days, any household size, any type of family and electric primary heating. From the *'HES survey'*, only 9 households match the mentioned conditions. The *'24-Hour Profile Chooser Tool'* generates an energy profile with 10 minutes intervals, which is then converted into an hourly profile (see Table 10).

Table 10 – Hourly energy demand extracted from the '24-Hour Profile Chooser Tool' for households with electric primary heating only.

Time	Cold	Cooking	Lighting	Audio-visual	ICT	Washing	Water heating	Heating	Other	Not known	Shower
00:00	36.6	6.4	21.3	40.0	12.1	11.9	140.8	1115.5	3.0	49.6	8.4
01:00	36.2	2.1	11.3	29.2	13.3	9.1	127.6	741.3	1.7	56.8	0.0
02:00	34.9	1.2	5.8	13.2	12.1	8.8	62.2	505.4	1.4	31.1	0.0
03:00	35.3	4.8	8.6	11.5	12.5	7.5	25.3	335.6	1.5	66.1	18.1
04:00	35.6	7.9	6.5	10.6	12.1	6.3	223.4	294.5	2.3	82.6	0.0
05:00	35.1	12.9	7.6	10.0	12.0	6.3	62.3	274.1	3.7	54.4	7.8
06:00	33.0	28.2	9.4	10.9	13.0	5.0	62.6	165.2	2.2	56.5	48.7
07:00	37.1	52.2	11.9	18.5	14.8	20.0	74.8	131.3	4.6	43.6	81.1
08:00	36.6	112.0	11.3	29.9	17.9	41.1	57.0	96.5	12.8	50.4	57.2
09:00	37.1	76.9	10.5	45.6	20.1	60.9	68.5	91.3	15.1	60.5	27.7
10:00	37.4	115.9	11.2	42.2	19.7	86.8	56.7	74.9	7.8	62.9	5.6
11:00	39.9	208.4	10.7	45.6	19.6	104.2	25.5	48.1	4.2	82.2	20.0
12:00	39.1	139.3	9.9	53.1	19.5	130.6	41.3	36.7	5.7	76.8	67.3
13:00	40.8	62.5	9.2	38.7	18.5	122.9	33.7	37.2	2.4	63.2	13.3
14:00	37.2	48.6	8.8	30.7	18.6	118.8	25.7	21.0	2.1	47.1	6.1
15:00	39.6	93.8	8.3	36.7	21.8	117.8	64.6	23.7	1.5	49.0	6.7
16:00	40.4	140.5	15.8	48.8	16.7	104.4	76.5	31.3	2.0	64.1	11.4
17:00	41.2	139.6	25.8	57.2	17.6	76.4	58.9	53.0	2.7	108.1	5.9
18:00	39.7	57.9	43.5	68.1	18.3	107.1	63.2	51.0	1.8	110.3	13.5
19:00	40.3	65.4	58.1	64.2	19.9	107.5	71.6	79.8	2.5	120.4	1.1
20:00	40.0	71.6	64.0	62.2	19.5	69.2	40.3	113.1	2.9	94.4	4.0
21:00	38.7	57.2	70.2	71.2	19.0	47.4	53.3	100.1	4.4	102.6	17.3
22:00	38.7	47.7	68.4	76.2	19.9	68.8	20.3	387.0	3.6	94.3	25.4
23:00	36.9	16.3	48.3	61.7	17.2	43.8	26.6	1121.1	3.1	74.7	4.0

Then, the raw data from the *'24-Hour Profile Chooser Tool'* is interpreted and adapted for its use in the EPH tool. As a result, the hourly energy profile is as shown in Table 11:

Table 11 – Hourly energy demand adapted for the EPH tool. Variations are as follows: 'Water heating' and 'Shower' are added together and renamed as 'DHW', also 'Audio-visuals' are renamed as 'Media', 'Other' as 'Kitchen appl.' and 'Not known' as 'Portable Units'.

Time	Cold	Cooking	Lighting	Media	ICT	Washing	Kitchen appl.	Portable Units	DHW
00:00	36.6	6.4	21.3	40.0	12.1	11.9	3.0	49.6	149.1
01:00	36.2	2.1	11.3	29.2	13.3	9.1	1.7	56.8	127.6
02:00	34.9	1.2	5.8	13.2	12.1	8.8	1.4	31.1	62.2
03:00	35.3	4.8	8.6	11.5	12.5	7.5	1.5	66.1	43.5
04:00	35.6	7.9	6.5	10.6	12.1	6.3	2.3	82.6	223.4
05:00	35.1	12.9	7.6	10.0	12.0	6.3	3.7	54.4	70.1
06:00	33.0	28.2	9.4	10.9	13.0	5.0	2.2	56.5	111.3
07:00	37.1	52.2	11.9	18.5	14.8	20.0	4.6	43.6	155.9
08:00	36.6	112.0	11.3	29.9	17.9	41.1	12.8	50.4	114.1
09:00	37.1	76.9	10.5	45.6	20.1	60.9	15.1	60.5	96.3
10:00	37.4	115.9	11.2	42.2	19.7	86.8	7.8	62.9	62.4
11:00	39.9	208.4	10.7	45.6	19.6	104.2	4.2	82.2	45.5
12:00	39.1	139.3	9.9	53.1	19.5	130.6	5.7	76.8	108.6
13:00	40.8	62.5	9.2	38.7	18.5	122.9	2.4	63.2	47.0
14:00	37.2	48.6	8.8	30.7	18.6	118.8	2.1	47.1	31.8
15:00	39.6	93.8	8.3	36.7	21.8	117.8	1.5	49.0	71.3
16:00	40.4	140.5	15.8	48.8	16.7	104.4	2.0	64.1	87.9
17:00	41.2	139.6	25.8	57.2	17.6	76.4	2.7	108.1	64.7
18:00	39.7	57.9	43.5	68.1	18.3	107.1	1.8	110.3	76.7
19:00	40.3	65.4	58.1	64.2	19.9	107.5	2.5	120.4	72.7
20:00	40.0	71.6	64.0	62.2	19.5	69.2	2.9	94.4	44.3
21:00	38.7	57.2	70.2	71.2	19.0	47.4	4.4	102.6	70.5
22:00	38.7	47.7	68.4	76.2	19.9	68.8	3.6	94.3	45.7
23:00	36.9	16.3	48.3	61.7	17.2	43.8	3.1	74.7	30.6

Finally, the final energy demand profile is defined with the following variables:

1. Family type: size (F_{1FS}) and environmental attitude (F_{1EA});
2. Building type: size (F_{2BS}) and typology (F_{2BT}). The average consumption on an m^2 basis is the same irrespective of the type of house under consideration (Yohanis, et al., 2008).
3. Demand type:
   - Existence of demand reduction technologies: energy savings from demand reduction technologies are considered to be of 15% (Palmer, et al., 2013b).
   - Groups of appliances ($F3_{DT}$) connected to the PV/battery system (see Table 7).
   - Choice off-peak of the grid reduction: batteries are always charged up to 100% from 5 until 6 pm, from renewables if available or from the grid, so the house can run with energy from the batteries and be off-grid between 6 and 7 pm.

The EPH tool also considers the following data considerations and extrapolations, which are used in the calculations to find the final energy demand profile:

- The UK's households' average occupancy – In 2011, the average occupancy was 2.3 people per household, compared to 2.4 in 2001 (Office for National Statistics, 2011).
- The UK's households' average size – The average home in the UK is 85 m^2 and has 5.2 rooms (RIBA, 2011).

At the end, the EPH tool performs the hourly calculations for each group of appliances (i):

$$D_{H-i} = D_{AH-i} \cdot F1_{FS} \cdot F1_{EA} \cdot F2_{BS} \cdot F2_{BT}$$

Where:

D_{H-I} = Hourly energy demand for the customised household profile
D_{AH-I} = Hourly energy demand from Table 11.
F_{1FS} = Family size
F_{1EA} = Environmental attitude
F_{2BS} = Building size
F_{2BT} = Building typology

Figure 86 – Equation used to calculate hourly energy demand profile for the EPH tool.

4.2.2.1.2 Heating loads

The space heating demand is calculated on an hourly time basis using HTB2 (WSA, 2007), accounting for the parameters shown in Table 12; and with external plug-ins to simulate the energy systems as shown in Figure 87. The results are then used to create a tabular database for all the different EPH design variations considering the different locations, orientations, sizes, occupancy types, etc. The total heating demand is calculated by adding the space heating to the domestic hot water heating, which has been estimated using the equation from Figure 28 from Yao & Steemers (2005) and according to hourly hot water usage profile for household with children (Energy Saving Trust, 2008).

Table 12 – Simulation parameters used to run the modelling of the heating demand with HTB2 software.

Building (*.bld)	
Spaces	1 House 2 North Loft 3 South Loft
Construction (*.con)	
Materials U-Value - External walls and North roof South Roof Floor slab Windows	0.12 W/m²K 4.80 W/m²K 0.15 W/m²K 1.20 W/m²K
Heating (*.htr)	
Output / Input	1,365W / 425 W
Type	Convective
Temperature set point - Night (1am to 8am) Day (9am to 12am)	18°C 21°C
Ventilation (*.vnt)	
Air permeability value @50Pa	15m³/h/m²
Mechanical ventilation rate	0.5 ach or 125m³/h
Operation time	24/7, all year
Fan power	93 W
Small power (*.spw)	
Appliances	See Table 11
Simulation parameters (*.top)	
Time steps	1h
Run length	365 days
Tolerance	±0.2
Ground temperature	12°C

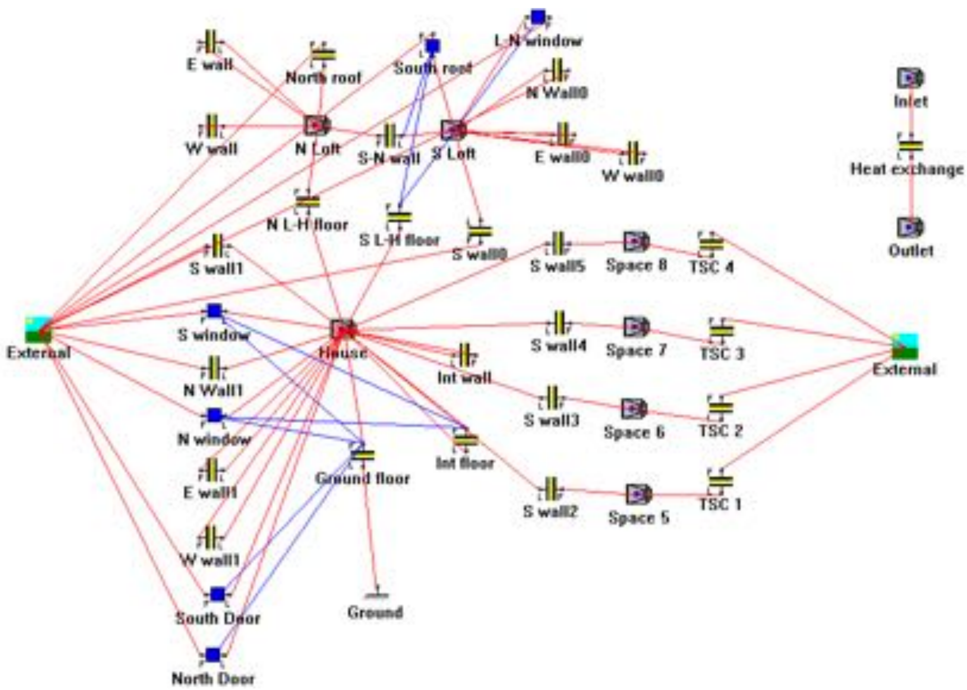


Figure 87 – Schematic of the model used to run the modelling of the heating demand with HTB2 software.

4.2.2.2 Renewables Supply

4.2.2.2.1 Solar Power

Literature indicates that modelling PV energy generation is reasonably straightforward and greatly dependent upon three factors (Thomas & Duffy, 2013), as follows:

- Solar angles: These include the latitude of the house, which depends on the location (see Table 8), and the azimuth and tilt of the PV system, which are chosen by the EPH tool user depending on the house design and orientation. With the solar angles for each system and the irradiance data for each location from Meteonorm; HTB2 is used to calculate the hourly irradiation incident on the PV panels per day, in kWh/m^2.
- Systems specifications: The HTB2's results are fed into the EPH tool, where the specifications are chosen. First, each hourly value (kWh/m^2) is multiplied by the PV area (m^2) and efficiency (%), to calculate the DC energy produced per hour every day (kWh) for each system. Next, following the methodology outlined in Goswami et al. (1999) the derate factors of the system are considered. These are multiplied by each hourly DC output to yield the hourly AC output of the customised PV system.
- Shading: Although the shading effect should also be considered, it is dismissed because the EPH tool aims to be used at early stages of the design process when the plot description is still unknown. However, if advanced users of the EPH tool want to consider shading by performing a shading analysis, the hourly shading data can be easily introduced into the EPH spread-sheet. Then, by multiplying the hourly AC output against the results of the shading analysis the EPH tool could potentially calculate a predicted AC energy output from the customised PV system for each hour, day, month and year.

To summarise, first the EPH tool user sets up the renewable energy supply options for a specific roof area, system size and building location (currently restricted to the UK); and then the EPH tool performs the hourly calculations based on the following equation:

$$S_{H\text{-}solar} = S_{H\text{-}roof} \cdot F_{Ar} \cdot F_{Eff} \cdot F_{DR}$$

Where:

$S_{H\text{-}roof}$ = Hourly Solar Irradiation falling on the roof (kWh/m^2). Note: 40 house prototypes modelled in HTB2, considering all roof variations (8 tilts and 5 orientations) for each location.
F_{Ar} = Roof area (m^2)
F_{Eff} = PV Efficiency Factor (%) Note: solar irradiation converted into electricity by the solar cell.
F_{DR} = Overall derate factor = 0.82. Note: PV module nameplate (0.95) and mismatch (0.98), inverter efficiency (0.95), diodes and connections losses (0.995), soiling (0.98), AC wiring losses (0.99), DC wiring losses (0.98), system availability (0.98) and components aging (1.0)

Figure 88 – Equation used to calculate hourly solar generation with the EPH tool.

4.2.2.2.2 Wind Power

Literature indicates that modelling of large wind turbines is reasonably straightforward but modelling of micro-wind is far more complex and is poorly understood (James, et al., 2010). However, the theoretical non-linear effect of the wind speed on the wind power is well known for being calculated with the following equation (Ziel, et al., 2016):

$$S_{H\text{-wind}} = \tfrac{1}{2} \cdot \rho \cdot C_P \cdot A \cdot (V_H)^3$$

Where:

$S_{H\text{-wind}}$ = Hourly supply from wind energy
ρ = Air density
C_P = Betz limit with a value of 0.4.
A = Swept area of the turbine blades. Note: For vertical axis, this is ($\Pi \cdot 2r \cdot h$), while for Horizontal Axis this is ($\Pi \cdot r^2$)
V_H = Hourly Wind Speed – From the weather data of each location, obtained with Meteonorm. Note: cut-in and cut-out speeds from typical wind turbine specifications.

Figure 89 – Equation used to calculate hourly wind generation with the EPH tool.

It should be noted that for the calculation of the wind output with the EPH tool, three important considerations are made to simplify calculations:

- The negative effect of turbulences is dismissed: Turbulence is a rapid change in wind speed, direction and incident angle and could particularly be an issue depending on the location of the wind turbine in the context of surrounding buildings and their impact on wind conditions. For example, micro-wind turbines mounted on buildings are within the turbulent boundary layer, hence are highly exposed to high turbulences.
- The exact location of the weather station is dismissed: Usually, wind speed data from commercial weather databases is measured in weather stations that are located in airports or urban locations. The exact context – i.e. rural, urban or sub-urban – of the modelled wind turbine may be very different and this can have a big impact on predicted performance. For example, James, et al. (2010) compared measured wind speed from 19 meteorological stations near micro-wind turbines against the 10 year average wind speed for the same sites provided by the weather database Meteonorm (Meteotest, 2009) and found that Meteonorm data was 6.1% higher than the measured. Considering that wind energy generation is proportional to the wind speed cubed, the wind output for a year could be 19% higher as a result.
- Air density is assumed to be constant; hence variations due to height, proximity to the sea or air temperature are dismissed.

4.2.2.3 Storage

The tool's user selects the desired energy storage system characteristics such as the battery size and its operating conditions. Once the customised battery settings are selected, the EPH tool proceeds to do the calculations.

First, the hourly energy balance between supply and demand is calculated by considering the hourly energy difference between total energy demand and supply. If result is positive it means that there is an energy excess, so electricity can be stored into the energy storage system or exported to the grid if batteries are full. Otherwise, if result is negative it means that there is an energy deficit, so electricity needs to be supplied from batteries or, in 'back-up' mode, provided from the grid. Another option, which does not depend on the energy balance between supply and demand, is when the 'peak of the grid reduction' option is chosen. Then, batteries are always charged up to 100% from 5 until 6 pm, from renewables if available or from the grid, so the house can run with energy from the batteries and be off-grid between 6 and 7 pm.

Second, the EPH tool models the performance of the battery across the year by simulating the percentage of battery capacity in an hourly basis. For this modelling, two important considerations are made. First, the initial state of charge of the battery is assumed to be fully charged at 100%. Second, the battery's status is defined by one of the following conditions:

- Full: Battery is at 100% so energy surplus from renewables is fed into the grid;
- Charging: Battery is charged from renewable energy only when it is not full and there is surplus of electricity from renewables;
- Discharging: Battery is discharged to supply the demand loads from the house, only when the demand cannot be met by the direct energy supply from renewable and the batteries are still not empty;
- Waiting: Battery's capacity has reached the depth of discharge limited by the tool's user and recommended by the battery's specification, therefore the battery goes in stand-by mode and waits to be charged when there is excess from renewables again. The battery is always only charged from renewables, unless the 'peak of the grid reduction' option is chosen.

Considering these considerations, the EPH tool models the hourly performance of the battery system by adding the hourly energy excess or subtracting the hourly energy deficit from the battery capacity of the previous hour. As a result, the current energy capacity is found for every hour of the day, all year around.

4.2.3 OUTPUTS

Assuming that appropriate information is at hand, the EPH tool can generate an entire energy assessment in less than 5 minutes. The outputs of the calculation are presented considering the three main elements of the systems approach – i.e. energy demand, energy supply, energy storage – and also considering the overall performance of the systems against the energy trilemma.

The EPH tool allows the user to instantly see how changes on the systems' characteristics have an impact on the output results. Therefore, the EPH tool not only provides a final solution but also allows the user to compare it with different design options and sizing variations. What differentiates the EPH tool from other existing modelling tools for hybrid energy systems, is the ease at which the user can consider the implication of introducing battery energy storage or a bigger PV area into the system. In account of that, size, dimensions and weight of the PV, wind or battery systems are known in the early design stage, so architects can integrate them in the building.

Regarding energy related outputs; these are presented at different metric levels – i.e. daily, monthly and annually – because the analysis at different scale aggregations can produce remarkably different results with unique and different outcomes. For example, daily data is useful as it is better for short-term/medium tactical forecasting, it allows identifying days of the week that have different patterns, and it allows a more detailed prediction of patterns of energy use as well as of peaks of demand and supply. However, the huge amount of data can make it slower to process and sometimes difficult to understand. Monthly data is faster to process, easier to model, easier to identify changes in trends and better for strategic long-term predictions. Finally, annual data allows evaluating the overall performance of the systems for one year, hence assessing the balance between seasons and evaluating if differences between them make the system still viable.

4.2.3.1 Demand

The electric demand profiles are shown in 'Page 2' of the EPH tool and are split into four different categories: appliances, lighting, cooking and heating. This allows the user to see which category consumes more or less and when the peaks of consumption occur. Although the appliances' calculations consider several types of appliances, as explained in section 4.2.2.1.1, the final graph shows all the appliances grouped together to make results clearer and more readable.

Figure 90 shows ‘Page 2’ of the EPH tool with three graphs that are respectively presented on an hourly per day, monthly per year and annual summary output. On the top of each of these graphs, the energy demand from lighting, appliances, cooking and space/water heating is shown also in numeric values.

Graph 1 allows the users to choose which day of the year they want to visualise by using the scroll bar located under the graph. Once the date is selected, the tool shows the hourly demand profile of each type of energy load category for the specific day. In graph 2, a bar chart shows the monthly profile of energy use for each type of energy demand category. Finally, graph 3 gives an annual summary of the amount of energy that each demand category consumes in kWh/m^2 and the percentage that this represents.

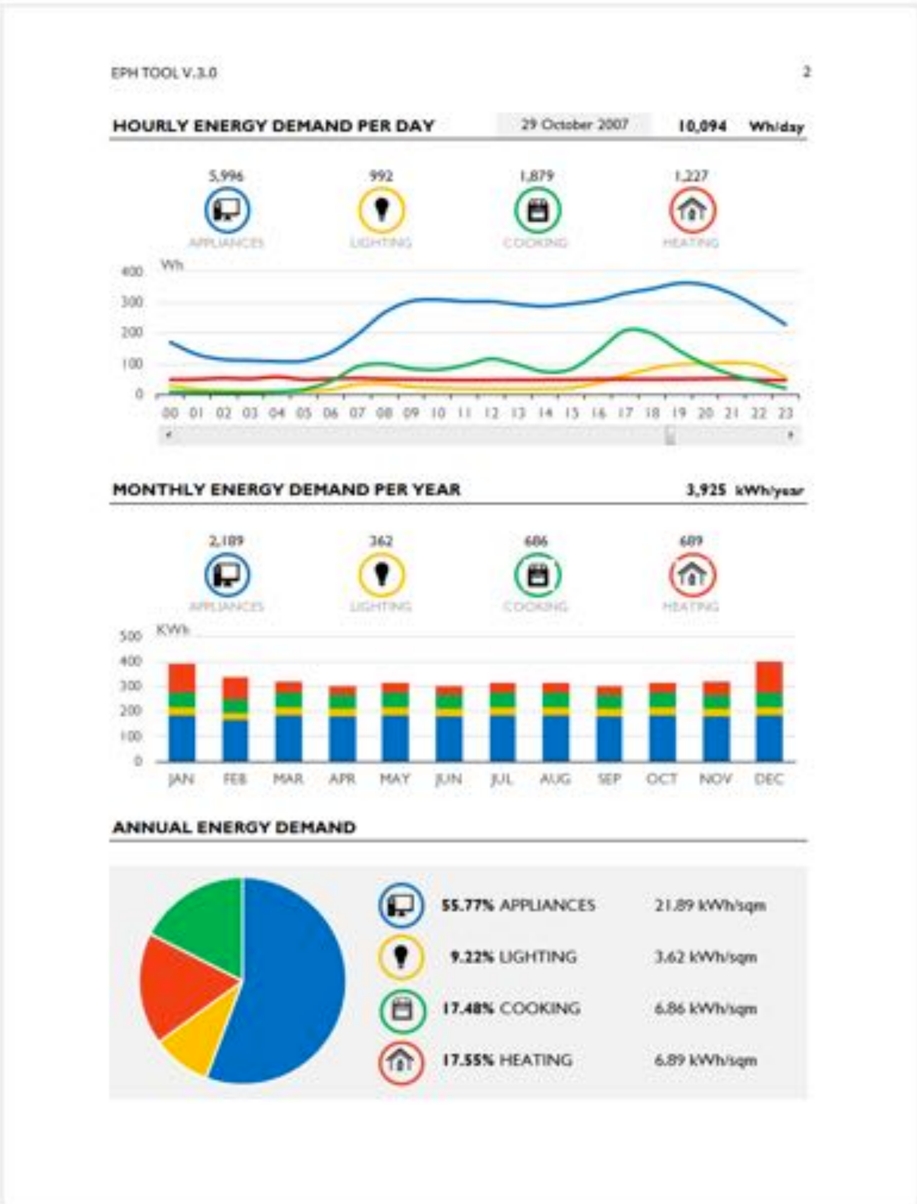


Figure 90 – Screenshot of the EPH tool v.3.0., page 2, showing Solcer House case study. Graph 1: Hourly energy demand per day. Graph 2: Monthly energy demand per year. Graph 3: Distribution of annual energy demand.

4.2.3.2 Supply

The energy supply results are shown in 'Page 3' and 'Page 4' of the EPH tool. The third page focuses on energy supply from renewables while the fourth page considers where the energy supply to meet the demand comes from – i.e. direct renewables, batteries or grid –.

Figure 91 shows 'Page 3' of the EPH tool with three graphs that represent respectively the hourly renewables supply per day, the monthly renewables supply per year and the annual PV area size optimization output. In these graphs, renewable supply profiles are separated by type of energy source, thus solar and wind energies are shown in yellow and blue respectively. Graph 1 allows the users to choose which day of the year they want to visualise by using the scroll bar located under the graph. Once the date is selected, the tool shows the hourly supply profile of both solar and wind power. In graph 2, the bar chart shows the monthly variations of solar and wind energy outputs, and also how the combination of both energy sources can contribute to the seasonal and annual balance. Finally, graph 3 indicates the optimised area of PV needed to achieve a Net Zero Energy (NZE) house and compares this given value with the PV area selected by the user of the EPH tool. To calculate the NZE area, the monthly energy demand is compared with the monthly supply from renewables to make sure that supply matches the demand on a monthly basis and there is no lack of energy from renewables, hence that the ratio between supply and demand is always at least 1:1.

Figure 92 shows 'Page 4' of the EPH tool with three graphs that represent the hourly energy supply per day, the monthly energy supply per year and the annual performance of the energy storage system. The graphs show the source of the energy supplied to meet the energy demand of the house. Therefore, they simulate the performance of the energy supply and how energy to the house comes directly from renewables (green), the battery store (blue) and/or the grid (red). Graph 1 allows the users to choose which day of the year they want to visualise by using the scroll bar located under the graph. Once the date is selected, the tool shows in an hourly basis whether the energy supplied to the house comes directly from renewables, from the batteries or from the grid. In graph 2, the bar chart shows the total monthly supply of energy coming directly from renewables, battery store or grid. Finally, graph 3 considers the energy storage performance and is described in the next section.

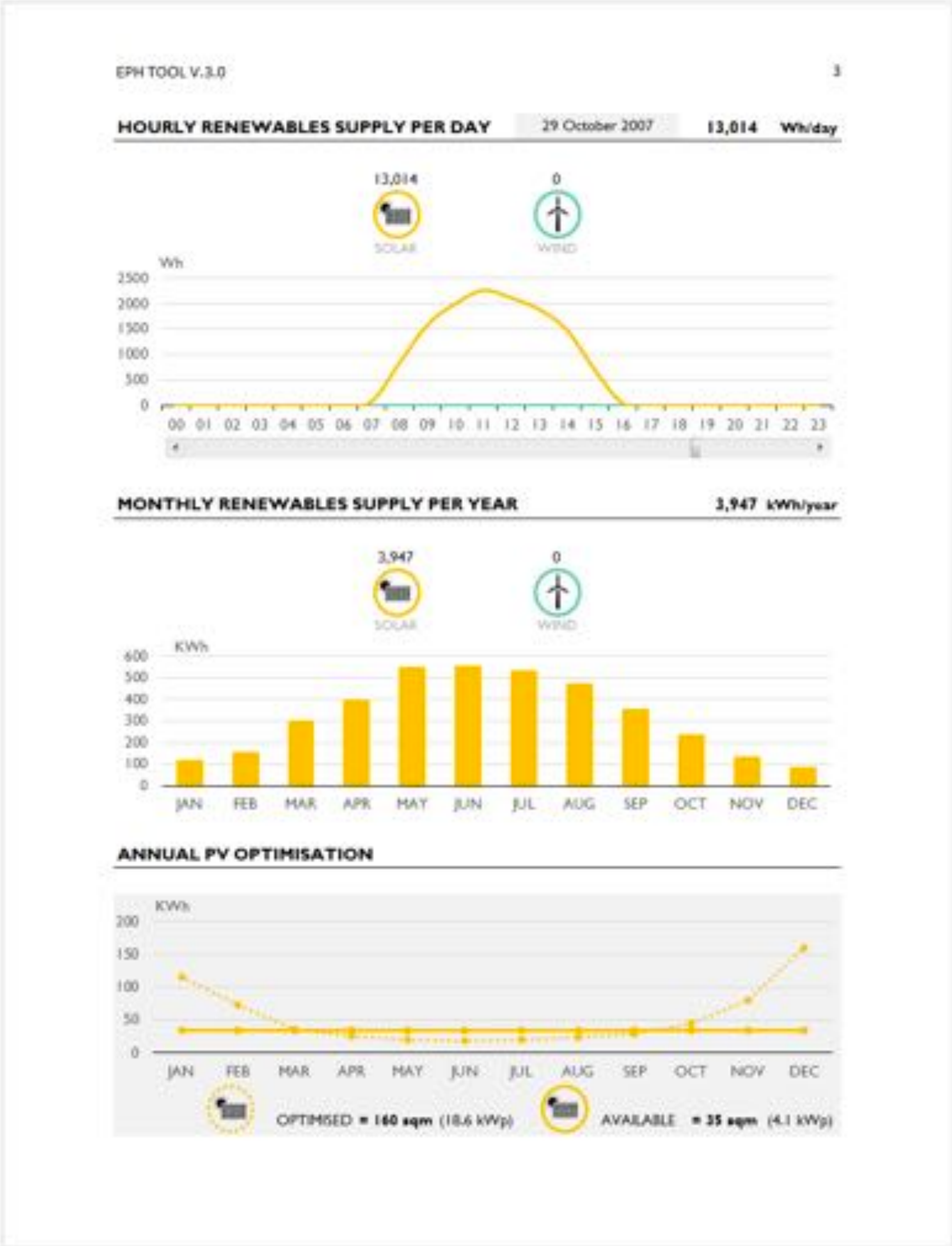


Figure 91 – Screenshot of the EPH tool v.3.0., page 3, showing Solcer House case study. Graph 1: Hourly energy supply from renewables per day. Graph 2: Monthly energy supply from renewables per year. Graph 3: Annual PV size optimisation for a NZE house.

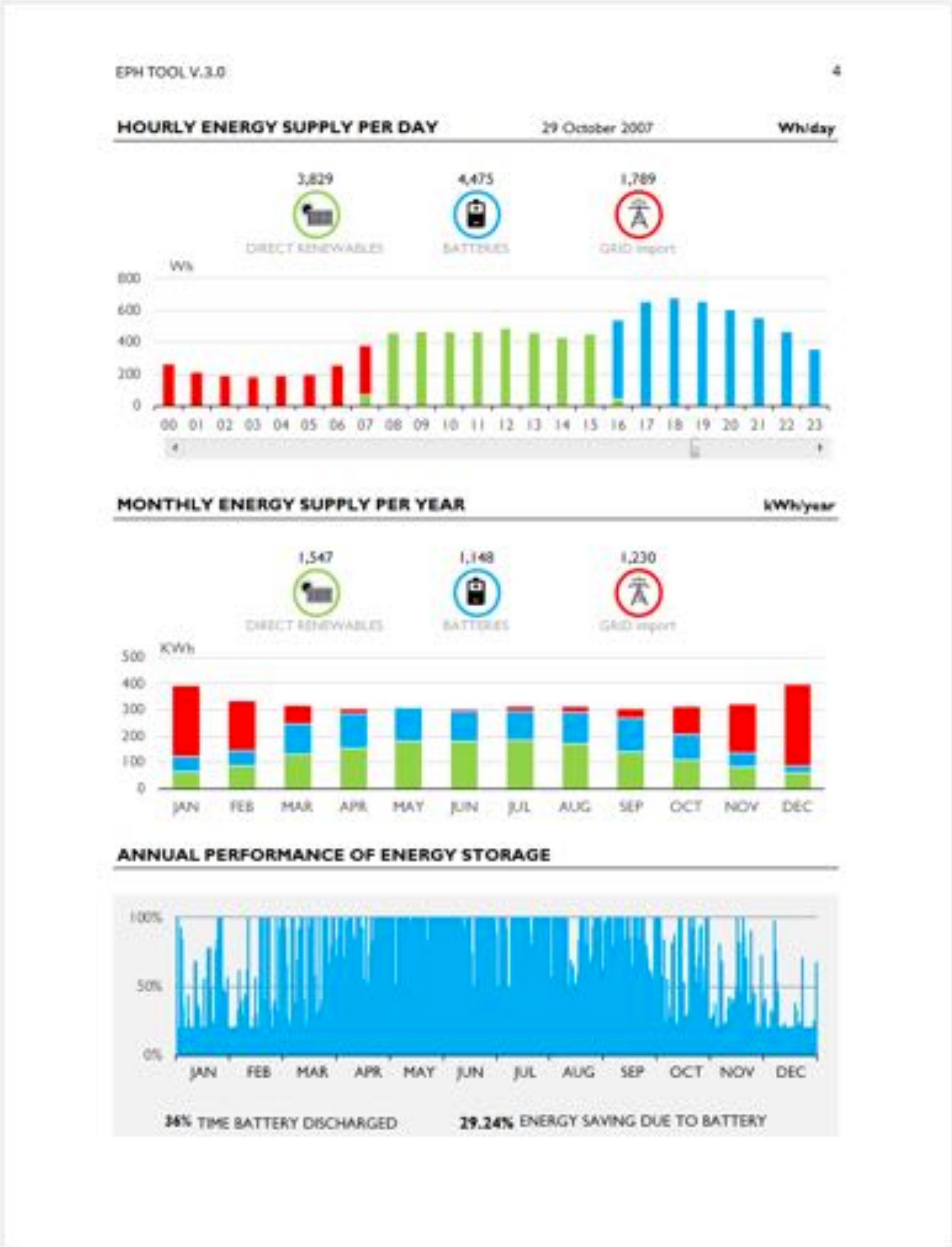


Figure 92 – Screenshot of the EPH tool v.3.0., page 4, showing Solcer House case study. Graph 1: Hourly energy supply per day. Graph 2: Monthly energy supply per year. Graph 3: Annual performance of energy storage.

4.2.3.3 Storage

The performance of the battery system is shown in the last graph of 'Page 4' (see Figure 92), which simulates the annual state of charge of the battery system at an hourly basis. The graph shows an indicative performance of the battery system across one year by plotting battery's hourly operational use as a percentage of its full charge capacity. It is important to highlight that the discharge rate has an impact on the overall battery system capacity, and this can be appreciated in this later graph. Also, the percentage of time that the battery is discharged and the percentage of energy saving due to the storage system are both indicated at the bottom of the graph.

4.2.3.4 Summary systems approach

Finally, 'Page 5' and 'Page 6' of the EPH tool show the performance of the whole energy system and how the different components or technologies work together from both an energy view and an economic view.

First, in 'Page 5' an evaluation from an energy perspective is done, by considering how the energy demand from the house is covered either with renewable energy used directly or stored in the batteries, or with the grid. To guarantee a good performance of the overall systems approach it is important to maintain always an energy balance between the energy going into the system and the energy going out. The systems energy balance is based on the following equation:

$$\mathbf{Ei = Eo}$$

$$\mathbf{I_{DR} + I_B + I_G = O_D + O_B + O_G}$$

Where:

E_I = Energy input or energy from outside the house. That being:

- I_{DR} = Energy from renewable sources that is used directly into the house.
- I_B = Energy from the batteries.
- I_G = Energy input from the grid at times when renewables or batteries are not sufficient.

E_O = Energy output or energy to the house. That being:

- O_D = Energy to the house's appliances, lighting, heating and cooking devices.
- O_B = Energy output to the batteries that is stored for a later use.
- O_G = Energy output to the grid that is exported when there is an excess of renewables generation and the batteries are already full.

Figure 93 – Equation used to calculate the systems energy balance with the EPH tool.

Figure 94 shows 'Page 5' of the EPH tool with three graphs that represent respectively the hourly system's performance per day, the monthly system's performance per year and the annual performance of the system's performance. The Y axis of the graphs show positive values for energy inputs to the house – i.e. renewables, battery, import from grid – and negative values for energy outputs from the house – i.e. demand, battery, export to grid. Moreover, the last graph evaluates the energy performance of the system by indicating:

- Autonomy: Percentage of energy self-sufficiency that the house achieves yearly.
- Supply / Demand: Ratio of energy supply from renewables against energy demand from the house. For example, 2:1 indicates that for each 2kWh of energy supplied from renewables, the house consumes 1 kWh; while 0.5:1 indicates that for each 0.5kWh of energy supplied from renewables, the house consumes 1 kWh. The value of this ratio is used to evaluate whether the house is 'Nearly Zero Energy' (ratio is below 1:1, 'Net Zero Energy' (ratio is 1:1) or 'Energy Plus' (ratio is above 1:1).
- Export / Import: Ratio of energy exported to the grid against energy imported from the grid. For example, 2:1 indicates that for each 2kWh of surplus energy from renewables fed into the grid, 1 kWh of energy is imported from the grid; while 0.5:1 indicates that for each 0.5kWh of energy fed into the grid, 1 kWh is needed from the grid. The value of this ratio is used to evaluate the potential of the house to be 'Energy Plus', being only an EPH design when the ratio is above 1:1.

Figure 95 shows 'Page 6' of the EPH tool, which evaluates the system from an economic point of view considering the household energy bills in a daily, monthly and annual basis. In contrast to the energy evaluation, the economic evaluation is highly variable as it depends on the Government schemes and subsidies defined by the 'Feed-in Tariff' (Ofgem, 2016) and on the price of the electricity from the grid. The rates of electricity used for the calculations with the EPH tool version 3.0 are as follows:

- Electricity bought from the grid: £0.132/kWh from the standard tariff for electricity from SAP 2012 (BRE, 2016).
- Generation rate for solar energy: £0.0425/kWh for solar photovoltaic (other than stand-alone) with total installed capacity of 10 kW or less. The higher rate is applicable since the proposed EPH design meets the Energy Efficiency Requirement (Kay, 2014).
- Generation rate for wind energy: £0.0839/kWh for wind with total installed capacity of 50kW or less (Ofgem, 2016).
- Export tariff: £4.91 for both solar and wind energy (Ofgem, 2016).

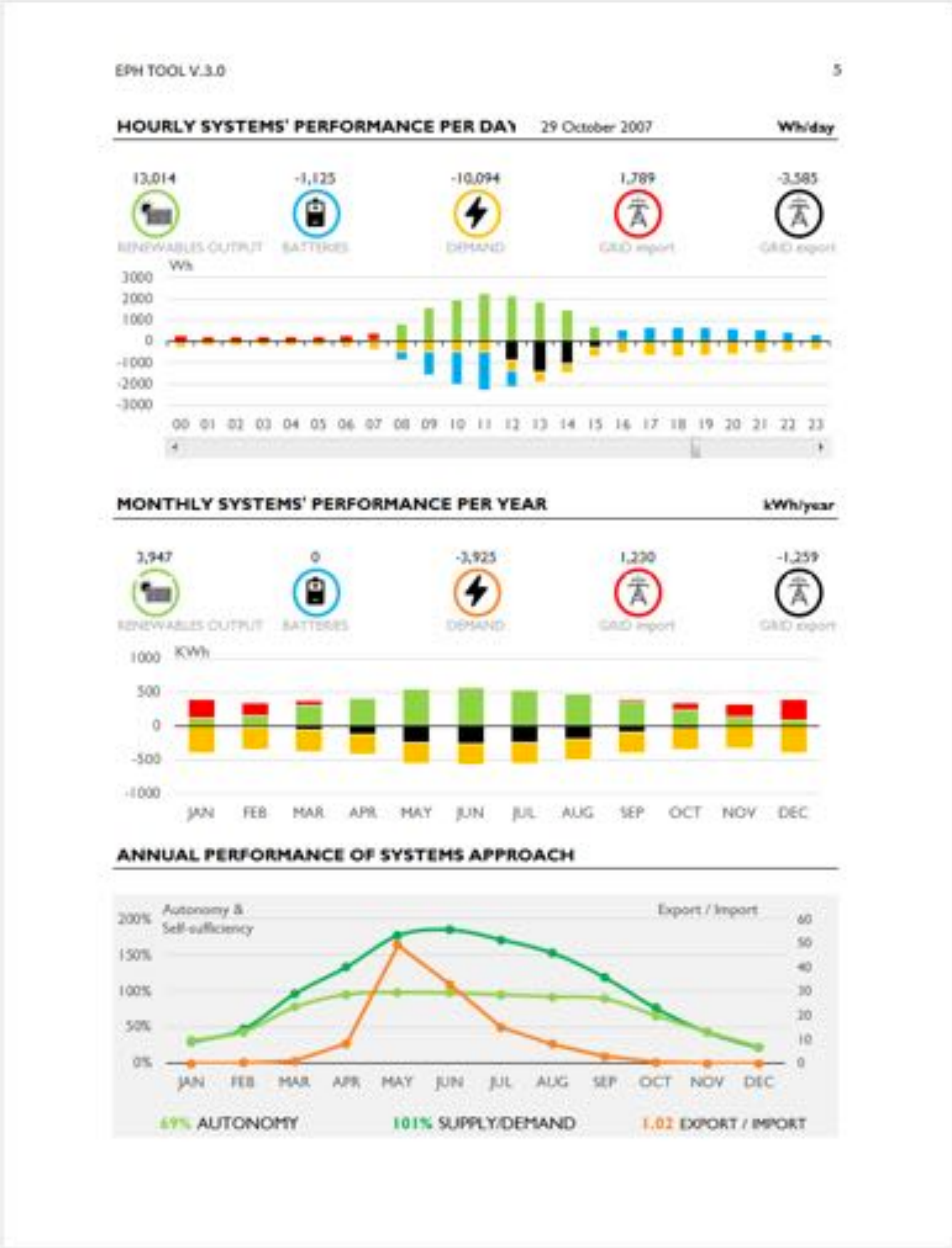


Figure 94 – Screenshot of the EPH tool v.3.0., page 5, showing Solcer House case study. Graph 1: Hourly systems' performance per day. Graph 2: Monthly systems' performance per year. Graph 3: Annual performance of the systems approach.

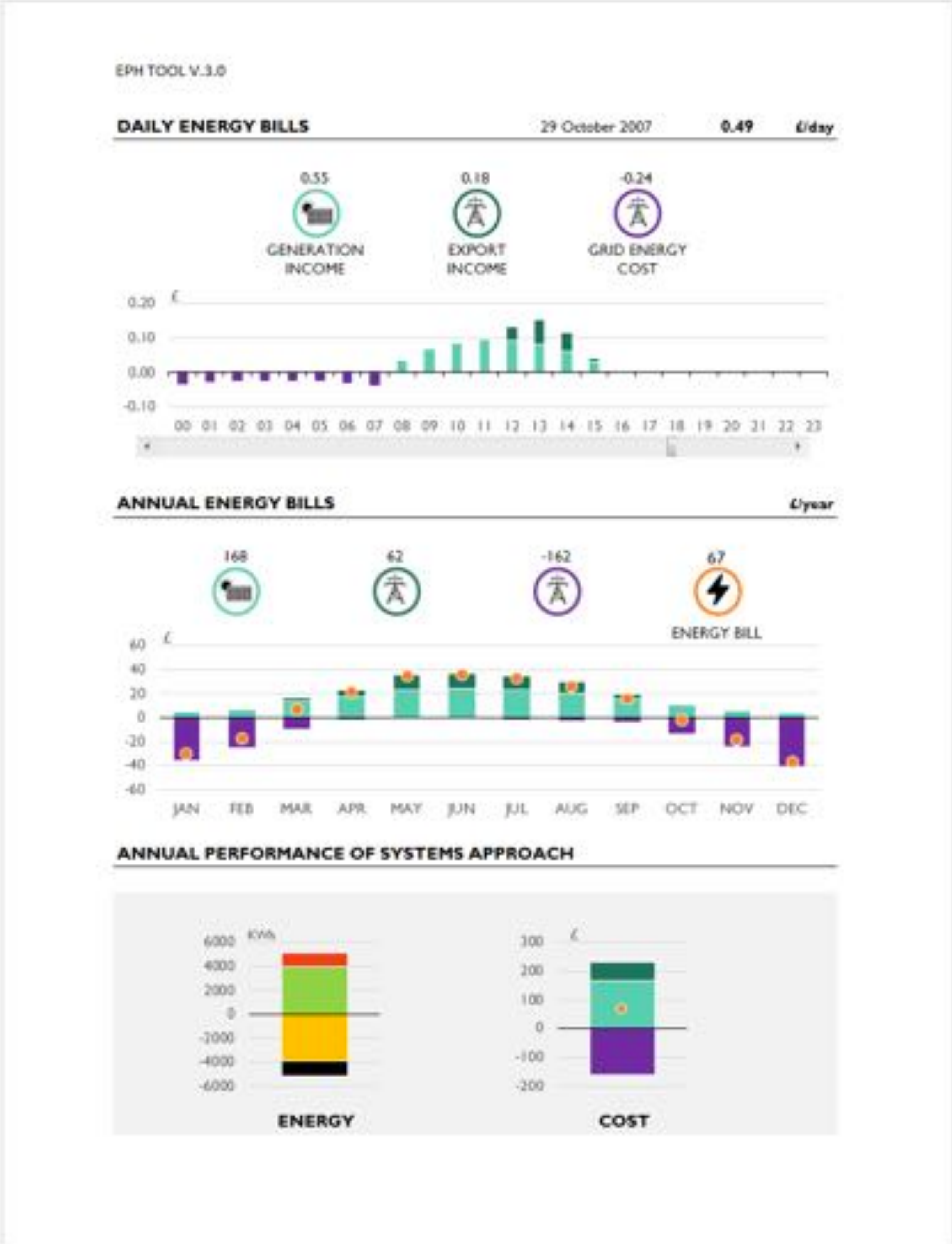


Figure 95 – Screenshot of the EPH tool v.3.0., page 6, showing Solcer House case study. Graph 1: Daily energy bills. Graph 2: Annual energy bills. Graph 3: Annual performance of the systems approach in terms of energy and cost.

4.2.5 APPLICATIONS

The review of existing research and literature allowed to identify the need for a simple and uncomplicated pre-design tool to run dynamic simulations with detailed data generated automatically in a visual environment. The EPH tool presented in this chapter has been developed as a versatile pre-design modelling tool to size renewable energy supply and storage integrated with the grid, to simulate the system's behaviour predicting demand, supply and storage profiles, and to evaluate the system's potential considering autonomy, supply/demand ratio and export/import ratio. All these different types of outputs indicate that the tool could potentially be used for a wide variety of applications. The next sections show examples of these different applications and give guidance on how to use the tool to achieve the results needed.

4.2.5.1 Parametric studies to size systems

The EPH tool can be used to size the energy system considering three different technologies: PV, wind turbines and batteries. For this type of application, the best approach is to run a parametric study of each technology, in other words, to maintain all the variables constant in the input page, 'Page 1', and only modify one variable at a time. For example:

- <u>PV design:</u> By changing the area, the orientation, the angle or the efficiency of the PV system in the energy supply section 'Page 1', the user could run a parametric study comparing these variables against the annual performance of the system in terms of its autonomy, supply/demand ratio or export/import ratio or the annual energy bills.

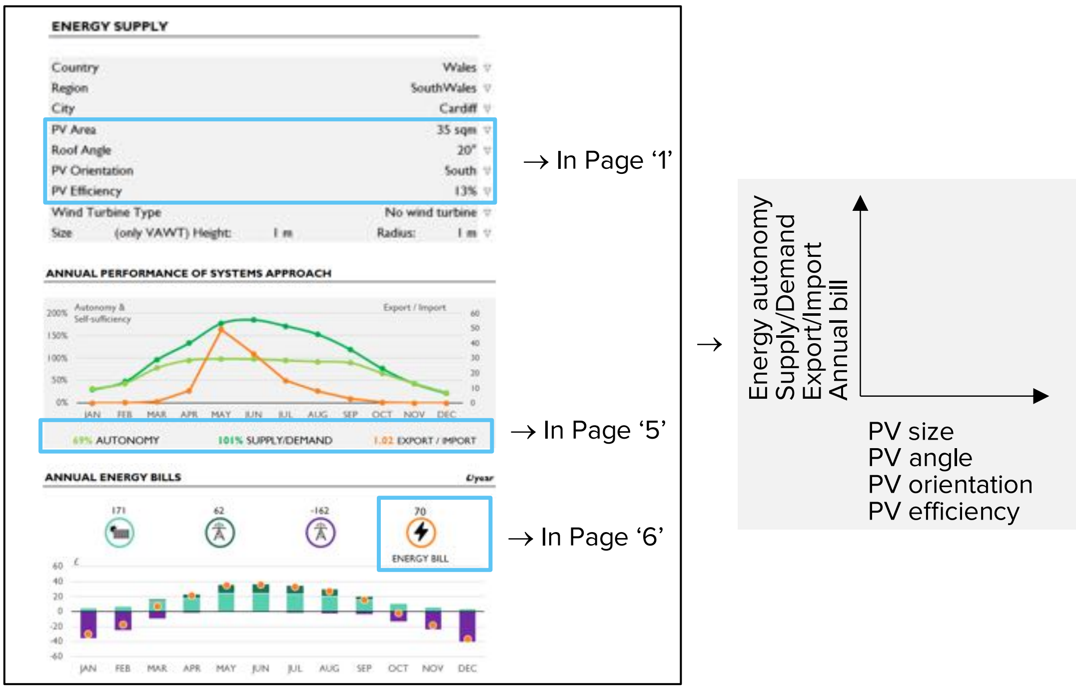


Figure 96 – Diagram showing how to run a parametric study for PV design with the EPH tool and potential graph outcomes.

- <u>Wind turbine design:</u> By changing the axis type, height, or radius of the wind turbine system in the energy supply section ‘Page 1’, the user could run a parametric study comparing these variables against the annual performance of the system in terms of its autonomy, supply/demand ratio or export/import ratio or the annual energy bills.

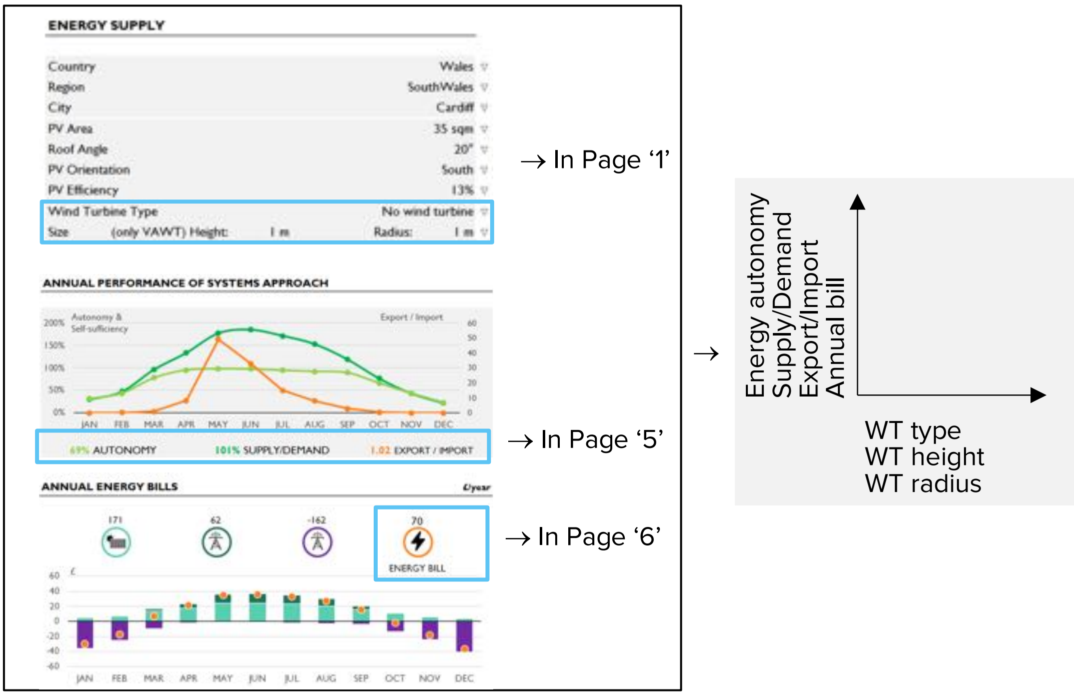


Figure 97 – Diagram showing how to run a parametric study for wind turbines design with the EPH tool and potential graph outcomes.

- <u>Batteries design:</u> By changing the type, size or depth of discharge of the battery system in the energy storage section ‘Page 1’, the user could run a parametric study comparing these variables against the annual performance of the system in terms of its autonomy, supply/demand ratio or export/import ratio or the annual energy bills.

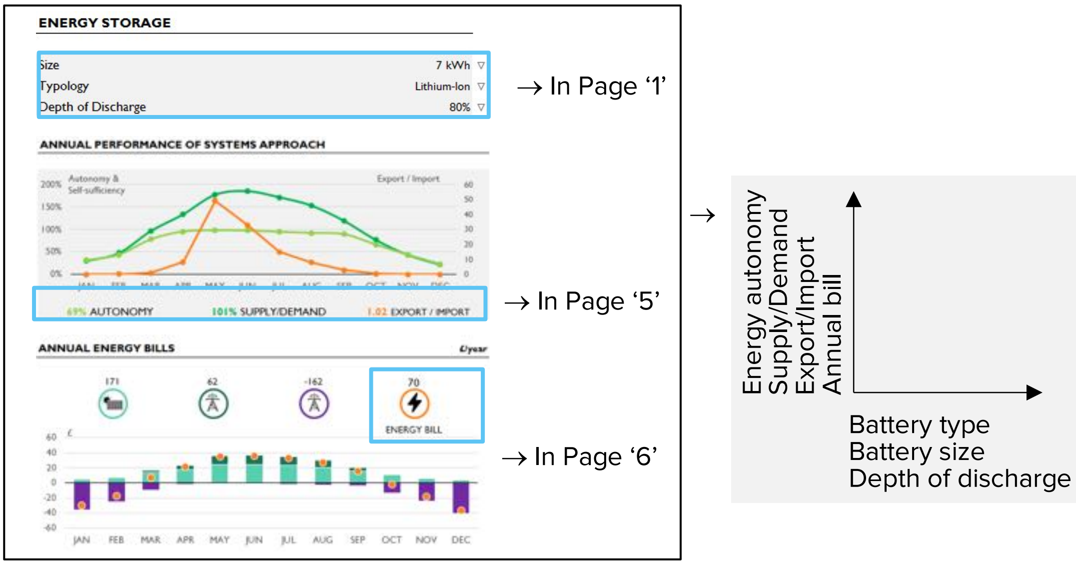


Figure 98 – Diagram showing how to run a parametric study for batteries design with the EPH tool and potential graph outcomes.

4.2.5.2 Daily analysis to understand seasonal performance

The EPH tool can be used to analyse the seasonal performance at a daily basis of different energy components as well as of the whole energy system. For this type of application, the best approach is to look at the EPH tool's daily graphs and select different days across the year that reflect the different climatic conditions across the seasons. For example:

- Sunny summer day: Figure 99 shows that energy generated from PV is three times the energy demand. Therefore, for the whole day, the house uses energy from renewables or batteries and is off-grid. In terms of energy costs, the daily bill for the householder is positive by about £2.20 thanks to the earnings from the FIT.

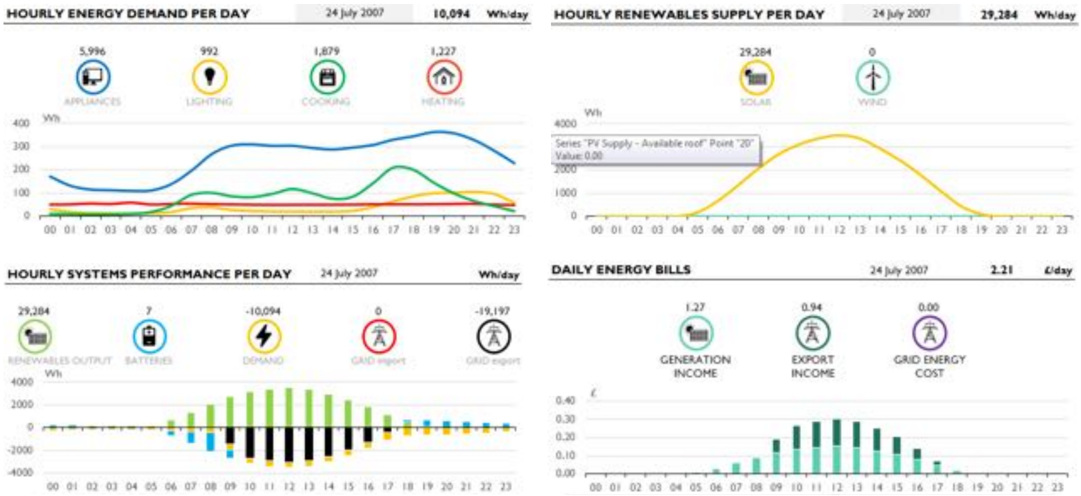


Figure 99 – Hourly graphs from the EPH tool used to run daily analysis for a sunny summer day.

- Overcast summer day: Figure 100 shows that energy generated from PV is less than the energy demand. Therefore, the house runs from renewables or batteries during the day but there is no solar excess to charge the batteries, thus the grid is needed at night. In terms of costs, the daily bill for the householder is about £0.

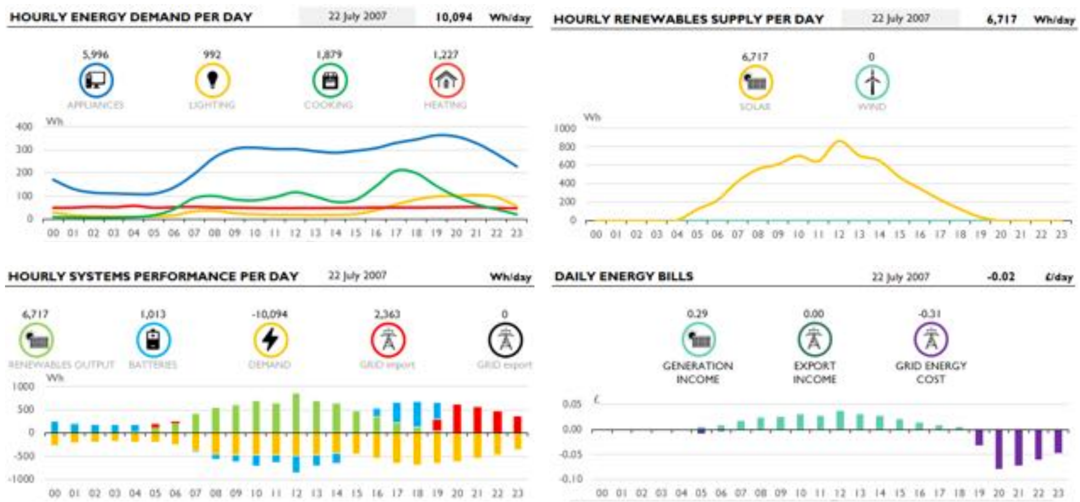


Figure 100 - Hourly graphs from the EPH tool used to run daily analysis for an overcast summer day.

- Sunny winter day: Figure 101 shows that energy generated from PV meets energy demand, which is lower because space heating benefits from solar gains. Therefore, the house runs from renewables or batteries from morning until midnight and only uses grid energy for a few hours in the early morning. In terms of costs, the daily bill for the householder is positive by about £0.50 thanks to the earnings from the FIT.

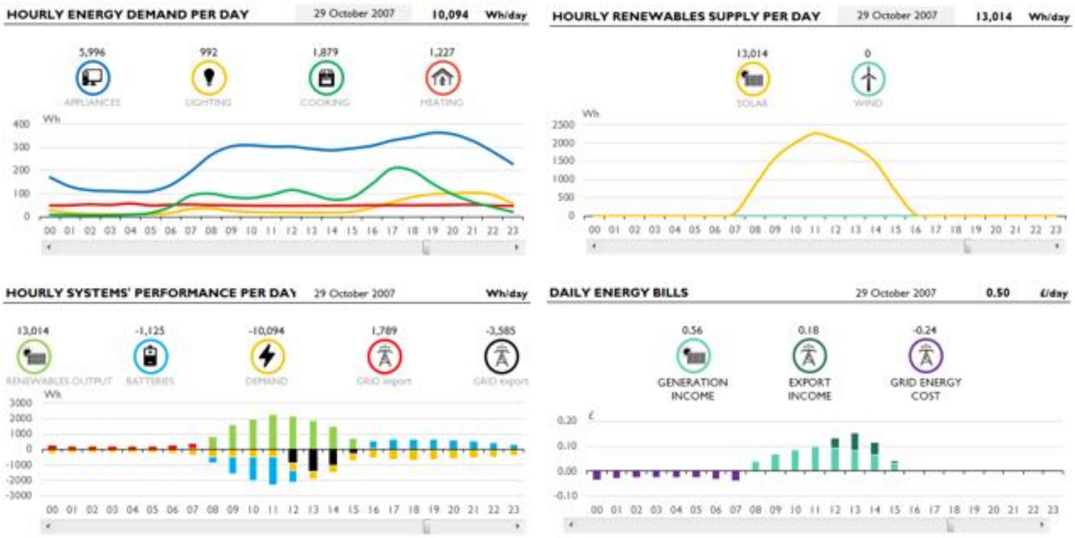


Figure 101 – Hourly graphs from the EPH tool used to run daily analysis for a sunny winter day.

- Overcast winter day: Figure 102 shows that energy generated from PV meets energy demand, which is higher because the house does not benefit from solar gains on that day. Therefore, the house can use only direct renewable for a few hours at noon and there is no solar excess to charge the batteries, thus energy from the grid is needed for most of the day. In terms of costs, the daily bill for the householder is negative by about £1, but still low in comparison with standard housing.

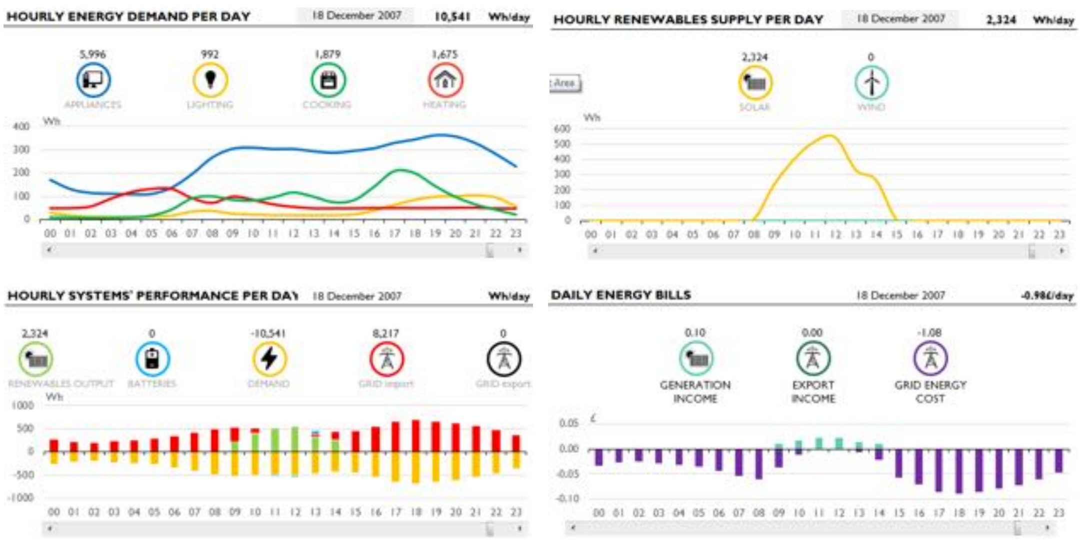


Figure 102 – Hourly graphs from the EPH tool used to run daily analysis for an overcast winter day.

4.2.5.3 Monthly analysis to select systems suitability

The EPH tool can be used to select the most appropriate energy technologies and calculate their payback time. For this type of application, the best approach is to look at the EPH tool's monthly graphs and evaluate the annual performance of the system in terms of its autonomy, supply/demand ratio or export/import ratio or the annual energy bills. For example:

- Batteries suitability: Figure 103 and Figure 104 show how the Solcer House will perform without batteries. As a result, the house reduces its energy performance significantly with autonomy going from 69% to 31% and the annual energy bills from earnings of £67/year to a payment of 28£/year. This indicates that batteries offer good energy benefits but not financial benefits because the cost of about £6,000 has a payback of over 60 years (excluding maintenance). Also, energy from grid is needed over the year although the supply/demand ratio is the same and still energy positive.

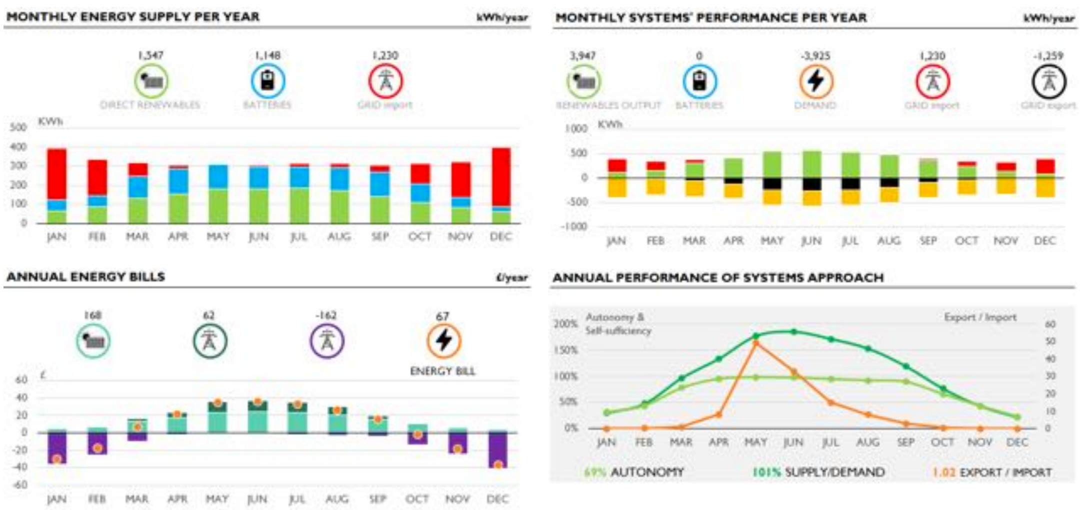


Figure 103 – Monthly graphs from the EPH tool showing the energy performance of the Solcer House case scenario with a 7kWh lithium-ion battery.

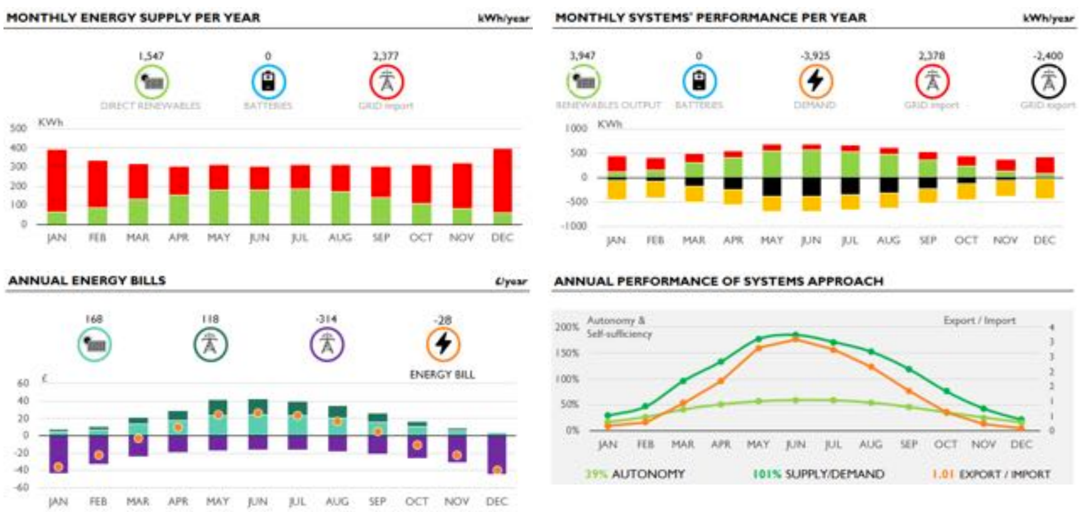


Figure 104 – Monthly graphs from the EPH tool showing the energy performance of the Solcer House case scenario without battery.

- Wind turbine suitability: Figure 105 and Figure 106 show how the Solcer House case study will perform after adding a small horizontal axis wind turbine into the energy system. As a result, the house increases its overall energy performance significantly with autonomy going from 69% to 91%, supply/demand ratio from 101% to 201%, export/import ration from 1.02 to 13.46 and the annual energy bills from earnings of £67/year to £349/year. This indicates that wind turbines offer good energy and financial benefits because the cost of about £3,000 has a payback of about 10 years (excluding maintenance). Also, the energy generation is more balanced across the year, with higher solar output in summer and higher wind output in winter.

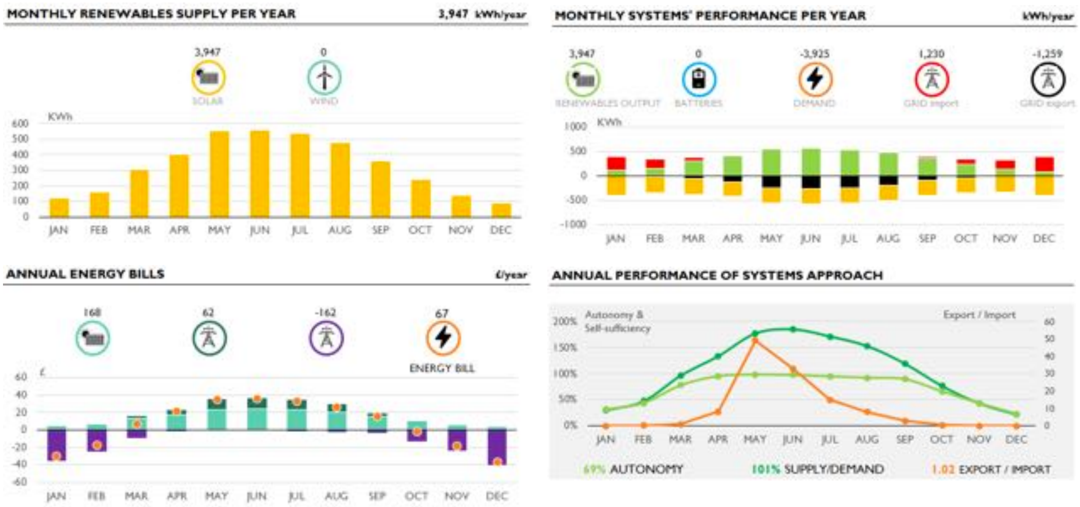


Figure 105 – Monthly graphs from the EPH tool showing the energy performance of the Solcer House case scenario with no wind turbine.

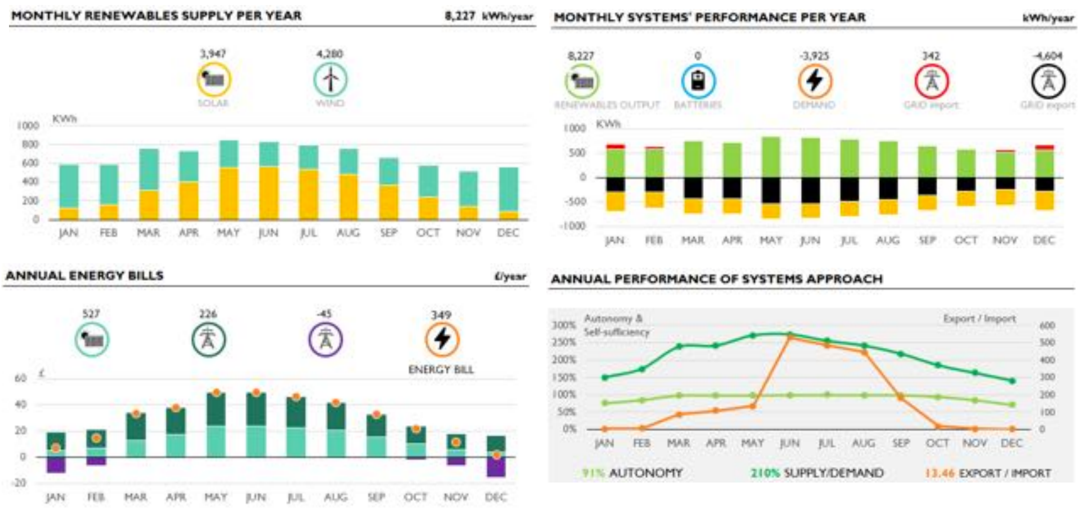


Figure 106 – Monthly graphs from the EPH tool showing the energy performance of the Solcer House case scenario adding a horizontal axis wind turbine of 2.5m height and 1.5m radius.

4.3 Summary

The modelling of building's energy systems is an interdisciplinary area of study which involves concepts and studies of electrical and electronics engineering, mechanical engineering, civil engineering and also, architecture (Harish & Kumar, 2016). The EPH tool aims to integrate all these disciplines together to achieve a holistic approach to energy modelling. While there is a wide variety of tools and software to model energy demand and supply, there is less software available to model energy storage. All of them were reviewed in section 2.2 to identify their pros and cons and their main outputs.

The EPH tool is operated through a simple MS Excel based user interface, which outputs the results of the system's simulated performance in an easy to understand reporting format. A major disadvantage of current simulation tools for architects and designers is their interface's complexity. Oppositely, the EPH tool has an intuitive interface and can be use in early stages of the design process by architects, designers or housing developers.

Literature suggests that various energy system configurations can be used for power generation, such as PV-wind-hydro systems, biomass-wind-hydrogen cell, PV-wind-diesel systems, etc. (Sinha & Chandel, 2014). The model presented in this thesis is a PV-wind-battery storage system and is chosen for its capability of being integrated into green building design, which could be applied to new build or retrofit. The EPH tool allows a detailed analysis of options to be carried out during early design stages to optimize the balance across reduced electricity energy demand, renewable supply and energy storage.

The EPH tool offers a combination of attributes, in the consideration of different approaches to the energy system design. It is a pre-feasibility tool to evaluate the cost-effectiveness and the potential savings of the systems. It is also a sizing tool for both renewable energy integrated systems and electrical energy storage systems. Finally, it is a simulation tool, which analyses the behaviour of the whole system by considering demand, supply and storage profiles. Moreover, the EPH tool addresses some of the main problems identified from the literature (Sinha & Chandel, 2014), by offering a sensitivity tool with full flexibility, a user-friendlier interface, a load demand management and an economic plan of system's cost.

5 Technology performance: EPH system

This thesis proposes the implementation of existing and emerging low carbon technologies into an EPH design through a systems-based approach by integrating energy demand, supply and storage technologies. The literature review presented in Chapter 2, section 2.3, studied existing and emerging low carbon technologies and the policy incentives to implement them and is used as a reference and guidance.

The design of the EPH system adopts a number of technologies and design approaches that are inspired from the literature review of this thesis. The selection of the technologies of the EPH system is a difficult decision because the technology market is constantly evolving and new products and equipment emerge every day. The UK Government acknowledges that innovation in energy technologies is essential if the UK is to meet the challenging energy security and carbon reduction objectives, hence in 2010 it established a Low Carbon Innovation Coordination Group to coordinate Low Carbon Technology Innovation (DECC, Oct 2012).

The technologies that constitute the EPH system need to be optimized through a systems approach, integrating reduced energy demand, renewable energy supply and energy storage. This systems approach allows combining electrical and thermal technologies, hence the EPH system can be all-electric and include space and domestic hot water heating, and electrical power.

The following sections describe all the technologies used for the EPH system and present the reason why they are chosen.

5.1 Analysis: Guidelines for the EPH system

5.1.1 ELECTRICAL ENERGY TECHNOLOGIES

The solar PV and battery storage are sized using the EPH tool presented in Chapter 4. The tool is used to optimise the sizing of the EPH system, to ensure the most efficient and effective balance is achieved between building integrated renewables, battery storage systems and grid-based electricity generation. The systems' sizing stage is a parametric study implemented once the EPH tool has completed calculating the energy performance of the whole system. This study allows to assess the optimum balance between electricity generated at the building, and grid-based supply, taking into consideration the energy demand, the size of the renewable energy system and the energy storage capacity.

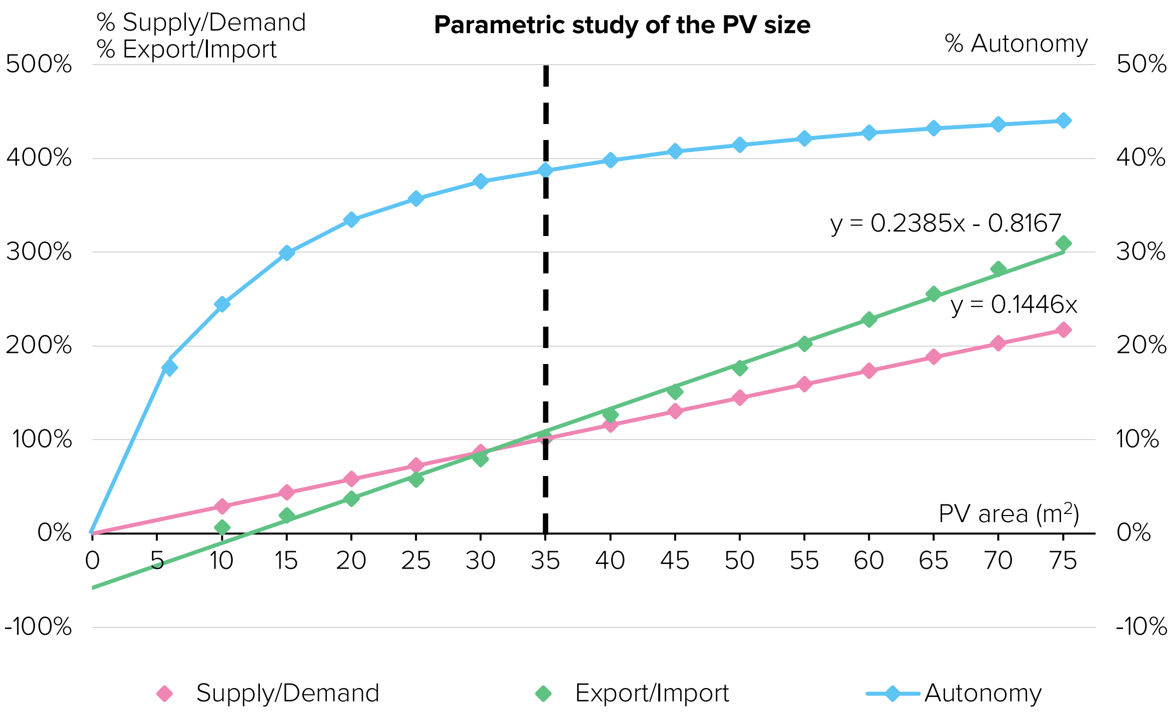


Figure 107 – Graph showing results of the parametric study for the optimisation of the PV size (system with no battery). Data source: EPH tool.

Figure 107 shows the influence that the PV size has on the EPH design's energy autonomy, the supply/demand ratio and the export/import ratio. It is found that an increase on the PV size has a linear effect on the increase of the supply/demand ratio and the export/import ratio, this means that a bigger area of PV has a proportionally higher export/import ratio. Instead, an increase on the PV size has a logarithmic effect on the increase of the house self-sufficiency, which means that a bigger area of PV has less apparent impact on the system's autonomy.

The optimum area of the PV system is chosen in regard to three conditions:

- Supply/Demand ratio ≥ 100%: To ensure that the annual energy supply from renewable technologies can meet the annual house energy demand. In other words, that over the course of one year the renewable energy generated on site is equal or more than the energy consumed by the house's appliances, lighting, cooking and heating systems.
- Export/import ratio ≥ 100%: To ensure that the annual energy imported from the grid can at least match the annual energy exported to the grid. In other words, that over the course of one year the energy imported from the grid, when there is no renewable energy available and the batteries are empty, is equal or less than the energy fed into the grid when there is an excess of renewable generation and the batteries are full.
- Autonomy: The house self-sufficiency will vary notably when the battery technology is added into the system, thus this parameter will be evaluated at a later stage.

Considering these three conditions, it is found that a PV area of 35m^2 will guarantee that the EPH design has at least 100% supply/demand ratio and 100% export/import ratio.

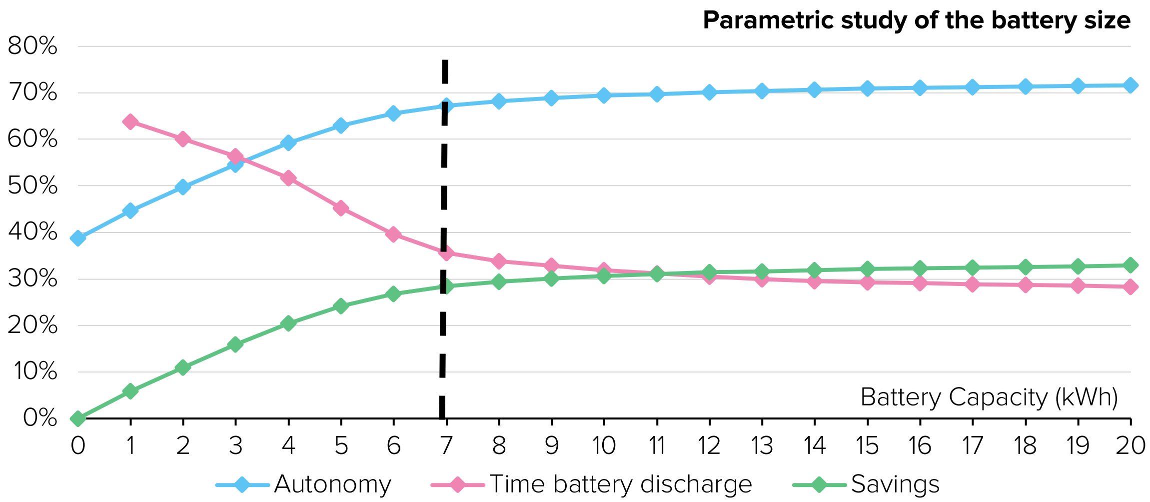


Figure 108 – Graph showing results of the parametric study for the optimisation of the battery size. Data source: EPH tool.

The next step is the sizing of the optimum battery capacity. Figure 108 shows the significant influence that the battery size has on the EPH design's energy autonomy, while it has no influence on the supply/demand and export/import ratio; hence these parameters are not plotted. To optimise the size of the batteries, two new parameters are analysed: the percentage of time that the batteries will be discharged over the year and the percentage of energy savings due to their implementation. It is found that an increase on the battery size has a logarithmic effect on the increase of the house energy autonomy and that the slope is almost flat after 7 to 8kWh. This means that an increase of the battery capacity from 1kWh to

7kWh would see the house autonomy going from 44.7% to 67.2%, an important 22.5% more; while an increase of the battery capacity from 7kWh to 20kWh would only see the autonomy of the house going from 67.2% to 71.2%, a meaningless improvement for such a big battery capacity. It is also found that energy savings achieved with an increased battery size follow a similar curve that runs almost in parallel to the autonomy curve, and that the slope is almost flat also after 7 to 8 kWh. Oppositely, the amount of time that the battery is discharged is less for a bigger battery size, but again the curve seems to have a much flatter slope after the 7 to 8 kWh. In conclusion, it is found that there is diminishing return for battery sizes greater than about 7kWh, hence the optimum battery capacity for the EPH system is 7kWh.

5.1.2 THERMAL ENERGY TECHNOLOGIES

A TSC is usually installed on all or part of a building's south-facing wall, where it will receive the maximum exposure to direct sunlight during autumn, winter and spring. The size of the TSC area varies depending on the climate as well as the heating and ventilation requirements. If space heating is a priority, the TSC should cover the maximum south-facing area available, but if ventilation is the only priority the TSC area should be optimised (US Dept. of Energy, 1998). Following the US Dept. of Energy method, the TSC area of the EPH system is calculated, which gives the area of TSC needed for pre-heating ventilation purpose. Calculations are as follows:

$$\mathbf{A_{TSC\,Min}} = \mathbf{V_B} / \mathbf{V_{Max}} = (120m^3/h) / (150\ m^3/h/m^2) = 0.8m^2$$

$$\mathbf{A_{TSC\,Max}} = \mathbf{V_B} / \mathbf{V_{Min}} = (120m^3/h) / (75\ m^3/h/m^2) = 1.6\ m^2$$

Where:

$A_{TSC\,Min}$ = Minimum area of TSC
$A_{TSC\,Max}$ = Maximum area of TSC
V_B = Building required ventilation rate = $120m^3/h$ (based on Passivhaus and BR standards)
V_{Min} = Minimum collector flow rate = typically about $75\ m^3/h/m^2$
V_{Max} = Maximum collector flow rate = typically about $150\ m^3/h/m^2$)

Figure 109 – Equation used to calculate the TSC area for pre-heating ventilation (US Dept. of Energy, 1998).

However, the aim of the designed TSC as part of the EPH system is to cover not only ventilation but also space heating needs, hence to maximise temperature rise and energy output. For this reason, the EPH system uses all the available area in the south elevation, which is $14m^2$, following the report from the US Dept. of Energy. The airflow rate through the TSC panels is reduced significantly due to this oversizing, being around $8.6m^3/m^2h$, which will have an implication on the systems efficiency. The relationship between airflow rate and efficiency of the TSC stated by the manufacturers is shown in Figure 110. Therefore, the TSC installed in the EPH system should have an expected efficiency of around 20%.

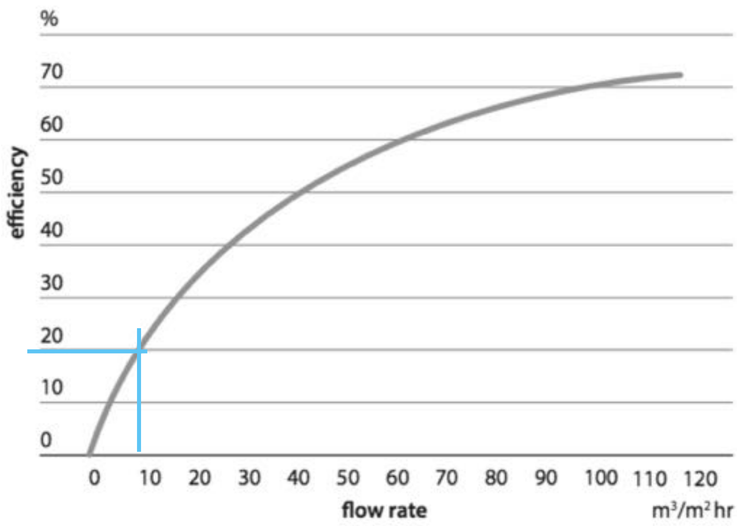


Figure 110 – Graph showing the TSC efficiency relative to airflow through the TSC collector (Tata Steel, 2016).

According to manufacturers, each square metre of TSC will raise the temperature of 75m^3/h by as much as 4.5°C, delivering as much as 750kWh/m^2 of installed TSC area (Tata Steel, 2016). Therefore, with a TSC area of 14 m^2 and a ventilation rate of 120m^3/h, the predicted temperature rise of the outside air after the TSC should be around 39°C in a winter sunny day. The amount of energy and money saved by a TSC depends on the type of conventional fuel being displaced, occupant use patterns, building design, length of heating season, and the availability of sunlight during the heating season. It is important to highlight that according to TSC manufacturers, small TSC collector installations will have proportionally higher construction costs, and that below a certain collector size, depending on the factors influencing project cost-effectiveness, construction costs will become prohibitive (Tata Steel, 2016).

5.2 Synthesis: Design of the EPH system

5.2.1 ELECTRICAL ENERGY TECHNOLOGIES

The results from the EPH tool presented in section 5.1 are used to choose the optimum design of the electrical energy technologies for the EPH system.

The electrical power system includes a large 4.35kWp glazed mono-crystalline PV array of 38m^2 in the south-facing roof, which consists on 40 panels of 100W each (1.2m x0.6m) and 8 panels of 44W each (0.6m x 0.6m). The PV system is fully integrated into the building fabric of the EPH design, which reduces costs compared to a solar PV system bolted on to a standard roof. It also provides a south roof space naturally lit, which makes the room more attractive and usable (see Figure 112).

The south-facing roof system uses transparent glazed PV panels, which are fitted onto an aluminium framework during installation (see Figure 111). This ensures a perfect seal without the need to install extra plastic membranes under the array. Also, as each PV panel is supplied complete with edge gaskets, there are no further membranes required to complete the sealing of the roof other than that you will find on a conventional tiled roof. Moreover, the aluminium framework has channels to remove condensation and to provide back-up drainage in the unlikely event the gasket is compromised. When the framework is in place, solar PV panels are added and the cap/sealing strips are riveted in place, retaining the panels by compressing the gaskets to form a perfect seal. The installation time is therefore less than a traditional tiled roof (GB-Sol, 2017).

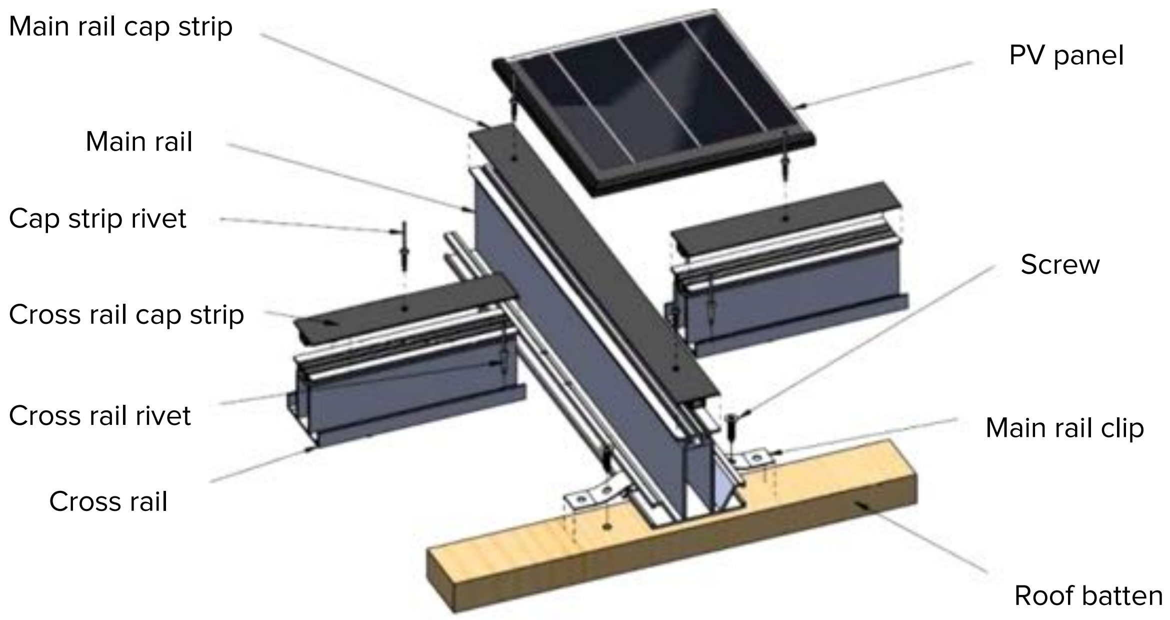


Figure 111 – Detail of the mounting schematic of the building integrated PV system. Source: (GB-Sol, 2017).

Figure 112 – Photos of the glazed mono-crystalline PV and LFP battery systems installed in the Solcer House.

The PV system is combined with a 7kWh lithium-iron-phosphate (LFP) battery, attached to the internal wall within the northerly roof space. LFP batteries, although more expensive than lead acid batteries, are preferred because they are lighter, have a bigger discharge rate and have a longer life (see Chapter 2).

The battery and PV array are connected through a DC-coupled system, which connects to an inverter to provide AC power to the house. This allows for higher system efficiency because there is only one total conversion DC to AC (Zipp, 2016). The backup grid supply connects into the AC circuit. The PV and battery storage system provides power to the EPH system, including appliances, LED lights, cooking and heating system, and any excess can be passed to the thermal store. The system draws from the grid when there is not enough power available for the PV and battery system.

5.2.2 THERMAL ENERGY TECHNOLOGIES

The thermal system includes a Transpired Solar Collector (TSC) and a compact unit with mechanical ventilation heat recovery (MVHR), an exhaust air heat pump and a thermal store. This system provides ventilation and space heating with air being supplied mechanically to the main living spaces and exhausted from the kitchen, shower room and bathroom. The internal temperature is set at 21°C. Details of the thermal system are presented in Table 13.

Table 13 – Specification of the technologies of the thermal system.

Technology	Specification	
TSC	Area	14 m^2
MVHR	Flow rate	120 m^3/h
Heat Pump	Capacity COP	585W 3.21
Thermal store	Volume	185L

The south elevation incorporates the TSC area, which collects solar thermal heat warming the incoming ventilation air to the building, which is used for space heating. The proposed EPH design has a very low heat demand and therefore should be heated through the ventilation system during most of the year. During the heating mode, external air preheated with the TSC is driven to the compact unit system.

The compact unit, commonly used in Passivhaus dwellings, combines heating, ventilation and hot water generation in one easy to handle unit; everything revolves around air, which acts as the transporting medium for heating and at the same time serves as the source of heat for the heat pump. The review of low carbon technologies in Chapter 2 shows that there are few options of compact units in the market capable to integrate within the same appliance an MVHR, an air heat pump for space and water heating and thermal store for domestic hot water (DHW). One of the technologies found at the time was the Genvex Combi 185 unit. This compact unit is powered either from the solar PV and battery system, or directly from the grid when the battery is exhausted. However, this unit as purchased does not allow to use the excess PV power to boost the temperature in the thermal storage; hence this solution would finally not be implemented in the EPH system as it would not be replicable.

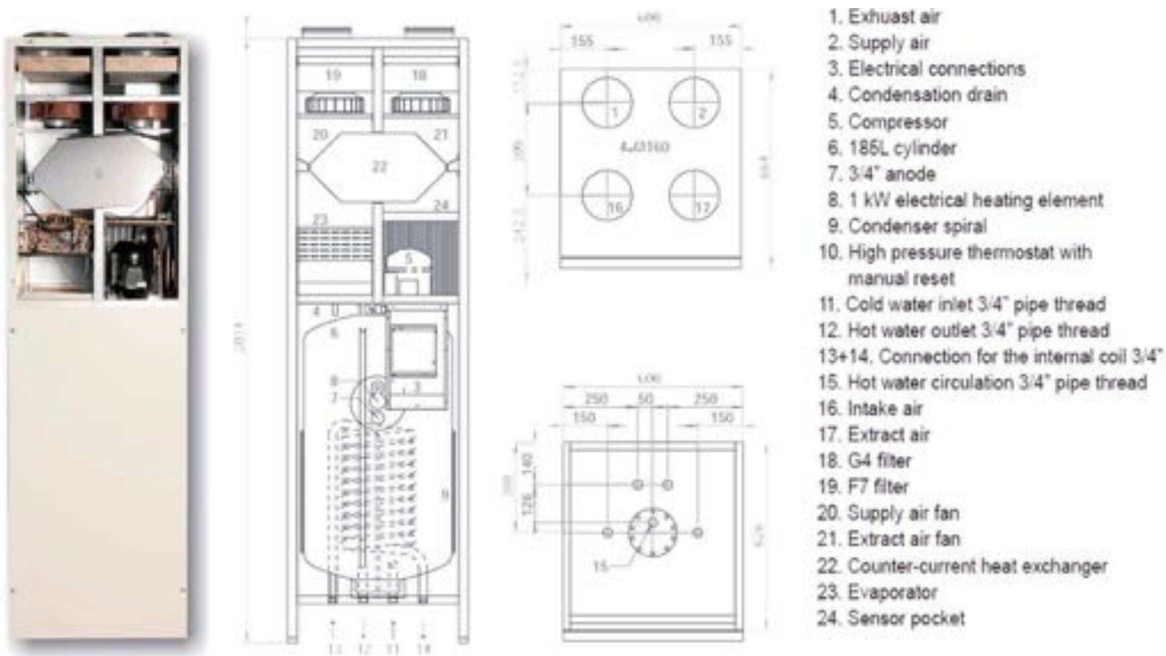


Figure 113 – Schematic of the Genvex Combi unit. Source: (Genvex, 2010).

Figure 113 shows the schematic of the Genvex Combi unit and helps to understand how the unit operates. First, the incoming supply air from the TSC passes through the MVHR. In the MVHR unit, the extract air from the house (17) passes through a heat exchange plate (22) where it exchanges heat with the incoming supply air (2) from the TSC, then the extract air is exhausted to outside (1).

When heating is required, the pre-heated supply air from the MVHR passes to the air heat pump to top up for space heating or for the DHW tank. The Genvex unit has one evaporator coil (23) and two condensing coils as part of the heat pump circuit. One condensing coil serves the water tank for DHW (9), and the other is located in the supply airflow for space heating (5). Depending on how the machine unit controls are set, it either heats the DHW store or space heating supply air, but it cannot do both at the same time. The user can set the priority, although the factory default setting is to prioritise heat for DHW. Once the 185 litres in the water tank (6) are up to temperature the unit automatically switches to space heating. It is important to highlight that the heat pump absorbs heat from the MVHR's exhausted air that is at internal air temperature, and as a result this allows to achieve a relatively high COP throughout the heating season. The manufacturers stated value of the COP of the heat pump is 3.21 (see Table 13).

When there is no demand for heat, the heat pump is switched off, but heat recovery through the MVHR continues. Also, when space heating is not required in milder weather, the TSC is bypassed, and the MVHR acts as a normal mechanical ventilation system. However, with the Genvex unit it is not possible to bypass the MVHR system in summer time, which could potentially lead to overheating problems.

Finally, air is delivered to the living room and bedroom, and extracted from the kitchen, bathrooms and utility area. The airflow design values are shown in Table 14. A rigid metal spiral duct system is installed in the ceiling, which provides the strength, longevity and airflow properties so often lacking in other duct types. The duct sizes are 160mm near the ventilation unit and 125mm to the ceiling terminals. The diameters are slightly larger than normal in order to lower the resistance to airflow, allowing better ventilation and lower running costs.

Table 14 – Design values for the heating/ventilation system.

	Extract air flow (l/s)			**Supply air flow (l/s)**	
	Low rate	**High rate**		**Low rate**	**High rate**
Kitchen	10.9	13	Living room	12.2	14.6
Utility	6.7	8	Bedroom 1	4.3	5
Bathroom	6.7	8	Bedroom 2	4.4	5.3
Shower room	6.7	8	Bedroom 3	10.2	12.2
Total extract	**31**	**37**	**Total supply**	**31.1**	**37.1**

In conclusion, the compact unit chosen for the EPH system combines heating, ventilation and hot water generation in one easy to handle unit; everything revolves around air, which acts as the transporting medium for heating and at the same time serves as the source of heat for the heat pump. This allows concentrating both the ventilation and the heating system on the element of air, avoiding the need of a wet heating system with radiators and pipework.

5.2.3 SYSTEMS APPROACH

Figure 114 illustrates the individual technologies and the overall EPH system. For electrical energy, power technologies of electrical supply (PV roof), electrical demand (LED lights and A+ appliances) and electrical storage (battery). For thermal energy, thermal technologies of heat supply (TSC), heat demand (compact unit) and heat storage (DHW water tank).

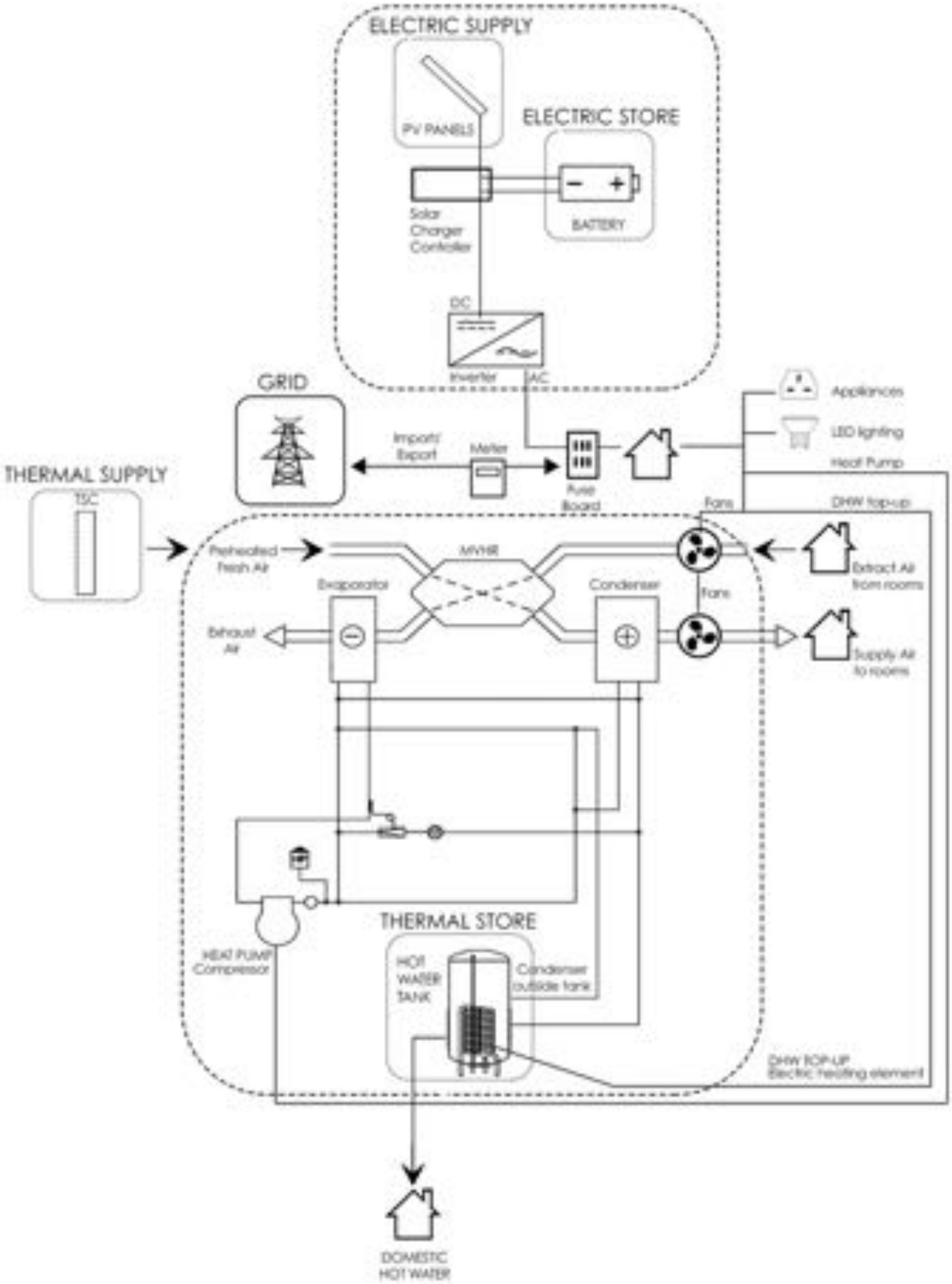


Figure 114 – Diagram of the EPH system with all the low carbon technologies integrated with a systems approach.

5.3 Summary

First, existing and emerging low carbon technologies reviewed in chapter 2 are analysed to select the most appropriate technologies for the EPH system. These are: PV and LFP batteries, for electrical energy; and TSC and compact unit with exhaust air heat pump and MVHR, for thermal energy. Their optimised size and specifications are calculated using the EPH tool. Accordingly, for electricity it is found that a 4.3kWp PV system could guarantee a supply/demand ratio and an export/import ratio of at least 100%, while a 7kWh LFP battery could guarantee at least 65% autonomy. For heating, the TSC is oversized with an area of 14m^2 to maximise temperature rise and energy output, despite the negative implication on the systems efficiency, which could drop to around 20%.

Second, the selected energy demand, supply and storage technologies are synthesised and combined to form a connected system which is then implemented and integrated into the EPH design described in the next chapter. Technologies' specifications are described justifying the reasons why they are chosen.

6 Architecture design: EPH design

The performance-driven approach proposed in this thesis aims to design an EPH design for a future low carbon built environment scenario. Accordingly, the EPH design should achieve a Passivhaus level of energy demand (Feist, et al., 2010), incorporating fully integrated renewable thermal and electrical energy supply, and thermal and electrical energy storage. The work relates to the ’Net Zero’ or ‘Energy Plus’ agenda (see section 2.4.9) being adopted by many governments in the bid to reduce CO_2 emissions and energy costs (European Commission, 2010).

As previously explained, the construction and use of the built environment currently accounts for almost half of the UK’s carbon emissions. Therefore, a major contribution to the energy trilemma debate could be achieved if modelling, design and performance were all integrated and involved across the decision-making cycle of housing projects – i.e. planning and design process, management and maintenance of buildings, advise on regional network strategies, or funding for new developments master plans. EPH approach could have a major bottom-up impact bringing together the many disciplines that make up our built environment.

To solve the energy trilemma, sustainable places have to be created, thus design needs to be used as a problem-solving process. Sustainable design is a fundamental part of any good design; they mutually support each other. No building can be considered well designed if it does not contribute to environmental, social and economic sustainability (CABE, 2007). Equally, no building can be considered sustainable if it is not well designed.

This chapter starts with an analysis of the green housing design principles and examples reviewed in Chapter 2 to learn the best of them, identify their limitations and establish the main design guidelines of the EPH design. The findings of the analysis of the review are then synthesised into the design of the proposed EPH design, which aims to integrate reduced energy demand, renewable energy supply and energy storage into the housing-scale modelling. Figure 115 shows the schematic of the design process of the EPH design.

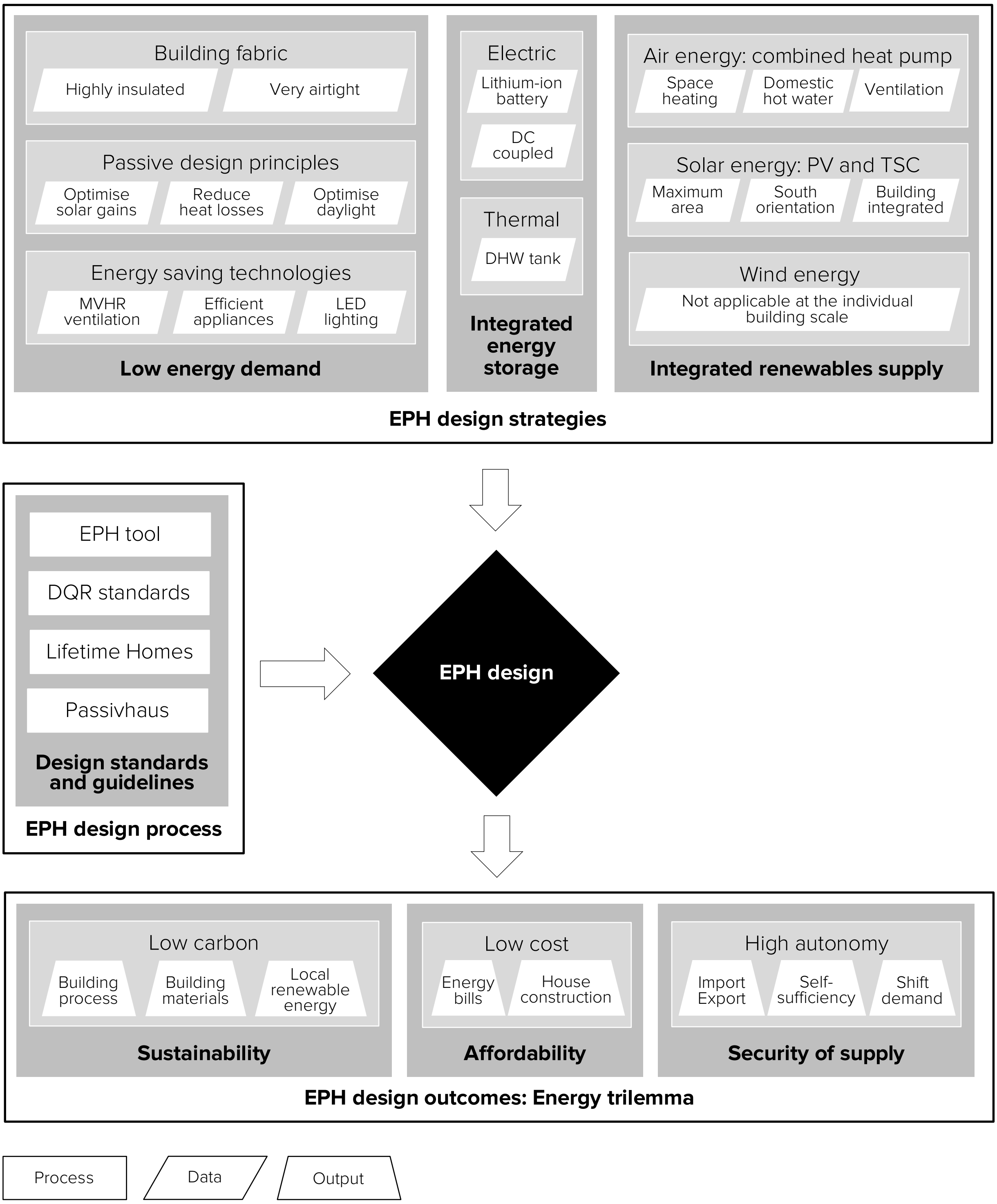


Figure 115 – Schematic of the methodology followed to develop the EPH design.

6.1 Analysis: Guidelines for the EPH design

Some people see sustainable design and quality design as two separate matters; one considering technical solutions to energy-related problems and the other at aesthetic solutions (CABE, 2008). But in fact, design quality should be defined by how a building looks, functions and meets the social, economic and environmental needs of its occupants on the short term as well as on the long term when it will need to be flexible to adapt to those needs changing over time. It is essential to think in an integrated way about the flexibility, longevity, and efficiency of buildings within our built environment.

The review in Chapter 2 has shown that green architectural design is not an easy matter and can be evaluated according to different criteria and points of views. It also has shown that houses with an integrated energy systems approach have been pursued from the early days of the green architectural movement, but cost, technologies reliability and public acceptance have always been the main barriers to let green housing hit the mass market.

The EPH design presented in this section aims to be a turning point, hence to be affordable, replicable and sustainable. The lessons learnt from the historical review of green housing projects presented in Chapter 2 have been used to establish the main design principles for the EPH design, especially the Passivhaus standards defined in section 2.4.7. The proposed EPH design guidelines are as follows:

- To minimise heating energy demand, a fabric approach is used with very high levels of insulation in walls, roofs and floors, and very high-performance windows. The Passivhaus design guidelines are used as a reference for walls, floors and roofs, but not for windows because triple glazing is considered too expensive and not compatible with the affordability requirement.

Table 15 – Comparison of the design guidelines for Passivhaus (BRE, 2011) and the EPH design.

	Passivhaus	EPH design
Walls U-Value	0.08 - 0.15 W/m^{2}K	0.12 W/m^{2}K
Floors U-Value	0.10 - 0.15 W/m^{2}K	0.15 W/m^{2}K
Roofs U-Value	0.08 - 0.15 W/m^{2}K	0.12 W/m^{2}K
Windows U-Value	0.85 W/m^{2}K	1.2 W/m^{2}K

- To control, manage and optimise solar gains in order to exploit the sun's energy for heating purposes in the heating season and to minimize overheating during the cooling season.

- To reduce building airtightness level, values below 0.6 air changes / hour at n50 as per Passivhaus standard involve an extra cost and specialised labour (PHI, 2015). Therefore, a more relax approach is used but always making sure that good quality design and detailing help to avoid unintended gaps and to achieve well sealed junctions.
- To reduce electrical energy demand, A+ appliances and LED lighting are used in the whole house. Also, external lights are controlled by a PIR mechanism to detect people's presence and are timed according to occupancy patterns.
- To maximise the energy generation through the building fabric, the whole south facing roof area is used for electricity generation from PV panels while the south facing walls are used for heat generation from transpired solar air collectors (TSC). These two solar energy systems are connected to a combined heating and ventilation system – i.e. exhaust air heat pump (EAHP) – which instead of cold fresh air uses the solar preheated air from the TSC and the heat recovered from the exhaust air and runs from renewable electricity when available. Since the house is all-electric with no gas, the same EAHP unit has to deliver domestic hot water. Previously, Chapter 5 described in more detail the components and technologies of the energy system, as well as their technical specifications and performance.
- To implement energy storage in order to increase the house self-sufficiency and reduce its dependency from the grid. A rank of batteries stores the excess of electrical energy from the PV system, while a domestic hot water tank stores the excess of thermal energy from the TSC system.

In the next section, the implementation and integration of all the above-mentioned design guidelines are described from an architectural design point of view.

6.2 Synthesis: Design of the EPH design

Of particular interest is a report titled ***'Building for life'*** which aims to establish the national standards for well-designed homes and communities in the UK (CABE, 2008). These standards are categorised under twenty criteria that embody the vision of what housing developments should be: functional, attractive and sustainable. Among them, the criteria under the 'Design and Construction' section consider the building scale and are considered during the design of the EPH design. These are explained in the following sections.

6.2.1 GOOD DESIGN

Architectural good design is about being fit for purpose, durable, well-built and pleasing to the mind and the eye (CABE, 2008). Good architecture fits its anticipated use; hence housing design should be carefully planned to satisfy the residents' needs. From the design of the interiors and exteriors to the adjacent landscaping; planners, contractors and design teams should ensure that architectural quality is satisfactory achieved. Good design is less to do with a particular style and more to do with the successful co-ordination of many aspects (CABE, 2008). These include:

- Orientation;
- Prospect and aspect;
- Detailing and materials;
- Structure, environmental services and energy use;
- Proportions, materials, colour and detail.

6.2.1.1 Orientation

The layout of the house is optimised considering the activity of each room, the internal gains from users and appliances, the hours of use and the daylight requirements. Therefore, the house layout (see Figure 116) is as follows:

- <u>South:</u> The living room and the children rooms are located in the south to take benefit of solar radiation during the day.
- <u>Centre:</u> The bathroom, shower room and utility area are located in the centre to keep internal heat gains and services in the core of the building.
- <u>North:</u> The kitchen and the parents' room are located in the northern area to reduce overheating from solar radiation.

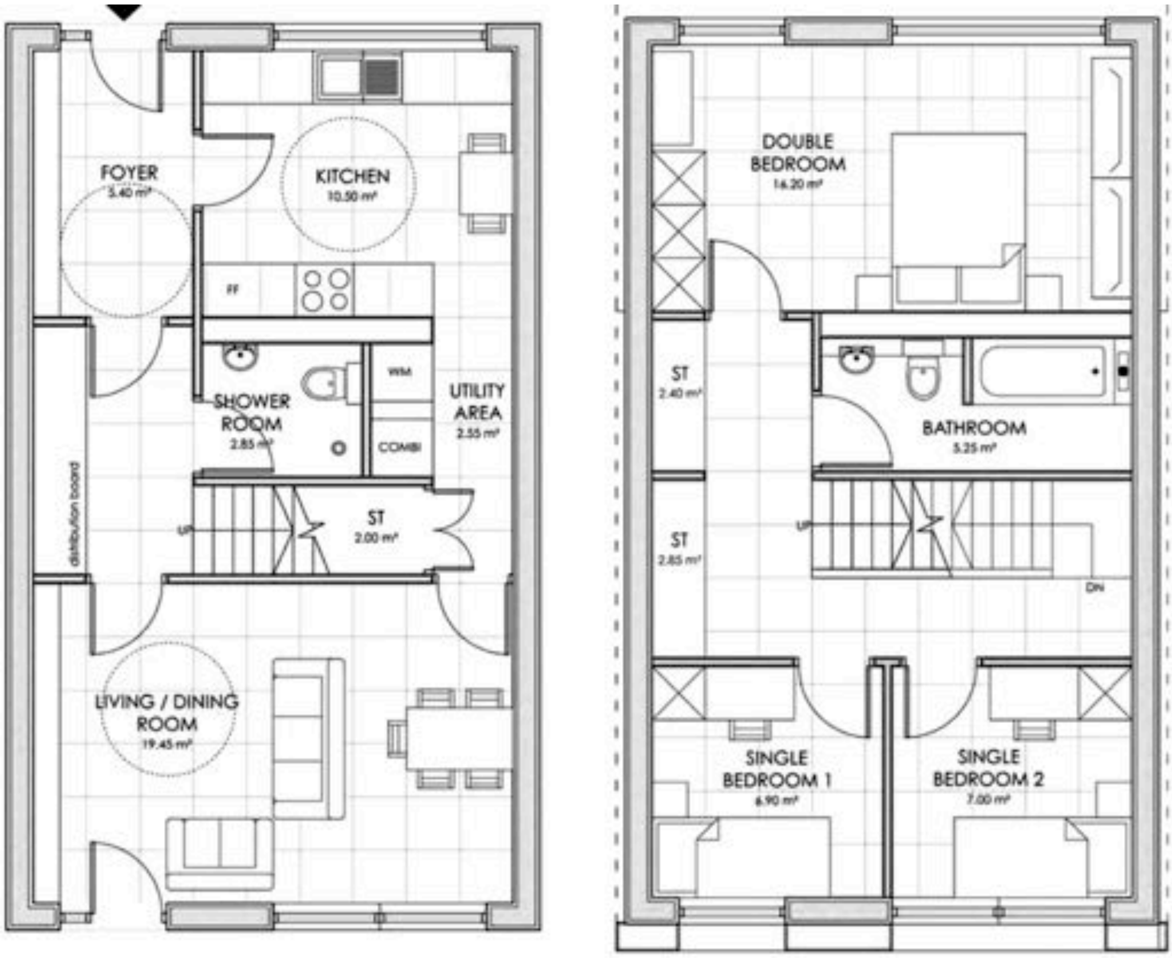


Figure 116 – Floor plan the EPH design. Left: Ground floor plan. Right: First floor plan.

Figure 117 – Section of the EPH design.

The orientation of the EPH design also considers the implications for renewable energy collection, passive energy use and building energy efficiency. Figure 118 illustrates the southern elevation of the house, which incorporates bigger windows to increase solar gains, a transpired solar collector (TSC) to collect solar thermal heat and a bigger roof area with building integrated PV panels to generate electricity from the sun. Oppositely, the northern elevation, illustrated in Figure 119, has smaller windows to reduce heat losses and a smaller area of standing seam roof.

Figure 118. South elevation of the EPH design.

Figure 119. North elevation of the EPH design.

6.2.1.2 Prospect and aspect

Views from windows and opportunities to see the sky and the landscape are important for home users. Therefore, the design of the EPH design's lighting and the daylighting is optimised for different times through the day – i.e. day and night – and through the year – i.e. different seasons. The following characteristics are considered (see also Table 16):

- Glare: All rooms are designed to reduce potential glare problems with effective methods of control and prevention. For example, the installation of blinds to control early morning or late afternoon direct sunlight, or the use of LED spotlights with adequate shielding design. Glare control strategies can potentially avoid increasing lighting energy consumption by maximising daylighting levels under all conditions.
- Views: All positions within living rooms are within 7m of a wall which has a window or permanent opening that provides an adequate view out from a normal standing or sitting position. The windows are at least 20% of the surrounding wall area.

Table 16 – Prospect and aspect considerations for the Solcer House.

Room	Depth	Number windows	Views seating level	Area of opening	% Opening to surrounding wall	Glare control	BREEAM Approved
Living room	3.6m	3	Yes	5.52m^2	40.37%	Blinds	✓
Double bed	3.0m	3	Yes	2.56m^2	20.5%	Blinds	✓
Single bed 1	2.6m	1	Yes	1.44m^2	23.07%	Blinds	✓
Single bed 2	2.6m	2	Yes	2.88m^2	46.07%	Blinds	✓

As previously mentioned, the Solcer House project was funded by the Welsh European Funding Office (WEFO), which requires that all new buildings promoted or supported by the Welsh Assembly Government have to achieve a BREEAM 'Excellent' rating. As a result, the EPH design has to be assessed for BREEAM compliance. BREEAM requires that a daylight analysis is done in order to determine the daylight factor levels in the occupied areas using the criteria set out in the BREEAM manual. The daylighting modelling and analysis is carried out using IES Virtual Environment 2014 dynamic simulation software. The application tools used are Suncast and FlucsDL. Suncast is used to model the solar gains for the building and FlucsDL is used to calculate the percentage of the occupied areas that have a daylight factor over 2%. The assessment is calculated using the following guidelines:

- Illuminance: based on a horizontal working plane at 0.70m as CIBSE LG10 guidance.
- Surface reflectance values: based on white paint on plaster with 70% reflectance.
- Glazing: assumed with a default transmittance value of 70%.
- Daylighting from neighbouring rooms: ignored for the purpose of this calculation.
- Luminance: 5000 Lux, that complies with CIE Standard overcast sky luminance.

In order to evaluate the results, BREEAM Assessment Criteria is used. This requires that at least 80% of the floor area in occupied spaces is adequately daylit as follows:

a) An average daylight factor of 2%. plus, either (b) or (c and d);
b) A uniformity of at least 0.4 or a minimum point daylight factor of at least 0.8% (Spaces with glazed roofs, such as atria, must achieve a uniformity ration of at least 0.7 or a minimum point daylight factor of at least 1.4%);
c) A view of the sky from desk height (0.7m) is achieved.
d) The following room depth criterion is satisfied.

$$(d / w) + (d / HW) < 2 / (1 - RB)$$

Where:

d = room depth,
w = room width
HW = Window head height from floor level
RB =Average reflectance of surfaces in the rear half of the room

Figure 120 – Equation to validate the daylight requirements of a room.

In order to be BREEAM compliant, a 2% average daylight factor must be achieved, in addition the rooms must either achieve a minimum daylight factor of 0.8% or a uniformity ratio of 0.4; if these cannot be achieved then a view of sky for at least 80% of the room depth must be achieved an also the room depth criteria must also be achieved.

A summary of the results of the daylight factor calculations for the occupied rooms is shown in Table 17, which highlights that all the 5 rooms that are analysed have an average daylight factor of at least 2%. Therefore, these rooms achieve the minimum requirement of achieving a daylight factor of at least 2%. The results for the daylight factor calculations can be found in Table 18.

Table 17 – Calculation results for the EPH design model.

	Kitchen	Living Room	Double bedroom	Single bedroom 1	Single bedroom 2
Area of Room (m^2)	10.5	19.45	16.2	6.9	7.0
Average Daylight Factor (%)	2.9	3.7	2.8	3.3	6.2
Uniformity Ratio	0.27	0.35	0.35	0.42	0.52
Minimum Point Daylight Factor	0.8	1.3	1.0	1.4	3.2
a) 2% DF Compliant	Yes	Yes	Yes	Yes	Yes
b) Uniformity Compliant	No	No	No	Yes	Yes
b) Minimum point DF >0.8%	Yes	Yes	Yes	Yes	Yes
c) View of Sky Compliant	Yes	Yes	Yes	Yes	Yes
d) Room Depth Compliant	Yes	Yes	Yes	Yes	Yes
Overall evaluation	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

Table 18 – Daylight factor (DF) calculation

Room	Quantity	Values			Uniformity (Min/Av)	Diversity (Min/Av)
		Min	Av	Max		
			(a)		(b)	(b)
Kitchen	Daylight factor	0.8 %	2.9 %	7.3 %	0.27	0.11
	Daylight illuminance	97.0 lux	353.2 lux	888.1 lux	0.27	0.11
	Sky view	1	1	1	1	1
Living Room	Daylight factor	1.3 %	3.7 %	10.1 %	0.35	0.13
	Daylight illuminance	156.9 lux	454.7 lux	1228.3lu x	0.35	0.13
	Sky view	1	1	1	1	1
Double bedroom	Daylight factor	1.0 %	2.8 %	6.8 %	0.35	0.14
	Daylight illuminance	119.3 lux	342.4 lux	831.4 lux	0.35	0.14
	Sky view	1	1	1	1	1
Single bed 1	Daylight factor	1.4 %	3.3 %	6.9 %	0.42	0.20
	Daylight illuminance	170.4 lux	401.2 lux	839.3 lux	0.42	0.20
	Sky view	1	1	1	1	1
Single bed 2	Daylight factor	3.2 %	6.2 %	10.6 %	0.52	0.31
	Daylight illuminance	394.3 lux	760.6 lux	1289.5 lux	0.52	0.31
	Sky view	1	1	1	1	1

The 5 rooms with a daylight factor of at least 2% also achieve a minimum point daylight factor of at least 0.8%. However, only 2 of the rooms achieve the uniformity ratio of 0.4.

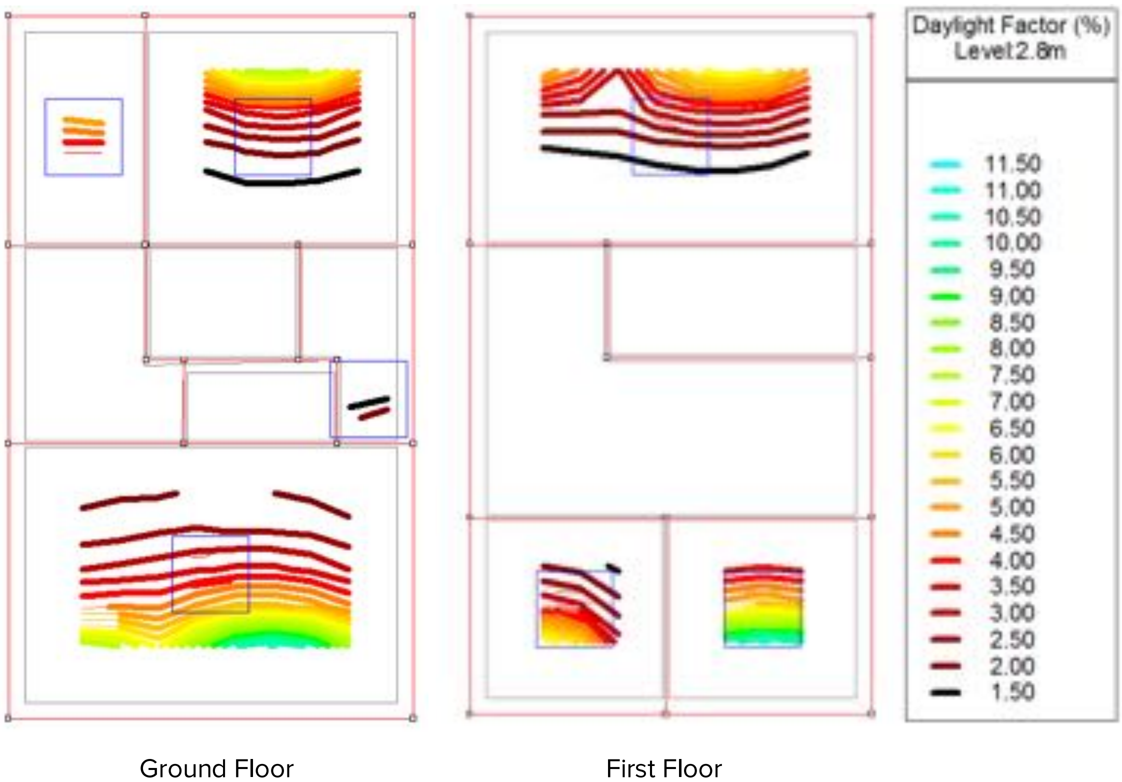


Figure 121 – Schematic of the daylight factor calculations

The view of sky is also calculated for each of the rooms. In order to do this, assumptions are made regarding the height of the obstruction. The results of this calculation are shown in Table 19.

Table 19 – View of the sky calculation

Room	Room depth	H	Y	X	XH / Y	% of room with view of sky	Compliant
							(c)
Kitchen	3.0m	1.4m	0.5m	12m	33.60	100%	Yes
Living Room	3.3m	1.4m	2.7m	7m	3.63	100%	Yes
Double bedroom	3.0m	1.4m	0.1m	100m	1400	100%	Yes
Single bed 1	2.6m	1.4m	1.2m	7m	8.17	100%	Yes
Single bed 2	2.6m	1.4m	1.2m	7m	8.17	100%	Yes

Finally, the room depth criterion calculations are carried out for each of the rooms and all rooms achieve the necessary results. Table 20 shows results for the room depth criterion.

Table 20 – Room depth calculation

Room	Room depth	Room width	Head above floor	Average Reflect.	d/w	d/hw	(d/w) + (d/hw)	2/(1-rb)	Compliant
									(d)
Kitchen	3	3.5	2.1	0.7	0.86	1.43	2.29	6.67	Yes
Living Room	3.6	5.4	2.1	0.7	0.67	1.71	2.38	6.67	Yes
Double bedroom	3	5.4	2.1	0.7	0.56	1.43	1.98	6.67	Yes
Single bed 1	2.6	2.7	2.1	0.7	0.96	1.24	2.20	6.67	Yes
Single bed 2	2.6	2.7	2.1	0.7	0.96	1.24	2.20	6.67	Yes

In conclusion, all the rooms achieved the results necessary to comply with BREEAM, thus meaning that they are all adequately daylit. Based on these results the proposed EPH design is defined as being adequately daylit as set out in the criterion of the BREEAM manual.

6.2.1.3 Detailing and materials

Plans, sections and elevations of the house are designed to detail level to reduce thermal bridging, air leakage and heat loss as much as possible. The choice of materials is equally important in regard to an understanding of heat transfer through building fabric as well as to issues of maintenance, resilience, sustainability and ageing.

The design does not follow the Passivhaus standards rigorously, in that accreditation was not sought, which allows greater freedom to use appropriate technologies and local suppliers. As with any green building, one of the first objectives is to reduce the energy demand, hence the house has a highly insulated building fabric.

Table 21 – Detailing and materials considerations for the EPH design. Embodied CO_2 data Source: Table 33.

Element	Layers / Materials	Area (m^2)	U-value ($W/^oC/m^2$)	Embodied CO_2 (kg)
Floor slab	Laminate flooring Foam underlay 65mm sand/cement screed 120mm Celotex xr400 insulation Polythene separating layer 100 mm concrete slab	47	0.15	2500
External Walls	30mm Parex EWI & Render 12.5mm Knauf Aquapanel boards Breather membrane (Protect TF 200) 11mm OSB board (SIPS) 172mm EPS Insulation (SIPS) 11mm OSB board (SIPS) Vapour barrier layer Plasterboard	163	0.12	4700
Window	Frame – Timber aluminium composite (SAS System) Glass – Pilkington EnergiKare ™ Advantage	8 11	1.12 - 1.51	950
Roof - South	Solar PV cells Single glazing Aluminium railing	40	-	9700
Roof - North	Aluminium sheet Breather membrane 11mm OSB board (SIPS) 172mm EPS Insulation (SIPS) 11mm OSB board (SIPS)	23	0.10	3450

Table 21 shows the specifications and characteristics of the design elements, which are:

- Foundations and slab: Made of low carbon cement with almost 95% reduction in the embodied CO_2 of the product in comparison with a conventional Portland cement (Patterson, et al., 2016). The floor slab is fully insulated, but with a layer of cement screed on top to increase the house thermal mass.
- External walls: Built with SIPs (Structural Insulated Panels), which are made of a layer of EPS insulation between two layers of OSB (Oriented Strand Board). SIPs are chosen because they are a lightweight method of construction that offers high levels of thermal insulation, low air leakage and a fast construction process. Even though SIPS have low thermal mass, literature suggest that they have a good thermal response to overheating risks from climate change (Sajjadian & Sharples, 2017). Moreover, external wall insulated (EWI) render is used to finish the walls, offering an even better energy performance and reducing the risks of thermal bridging.

- Openings: Aluminium clad timber frame windows and doors with low-emissivity double-glazing are used, which offer high levels of insulation and low maintenance.
- South-facing roof: Made of glazed PV panels, which are fully integrated into the design of the building, with the south roof space naturally lit.
- North-facing roof: Constructed from a standing seam metal cladding system.

6.2.1.4 Structure, environmental services and energy use

The structure and dimensions of the house are planned from the beginning as an integral part of the design of plans, sections and elevations. For this reason, in all directions, the building is modular in its design, on a 0.6m by 0.6m dimension grid, which is the most common or standard dimension in the construction sector. This could potentially help in terms of scalability and functionality if the house prototype is replicated in the future.

In terms of environmental services and energy use, the energy system includes electrical power and space and domestic hot water heating. The EPH system and its technologies were fully described in Chapter 5.

6.2.1.5 Proportions, materials, colour and detail

Details are studied as an important part of the building and not as an add-on. They have a significant effect on the overall impression of a building, so a successful co-ordination between their proportion, materials and colours is essential to guarantee that the house is pleasing to the eye.

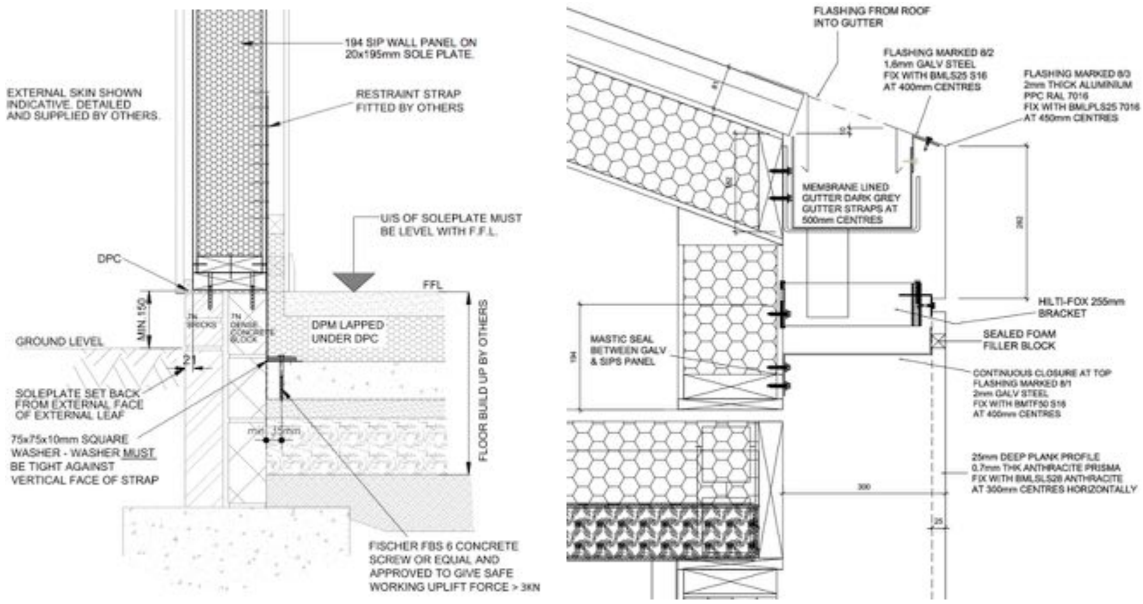


Figure 122 – Construction details of the EPH design. Left: Detail of the sole plate, floor slab and foundations. Right: Detail of the eaves in the southern elevation.

Particular care is given to corners, roof and floor slab (see Figure 122) to improve durability and robustness of chosen materials. Also, proportions of windows are designed to look good but also to work for views and light inside the house, so as to create a positive relationship between the inside spaces of the building and the outside landscape.

6.2.2 QUALITY

In Wales, Welsh Assembly Government introduced *'The Welsh Housing Quality Standard'* (WHQS) in 2002 to ensure that dwellings were designed of good quality and suitable for the needs of existing and future residents. According to the latest version of the WHQS, a good EPH dwelling model should meet the following criteria (Welsh Assembly Government, 2008):

- In a good state of repair: The dwelling must be structurally stable, free from damp and from disrepair, and with key building components in good condition.
- Safe and secure: To reduce accidental injury, the dwelling must have well designed staircases, good bathroom and kitchen layouts, easy access to fire escape routes, safely designed electrical and gas installations, physical security measures and safe and secure gardens.
- Adequately heated, fuel efficient and well insulated: The dwelling must be capable of being heated at an affordable cost to the residents in order to reduce discomfort and health risks as well as to eradicate fuel poverty.
- Contain up-to-date kitchens and bathrooms: All dwellings must have reasonably modern facilities, services and amenities for preparing, cooking and storing food.
- Located in attractive and safe environments: The dwelling should be located in an environment to which residents can relate and in which they can be proud to live.
- Suit the specific requirements of the household: The accommodation provided within the dwelling should, as far as possible, suit the needs of the household. The dwelling should provide sufficient space needed for everyday living and be appropriate for household numbers.

6.2.3 ADAPTABILITY

Sustainability is also about the ability of a building to adapt to changes in three different aspects of function – i.e. social, technological and economical – with a near-term as well as longer-term planning horizon. Without such adaptation, building models have the risk of becoming obsolete for causes that can range from competitive weakness, to economic failure, or to social or environmental limits. For this reason, buildings need to adapt to users' needs and their changing demands and lifestyles of the future by providing flexible internal layouts, complying with policies and standards and allowing for cost-effective alterations and improvements. To summarise, to guarantee design adaptability, three main considerations are important: accessibility, flexibility and replicability.

6.2.3.1 Accessibility

A well-designed building should integrate inclusive design features so that a barrier-free environment is maintained providing equality of access for all. This means that ensured intellectual, emotional and physical accesses are all contemplated at the beginning of any project and remain intact through the design process to prevent expensive remedial works. Creative and innovative thinking should be applied to design novel and individual solutions thought for real people and all the diverse needs they may have.

To guarantee the accessibility criterion in the EPH design, the '*Life Time Homes Standard'* was considered at an early stage of the design process. This standard was developed in 1991 and consists of sixteen design criteria intended to make homes more easily adaptable for lifetime use (Lifetime Homes, 2010). For example, the EPH design accommodates a downstairs toilet and shower, wider doorways, level access entrances and also allows for a lift or stair lift to be fitted in the future.

6.2.3.2 Flexibility

The ways in which a building, its spaces and technologies are used are likely to change over their lifetime. A well-designed house should be flexible to allow changing uses without major remedial works and altering its size conveniently when necessary. In terms of spatial flexibility, the EPH design incorporates load-bearing external walls that allow for partitions to be added suiting the occupants' needs or removed creating open-plan living, rectangular shape big rooms that allow them to be used in a variety of ways – e.g. as work space, study, bedroom or playroom – and an easy access to the current unused loft space that offers the potential to extend the house upwards if the family grows in size or changes their needs.

6.2.3.3 Replicability

One of the aims of the EPH design is to demonstrate that it is possible to design a replicable low carbon house at an affordable cost using existing technologies and skills. Building low carbon dwellings is generally perceived to be costly and difficult in the current economic climate (Osmani & O'reilly, 2009). For this reason, the EPH design uses market available technologies that are affordable, available off the shelf and from local suppliers. The innovation is the combination of the components into a system and into the architectural design, to demonstrate how houses should be built for a future low carbon built environment. The intention of this thesis is to provided evidence that similar low carbon houses could be replicated at a regional scale at an affordable cost whilst stimulating the local economy. Providing further evidence of the replicability of the EPH design should enable organisations to implement the house in other locations and stimulate the supply chain and housing developers, who tend to be reluctant to changes (Heffernan, 2013) .

6.2.4 FUNCTIONALITY

Functionality can significantly improve the popularity of a home and the quality of life for its occupiers. If the floor plan layout and the section are clear and consider functional aspects such as generous space, good natural light, energy efficiency and good sound insulation; then it is difficult that the project falls into place. In the case of the EPH design, these aspects have been considered in detail. They are guaranteed as follows:

- The house plan provides a generous and organised space for its occupants, with a floor area of 100m^2 that is slightly bigger than the notional floor area recommended for a comparable dwelling within a Social Housing development (Welsh Government, 2015).
- Provision of good natural light is considered at early-design stages and daylight calculations are done for all the habitable rooms – i.e. kitchen, living room and bedrooms.
- To achieve the energy positive aim, the EPH design has an optimised building performance, energy efficiency of all the technologies and elements of building fabric.
- The model of the EPH design is a mid-terrace house, thus good sound insulation in the party wall is very important to guarantee privacy between neighbours.

6.2.5 NOVELTY

For the construction of the EPH design, advanced construction methods and novel energy systems and technologies are used to enhance the house performance, quality and desirability. Figure 123 shows a section of the house with the main methods and technologies used in the house, which have already been described in Chapter 5 and 6. For example, prefabricated SIPS panels for the external walls, low emissivity double glazing for windows, TSC collectors for solar thermal heat, building integrated glazed PV system, electric batteries, LED lights, A+ appliances and a combined space and water heating system. This systems approach aims to use a very low amount of energy to provide a comfortable environment for the building's occupants.

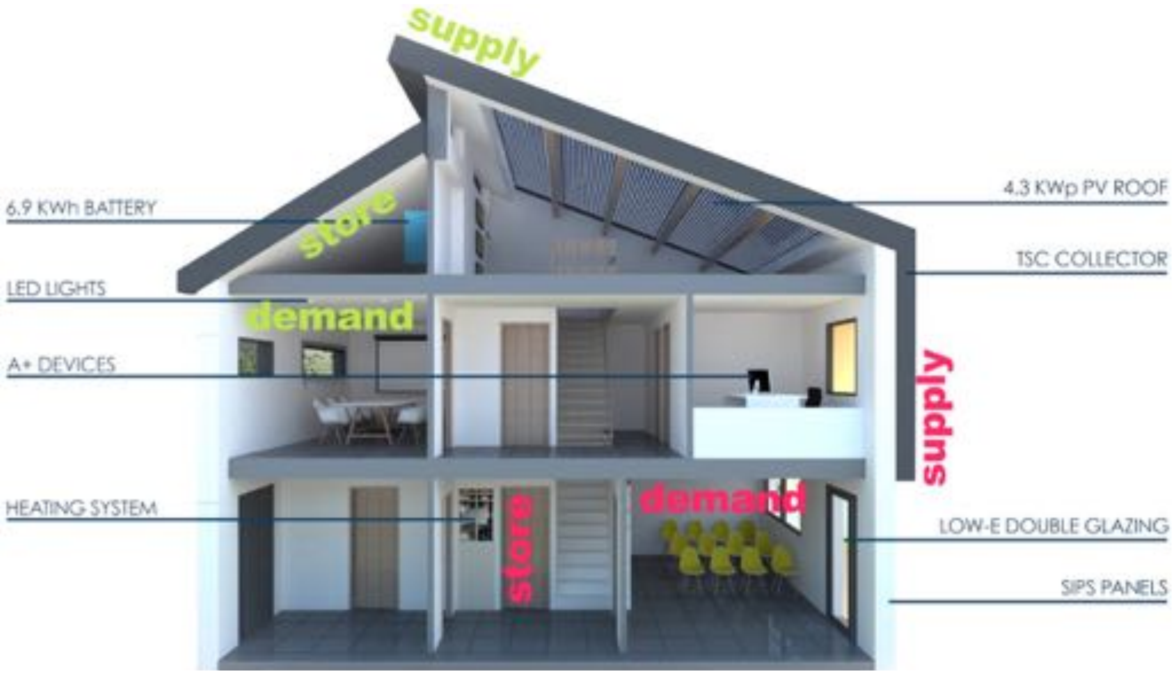


Figure 123 – Schematic of the EPH design showing the novel technologies and construction methods used.

The design of the house considers the whole-life cost of the building rather than short-term economic returns. For example, using low carbon materials, natural resources and energy more efficiently and responsibly; managing sustainable design features so that they are used effectively; reducing waste on site and emissions to land, air and water during construction and use, and effectively engaging with the local community and supply chain during the planning, design and construction process. To reduce carbon emissions related with transport of materials to site, the components of the building are sourced as far as reasonably practicable from local manufacturers, suppliers and installers. The low carbon EPH system integrated in the EPH design aims to be affordable and replicable, for local developers to build houses, using market available technologies.

Finally, a SAP report of the EPH design is done in order to evaluate the sustainability and carbon impact of the proposed model against national benchmarks. Results from the SAP modelling are found in Appendix 3 and indicate a SAP rating A (92), a Dwelling CO_2 Emissions Rate (DER) of 11.3 and a Target CO_2 Emissions Rate (TER) of 26.4, which indicates a 57% reduction. In regard to the energy and carbon savings, SAP results indicate that the predicted total CO_2 emissions are 1,130 $kgCO_2$/year, which are much lower thanks to the 1,927 $kgCO_2$/year saved with renewable energy generation technologies. It is important to highlight that SAP calculations do not allow to model the benefits from the TSC and the battery system. Therefore, the above-mentioned results are lower than they should be. Further research should investigate how to incorporate these novel technologies into the SAP modelling calculations.

6.3 Summary

The term EPH design does not primarily describe a quantitatively defined standard, but rather a performance-driven design strategy. It pays attention to the principles of passive solar construction in the design by developing the building starting with the climate, creating a balanced system even without technologies, and integrates the environment as directly and comprehensively as possible into the provision of comfortable living conditions. This strategy moves away from the idea that technologies alone can perform the task of space conditioning, which has prevailed in buildings since the start of industrialisation, and in particular since the age of modern architecture and its fascination with technology.

To minimise the energy demand, the EPH design is designed with high levels of thermal insulation and reduced air leakage. It uses an innovative energy efficient design that includes low carbon cement, structural insulated panels (SIPS), external insulated render, transpired solar air collectors (TSC), and low-emissivity double-glazed aluminium clad timber frame windows and doors. The integrative approach to construction uses renewable energy systems as building elements; the upper first floor wall incorporates the TSC and the south facing roof is a glazed PV panel system. This reduces costs and improves aesthetics, avoiding the bolt-on approach often associated with renewable energy systems.

The direct and active use of renewable energy, in particular solar radiation, frees the EPH design from the limitations of purely passive strategies such as the Passivhaus standard. An EPH design is not forced to stay below the rigid limit of only 15kWh/m^{2}a for heating energy demand, which can only be achieved at high economic cost. It considers that sometimes it is more economic to compensate for a slightly higher heating demand, with the active use of renewable energy on site. This can potentially avoid installing a disproportionate amount of extra insulation that result in excessively thick walls, installing overpriced triple glazed windows or having compulsory large openings facing south to increase solar gains in winter and therefore avoid the risk of undesirable summer overheating. However, this slightly reduced rigorousness in the thermal insulation standards of the building fabric must not lead to a loss of comfort.

The EPH's performance-driven design approach leaves room for creativity. The EPH design can be freely twisted and modified because is less oriented towards strict requirements. The critical factor is to show an optimised energy balance between generation and consumption, or supply and demand; thus, a building that in the end produces an excess of energy in terms of its energy balance. However, this cannot be applied universally, because it depends on the use, the density of development and the availability of renewable sources.

7 Evaluation: Results and discussion

The EPH design is designed to achieve zero or positive energy balance annually – i.e. to produce approximately as much energy as it consumes. In this context, the actual energy performance of the proposed EPH design is examined and assessed to verify the design assumptions and the performance of the energy systems described in previous chapters. The findings of the overall house performance are presented in three different sections.

First, Section 7.1 presents the validation of the EPH tool by comparing the tool's results of the simulation of the Solcer House against the monitoring data of the Solcer House and investigate the factors that influence on these variations between predictions and real life.

Second, Section 7.2 assesses the EPH system by comparing the technologies' specifications claimed by manufacturers against the real specifications calculated using the monitored data of the Solcer House. The factors that influence on these variations between predictions and real life are investigated. This section is divided in two sub-sections, the first focuses on electrical energy and the second focuses on thermal energy. For each type of energy, an overall evaluation looking at the whole system performance is done.

Finally, Sections 7.3, 7.4 and 7.5 assess the environmental, economic and social impact of the EPH design by calculating a full Life Cycle Assessment (LCA) from cradle-to-grave, monitoring the build costs and collecting the opinion from visitors to the Solcer House with an online survey that intends to evaluate the most relevant architectural and aesthetical aspects.

7.1 EPH tool: validation and calibration

The real energy performance of the built case study Solcer House is examined and assessed to verify the EPH tool and its prediction of the performance of the energy systems. By its nature, a simulation model is more abstract than the system it represents, and this inevitably introduces inaccuracy, which may be needed at some degree to make the model solution manageable and effective. Abstractions and assumptions are made to exclude unnecessary details from the model and focus on the elements within the system that are important from a performance point of view. But, acknowledging such assumptions means that some effort is needed to evaluate the quality of the model. There are two steps to judge how good a model is in respect to the system it represents:

- Verification: To ascertain whether the model implements the assumptions correctly and to ensure that the model does what it is intended to do.
- Validation: To ascertain whether the assumptions that have been made are reasonable with respect to the real system and to demonstrate that the model is a reasonable and accurate representation of the actual system.

Although validation does not imply verification, nor verification imply validation; in practice, validation is often combined with verification, especially when monitored data is available for the system being modelled. Therefore, the EPH tool will be assumed to be verified and valid if a comparison of monitored and modelled data suggests that the results produced by the model are close to data collected from the case study Solcer House.

The methodology followed in this section is similar to the evaluation process for NZE buildings proposed by Deng et al. (2014) in their comprehensive review, where they outline a method to evaluate performance from a life cycle perspective and summarise the process as follows: first, simulation of the performance of NZE buildings during the design stage; second, monitoring of the performance of NZE buildings using sensor instrumentation after the construction stage; third, validation of the simulation model with the monitored data. Deng et al. (2014) also review the most common evaluation indicators for NZE buildings, comprising amount of energy, efficiency of systems and technologies, assessment of life cycle or embodied energy to name a few. Following a similar approach, this section considers the energy demand, the energy supply from renewables and from the grid and the energy storage capacity; and compares the modelled data from the EPH tool against the monitored data of the real Solcer House, which is collected, ordered and analysed in great detail.

7.1.1 ENERGY DEMAND

Initially, the Solcer House monitored data was analysed for a period of two years, from July 2015 to July 2017. Figure 124 presents the results from the collected data during this period for the electrical energy demand from appliances, lighting, cooking and heating. The graph shows clearly that during the first year, the heating system of the Solcer House had major issues, which resulted in a huge excess of electricity demand.

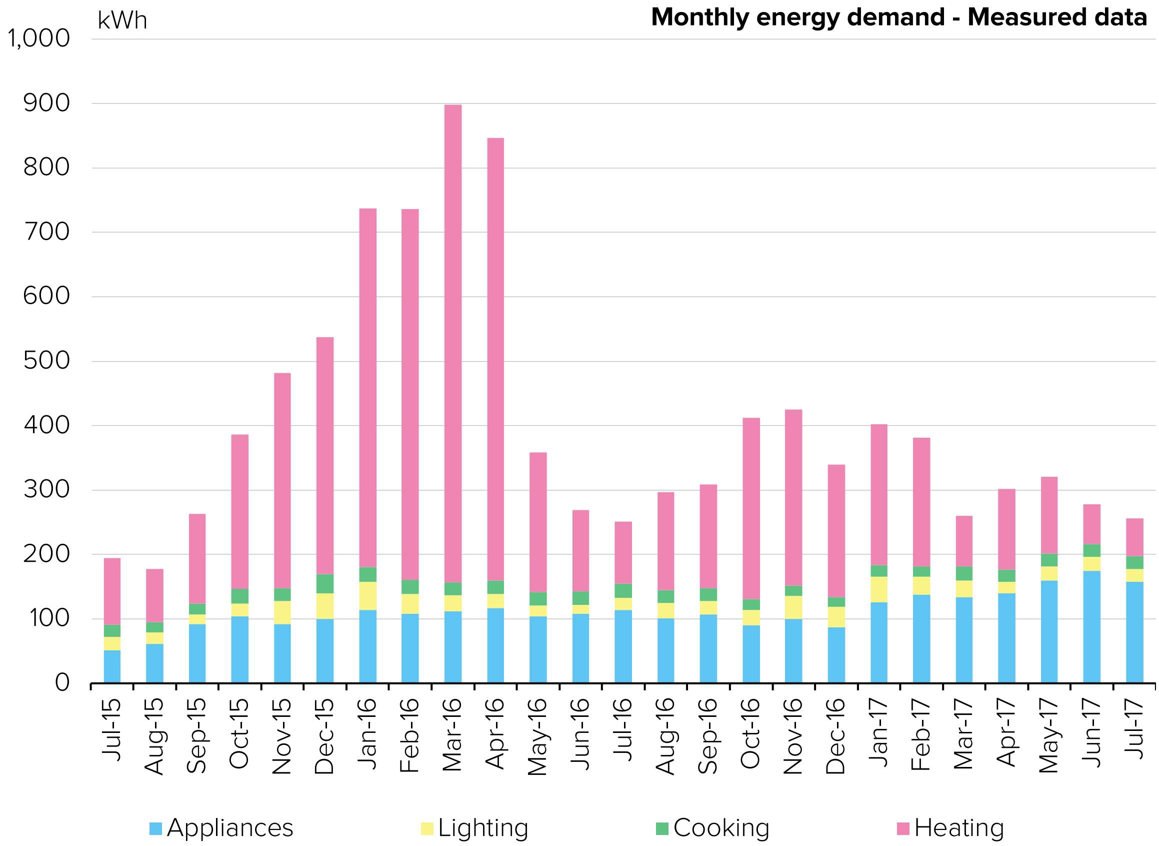


Figure 124 – Graph showing monthly energy demand from July 2015 to July 2017. Data source: Measured data from the Solcer House.

The heating demand problem is investigated by analysing the internal temperature of the house. Annex 2 presents the results of this temperature analysis. The aim of the analysis was to determine whether the heating system of the Solcer House was using more energy than predicted because of an incorrect sizing or selection of the system or because of the type of occupancy and use of the building. After collecting, ordering and analysing the monitored data from the Solcer House, two aspects were assessed: the minimum, average and maximum hourly temperature, and the temperature distribution in number of hours in each room. This analysis was done for the winter season, between November 2015 to March 2016, and for all the rooms of the Solcer House. The results of the analysis clearly showed the main causes of the heating problem.

First, the temperature distribution analysis showed that most of the time the temperature of the rooms in the first floor (used as staff offices) was between 21ºC and 24ºC, and even detected times of overheating with temperatures going as high as 28ºC. This problem was not detected downstairs in the kitchen and living room (used as meeting room), were most of the time the temperature was between 18ºC and 20ºC. Therefore, it was found that the room temperatures of the monitored Solcer House were much higher than the temperatures used in the modelled house of 21°C in the living areas and 18°C in the others, as recommended by the World Health Organization, (2007).

Second, the roof space under the glazed PV area was always under the comfort zone. However, this was already expected because this room was designed as non-habitable space with the insulation at the floor level and the PV panels made of single glass with a very high U-value. Although the roof space was designed to act as a buffer zone and is well insulated, the heat transfer between this room and the first floor could be affecting the heating demand.

After doing the analysis, the Solcer House's occupants were interviewed to find whether they were feeling uncomfortable. It was found that the occupiers liked to feel very warm because, according to their own words, "we are doing office work and are sitting all the time". As a result, they setup the thermostat control at 24ºC during 24h to make sure that offices were warm also in the morning when they arrived. This was much higher than the average thermostat setting in the UK, 20.1ºC (DECC, Jan 2014), and leaded to the higher room temperatures described above. Also, they played with the settings of the control panel of the heating system and they switched on permanently the 1kWh electric resistive heater, which should only be used as an emergency for very cold days to boost the heat from the heat pump. This proved that "domestic consumer use of heating controls is often driven by a desire to achieve thermal comfort rather than a wish to save energy" (DECC, Jan 2014).

In May 2016, after the heating problem was spotted and discussed with the occupants of the Solcer House, the settings of the heating system were corrected and brought back to the recommended values from the manufacturers. Since then, data collection for heating energy demand presented a profile much more in line with the expected heating load of a highly insulated house. This data, together with the demand from appliances, lighting and cooking, was used to plot the monthly demand of the real Solcer House for one year, which could then be compared against modelled data and used to validate the EPH tool predictions. Figure 125 presents the energy demand comparison between the measured data and the modelled data.

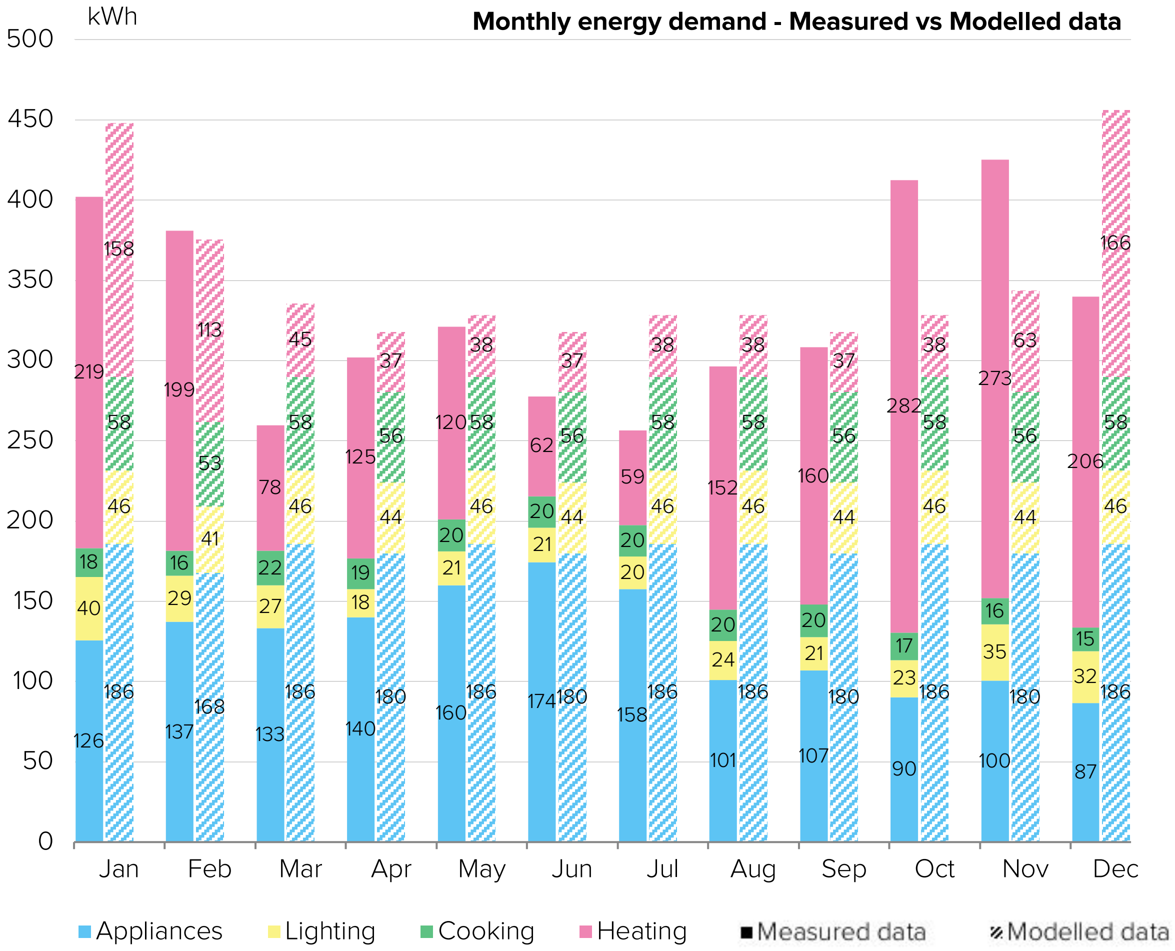


Figure 125 – Graph showing the comparison between the measured and the modelled monthly energy demand from August 2016 to July 2017. Data source: Measured data from the Solcer House and EPH tool's modelling of the Solcer House

The difference between the data predicted by the EPH tool and the data measured at the Solcer House is apparent when analysing the whole year on a monthly distribution (see Figure 125). On one hand, the fully painted bars show the monitored performance of the Solcer House for one year. In this case, the demand from appliances, lighting and cooking is slightly constant across the year, totalling between 150 to 200 kWh per month; while the heating demand is less constant and much higher during the winter months (October to February). On the other hand, the patterned painted bars show the predicted demand from the EPH tool. In this case, the demand from appliances, lighting and cooking is higher and very constant across the year totalling between 250 to 300 kWh per month; while the demand from heating is slightly lower in the winter months and for a shorter period (November to February).

However, discrepancies were already expected due to the difference in occupancy types between the modelled data – i.e. house – and the monitored data – i.e. office. For example, the use of appliances is much lower in the Solcer House because there are not highly consuming appliances such as washing machine, dryer, dishwasher or TV. The lighting demand in the Solcer House is also lower because the building is only occupied from 9 to 6, which means that the use of lights at night-time does not happen. Also, the demand from cooking appliances is much lesser because the occupiers only use the cooking appliances in very sporadic occasions. Nevertheless, the annual predicted demand from the EPH tool of 4,223kWh/year is close to the measured data in the Solcer House, 3,982kWh/year.

A more detailed daily comparison of the energy demand shows that there is a big difference between the modelled and the monitored data. On a daily basis, the hourly profiles of energy use are totally different for either a typical winter day (see Figure 126 and Figure 127) or a typical summer day (see Figure 128 and Figure 129). These hourly profiles are generated by normalising the collected data, for winter the hourly average of all days in December and January and for summer the hourly average of all days in June and July.

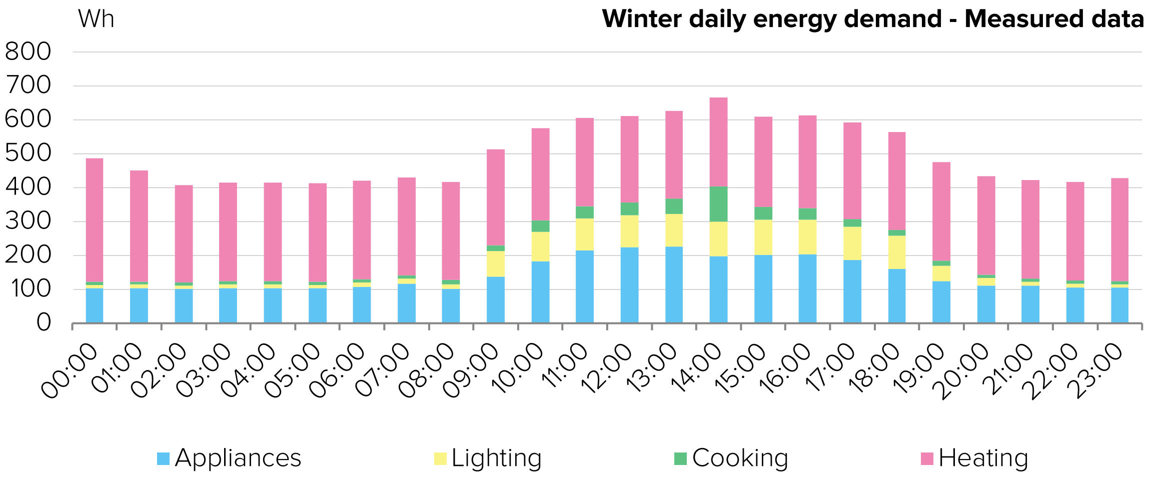


Figure 126 – Graph showing hourly energy demand profile for a typical winter day. Data source: Measured data from the Solcer House.

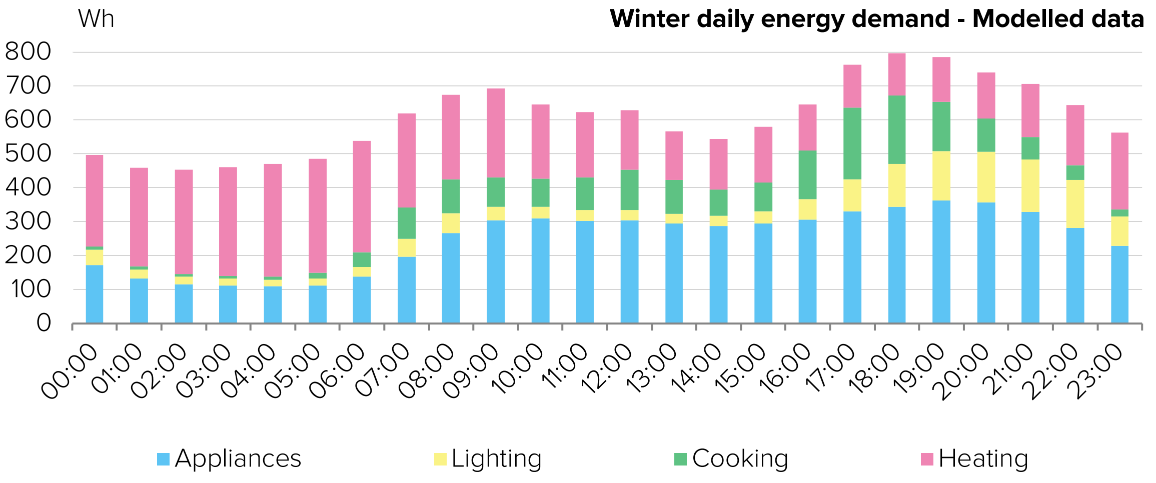


Figure 127 – Graph showing predicted hourly energy demand profile for a typical winter day. Data source: EPH tool's modelling of the Solcer House.

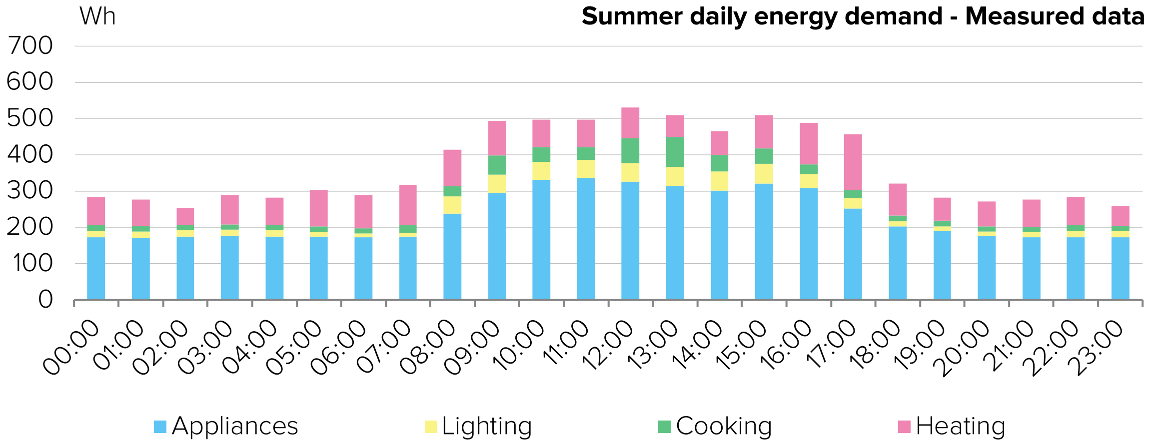


Figure 128 – Graph showing hourly energy demand profile for a typical summer day. Data source: Measured data from the Solcer House.

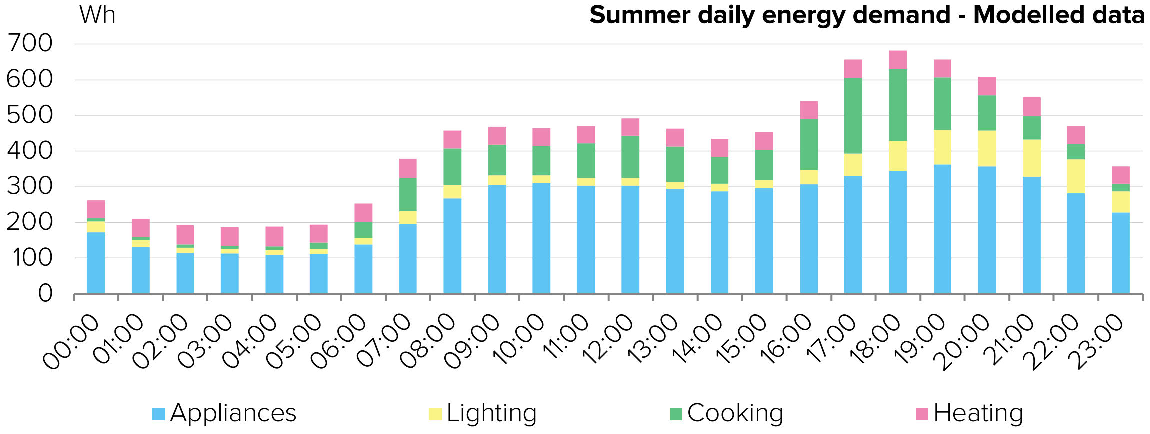


Figure 129 – Graph showing predicted hourly energy demand profile for a typical summer day. Data source: EPH tool's modelling of the Solcer House.

The highlights of the comparison between the modelled and the monitored daily energy demand are as follows:

- Appliances: In the monitored data, the energy demand occurs during the working hours due to the use of office equipment in the Solcer House. Instead, the tool predicted a higher energy demand, especially during the peak time evening hours. Regarding the difference between seasons; monitored and modelled data both show that consumption from appliances is stable and does not vary across the year.
- Lighting: In the Solcer House, the occupants have the lights on in the first-floor rooms, which are used as offices, during most of the day from 9am until 6pm; while in the modelled house, lights are on mainly from 5pm until midnight. Regarding the difference between seasons, monitored data shows that energy demand from lighting is 70% higher in winter days compared to summer days, which are brighter; while in the modelled data the difference is less apparent, around 50%.

- Cooking: The use of cooking appliances in the Solcer House is very sporadic with a slightly peak at lunchtime. Oppositely, the predicted data from the EPH tool is much higher and has a more relevant peak from 5pm until 7pm. This difference was totally expected because the users of the Solcer House do not use the hob and the oven available, they tend to use only the microwave and the kettle.
- Heating: In the Solcer House the heating demand in winter is high and constant at around 300Wh, which indicates that the heat pump is at full power during 24h. Instead, the EPH tool predicts a lower demand from the heat pump during the day, when the solar gains from the TSC and windows help heating the building, and a higher demand during the night and early morning when there are no solar gains. In summer days, the heating is off in both cases, but it seems that the energy consumed for the mechanical ventilation system is higher than predicted. After investigating the fan power from the manufacturer's specifications, it is found from monitored data that the fan consumes more energy than expected possibly due to the TSC integration with the ventilation system.

Overall, the predicted energy demand from the EPH tool is about 22% higher for a typical day in winter and 14% higher for a typical day in summer, in comparison with the measured data from the Solcer House; but the occupancy of the real case study as offices might explain these discrepancies. Therefore, it is concluded that the use of the case study to validate and verify the EPH tool predicted energy demand is not ideal and that further validations with real housing case studies would be recommended. However, this is not considered a critical issue due to the fact that the energy demand profiles used to generate the EPH tool are based in highly reputable reports *'Household Energy Survey'* and *'24-Hour Profile Chooser Tool'* from DECC (see Chapter 2).

7.1.2 ENERGY SUPPLY FROM RENEWABLES

Initially, the Solcer House monitored data was analysed for a period of two years, from July 2015 to July 2017. The comparison of the monthly energy supply from the PV panels in Figure 130 shows that predictions from the EPH tool were slightly lower (3,947kWh/year) than the monitored data from the real case study (4,074kWh/year). Therefore, it was found that the EPH tool was slightly less optimistic predicting around 3.5% less PV output. As a result, the reasons behind this difference are investigated to not only increase the accuracy of the EPH tool but also to validate and verify the model.

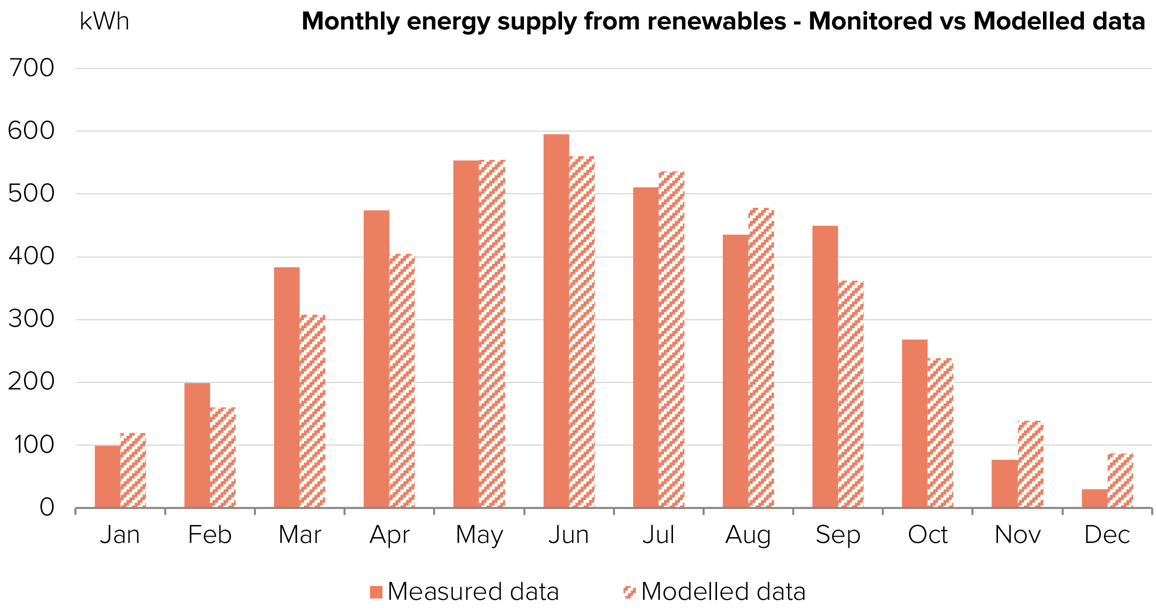


Figure 130 – Graph showing the comparison between the measured and the modelled monthly energy generation output from PV from August 2016 to July 2017. Data source: Measured data from the Solcer House and EPH tool's modelling of the Solcer House.

Literature suggests (see Figure 88, section 4.2.2.2.1) that the annual solar energy output from a PV system generation depends on the following factors:

- Solar radiation incident on the PV panels: The weather data used in the EPH tool is from Meteonorm and is an average of historical hourly data for the city of Cardiff, while the measured data is based in real weather at the exact location of the Solcer House, which is about 30 miles from Cardiff. This can explain the slightly difference between the measured data from the case study and the modelled results from the EPH tool (see Figure 130).
- Area and efficiency of the PV panels: These are specified by the manufacturer as $35m^2$ and 13%, respectively and will be fully investigated in Chapter 6.
- System's overall de-rate factor: Using the equation from Goswami et al. (1999) to calculate the de-rate factor, the result is 0.82. However, the equation is based in a wide range of factors, which include some assumptions.

To validate the EPH design, the first step is to isolate the influence that different weather data can have on the final PV output. To do that, the monitored weather data at the Solcer House for the hourly solar radiation falling on the PV panels is introduced into the EPH tool. Then, the PV output measured by the PV control system and the PV output modelled by the EPH tool using measured weather data should be very similar. Figure 131 shows that the agreement between the predicted and the measured results is remarkably good, with a mean accuracy of 97.95% according to the trend line slope.

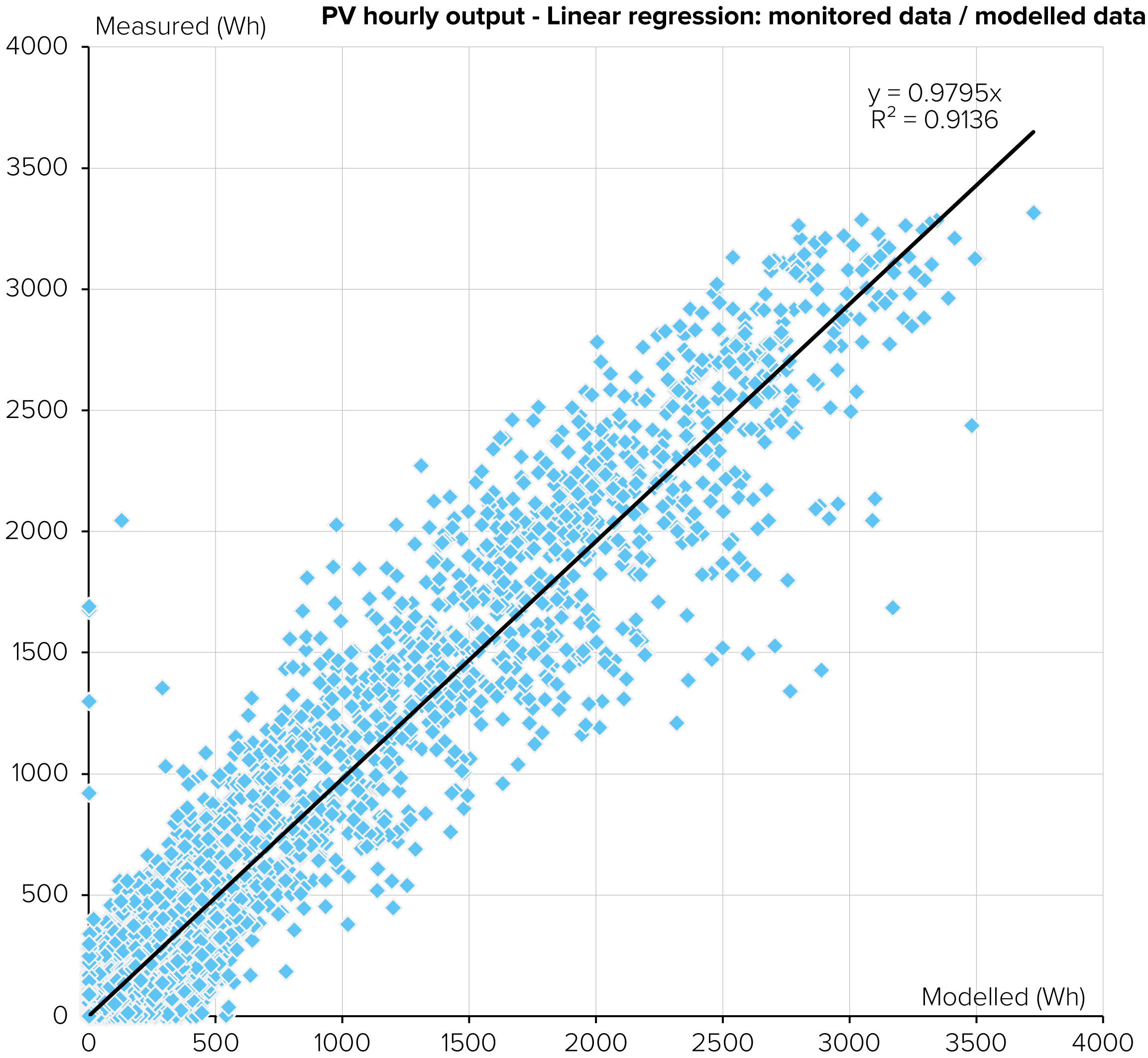


Figure 131 – Graph showing hourly PV output's correlation between measured data from the Solcer House and modelled data from the EPH tool's simulation of the Solcer House using measured weather data.

The second step is to improve even more the accuracy of the model by calculating the EPH system calibration factor. To do so, the total modelled energy output is divided by the total measured energy output to find their ratio factor, which is 1.036. This calibration factor is then introduced into the algorithm of the EPH tool.

Figure 132 shows the updated comparison between the PV output measured by the PV control system and the PV output modelled by the EPH tool using measured weather data and the EPH system calibration factor. The graph indicates that the agreement between the predicted and the measured results is remarkably good, with a mean accuracy of 100% according to the trend line slope.

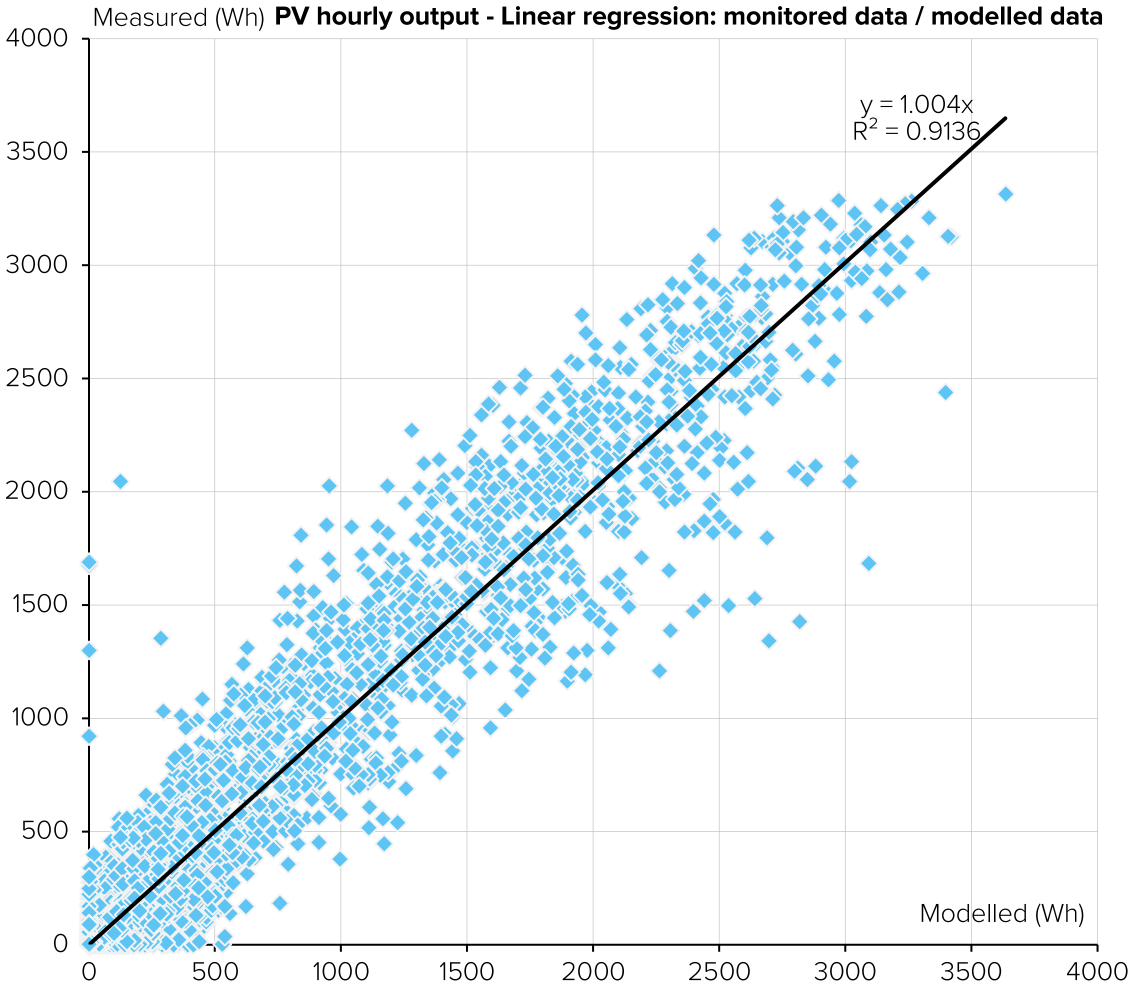


Figure 132 – Graph showing hourly PV output's correlation between measured data from the Solcer House and modelled data from the calibrated EPH tool's simulation of the Solcer House.

With the verified EPH tool, the comparison of the annual energy supply from the PV panels shows that predictions from the verified EPH tool are still slightly higher (4,089 kWh/year) than the monitored data from the real case study (4,074 kWh/year) by about 0.5%. However, this error is below the desired 5% benchmark, thus it is considered acceptable because it could be caused by the difference in weather data and by the monitoring sensors' uncertainty budget. It is important to highlight that PV panels tend to degrade over the time and this degradation rate is not considered by the EPH tool. However, the data from the Solcer House is measured from a new installed PV system; hence the degradation rate should not influence the tool evaluation process.

7.1.4 ENERGY STORAGE

The Solcer House monitored data was analysed for a period of two years, from July 2015 to July 2017. The performance of the battery is driven by two factors: energy demand from the house and energy generation from renewables being fed into the battery. Therefore, it is clear that in order to validate the algorithm for the EPH tool's calculations of the battery performance, those two factors need to be the same when comparing battery's modelling results against measured results. For this reason, the measured hourly energy demand and the measured hourly energy generation from the PV system were introduced into the EPH tool, hence to validate the EPH design algorithms based on the same demand and supply conditions.

To evaluate the battery performance, the attention is focused on the state of charge (SoC). Figure 131 compares the measured hourly percentage of SoC at the Solcer House against the percentage predicted by the EPH tool.

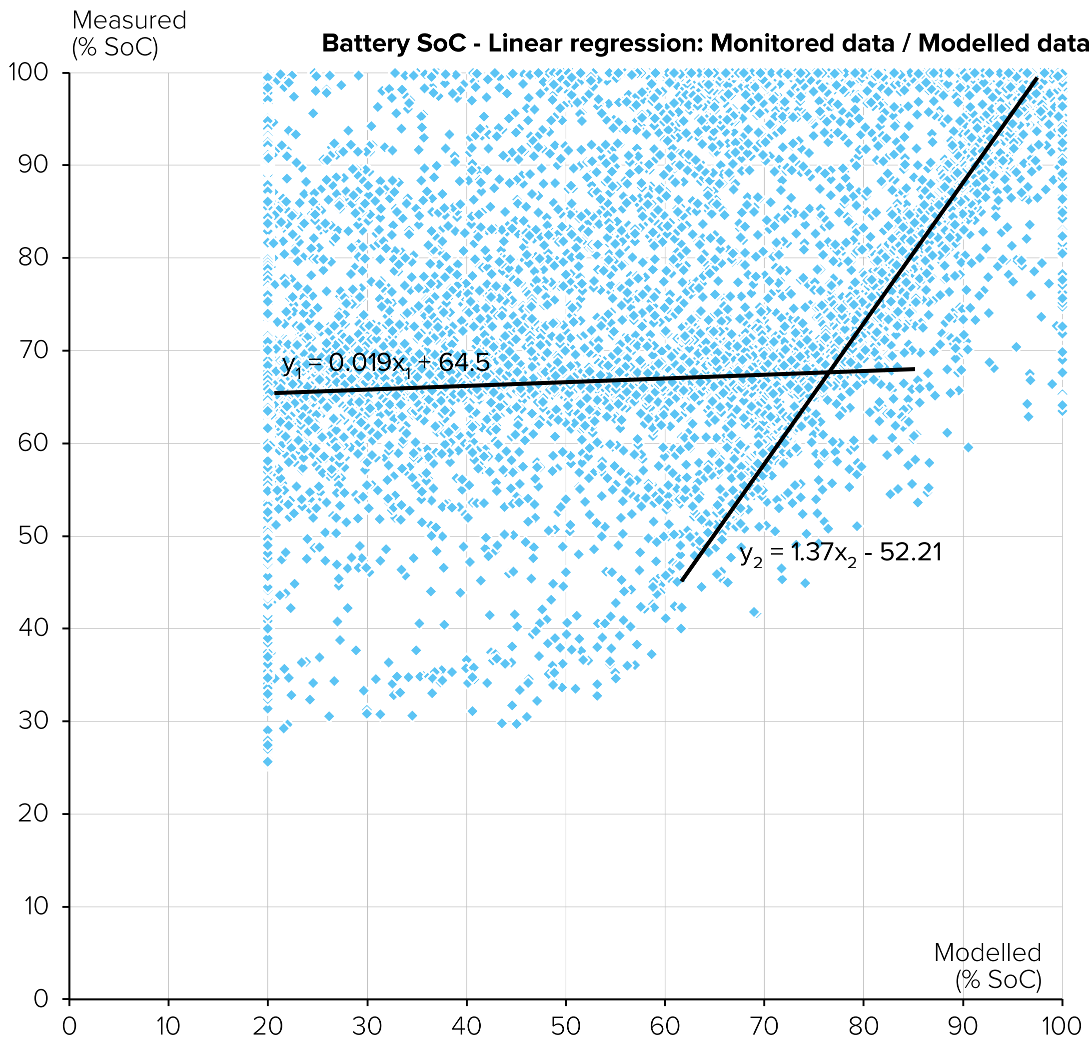


Figure 133 – Graph showing hourly battery's SoC correlation between measured data from the Solcer House and modelled data from the EPH tool's simulation of the Solcer House using monitored demand and PV generation.

The graph clearly shows that there are two tendency lines:

- Y1 trend shows the more frequent lowest SoC of the batteries, which is at around 65%. This indicates that the real depth of discharge of the batteries is not the 80% claimed by the manufacturers, which is the value introduced in the EPH tool.
- Y2 trend shows a linear relation between the predicted and the measured data when the SoC is within the battery's operation range – i.e. 65 to 100%. However, this trend line has a slope of 1.37, which indicates a significant error of 37% between predicted and measured data. This error could be caused by the energy losses of the battery system, which are not accounted in the EPH tool.

Two stages are done in order to calibrate the EPH battery algorithms. First, the EPH design is run again for a 25% depth of discharge, just focusing on the Y2's slope of 1.37 and its correlation coefficient of 0.5408 (see Figure 134a). Then, the slope is corrected to 1 to improve the calibration of the model by adding a calibration factor of 1/1.37, which is applied to the algorithm to consider battery's energy losses. Once this calibration factor is added into the algorithm, the EPH tool is ran again. Figure 134b plots the results of the calibrated model against measured data, showing a slope of 1 and an improved correlation coefficient of 0.5429.

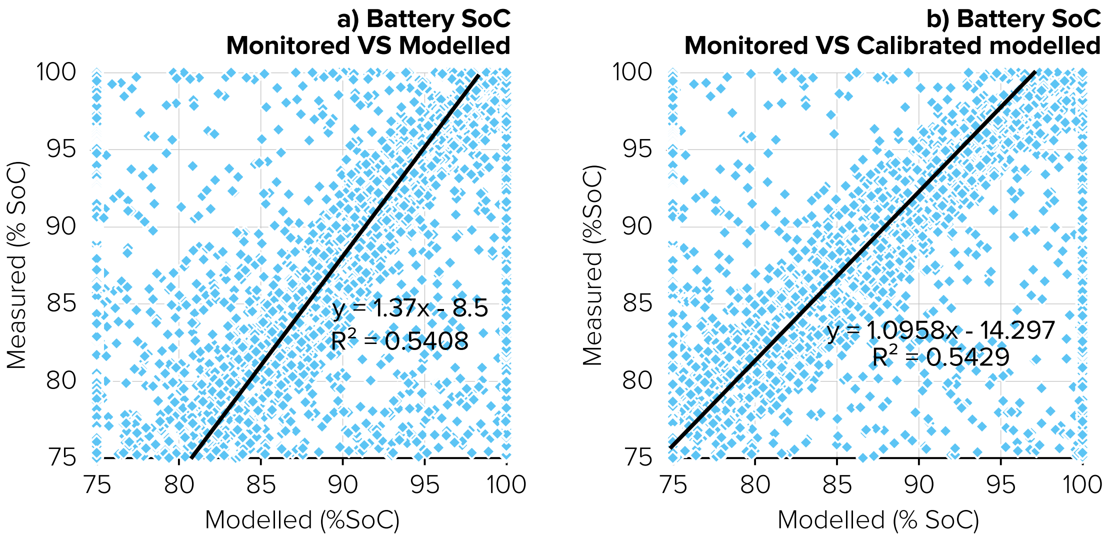


Figure 134 – Graphs showing hourly battery's SoC correlation between measured data from the Solcer House and modelled data from the EPH tool using monitored energy demand and PV generation. a) Not calibrated model. b) Calibrated model.

In conclusion, the calibrated EPH tool is considerably accurate when predicting battery's SoC, as is shown in the slope of Y2 in Figure 135. However, it uses a fixed depth of discharge value across the year, which according to measured data it is not constant and is difficult to predict. A further investigation of this issue will be done in the next section, which focuses on the evaluation of technologies performance.

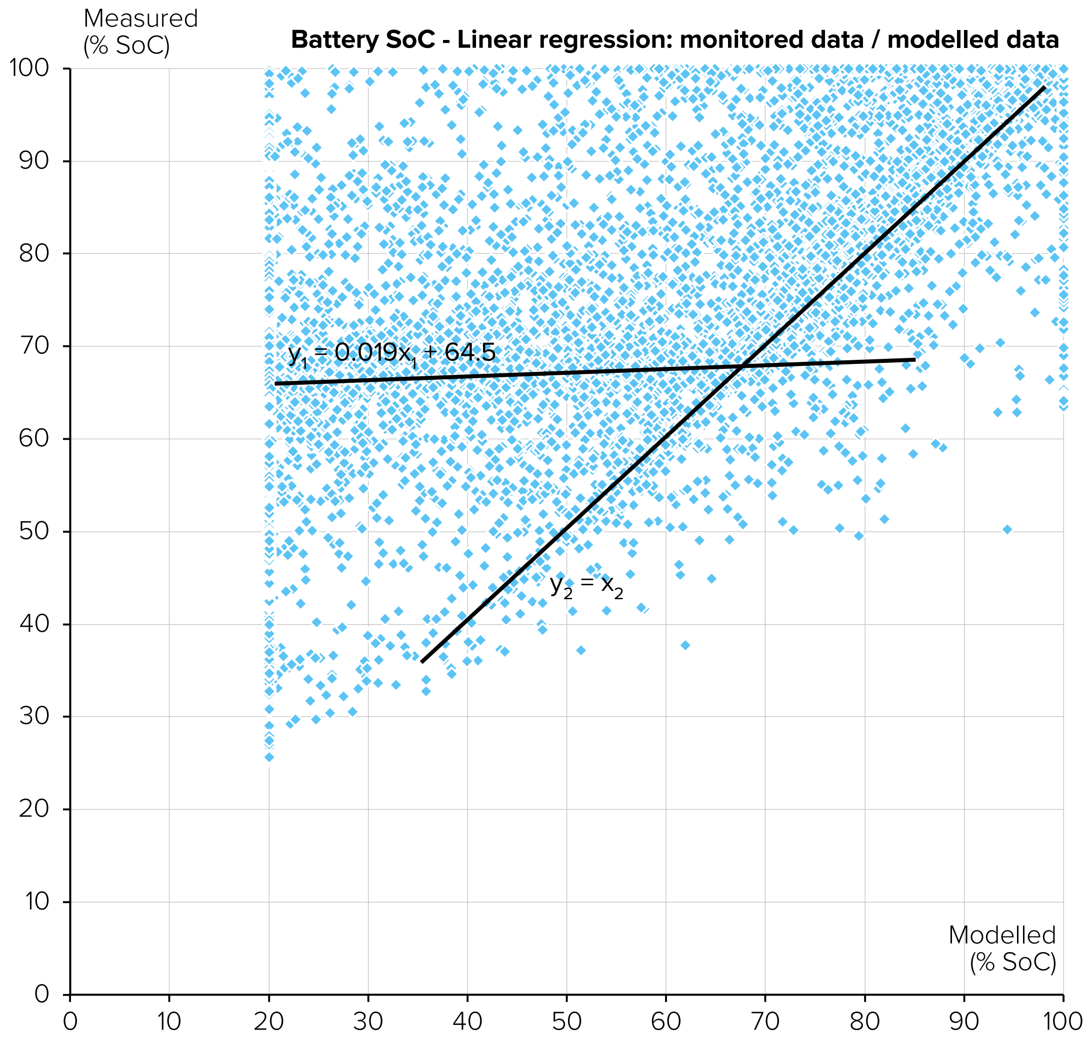


Figure 135 – Graph showing hourly battery's SoC correlation between measured data from the Solcer House and modelled data from the calibrated EPH tool's simulation of the Solcer House using monitored demand and PV generation.

7.2 EPH system: analysis of performance

This section presents the results of the technologies performance of the Solcer House and uses monitored data to evaluate their implementation. It is important to highlight that this section uses monitored data collected from the Solcer House project, which was built as part of the LCRI SOLCER project, hence the presented data belongs to WSA.

Many examples of evaluation of real energy performance of green buildings have been published to date. In Canada, Li et al. (2016) created an evaluation framework of the energy performance of NZE homes that was then applied to a real case study; Sharmin et al. (2014) implemented a sensor based monitoring system in an occupied building to measure energy usage, thermal performance and indoor air quality; and Yu et al. (2013) reviewed the more common methodologies of data analysis and proposed a data mining methodology to model energy consumption identifying the most influencing factors. In US, Thomas & Duffy (2013) studied the performance of nineteen NZE homes located in New England by modelling their energy consumption and production, compared the predicted results against the real data from the utility bills of one-year period and found that actual energy performance was more dependent on users' behaviour than on design. In Europe, Rodriguez-Ubinas et al. (2014) analysed the predicted interior comfort, functioning and energy performance of the houses presented in the Solar Decathlon Europe 2012 and compared it with the monitored data. In the UK, Ridley et al. (2014) studied the performance of two Passivhaus homes with CSH Level 6 located in Wales by comparing the predicted performance from PHPP and CSH modelling packages with the monitored data collected over two years, while focusing in overheating risk, occupants' behaviour and appliances choices. All these examples have been used as a reference for the evaluation carried out in this section.

7.2.1 ELECTRICAL ENERGY TECHNOLOGIES

First, the performance of the solar PV and the battery storage technologies is evaluated by calculating their real efficiency using the monitored data from the Solcer House. This allows comparing the real performance against the predicted performance claimed by manufacturers specifications. Afterwards, an overall evaluation of the whole electrical system is done. Accordingly, electrical monthly and annual values are presented for energy supply and demand, and variations on the energy loads. Also, typical daily profiles for a week are presented for electrical energy demand, energy supply from the PV and the grid and energy stored into the batteries; for sunny and overcast periods in winter and summer.

7.2.1.1 Solar PV

Solar efficiency refers to the portion of energy in the form of sunlight that can be converted via photovoltaic into electricity. Efficiency is a measurement of the output divided by a certain factor. The efficiency of solar cells and PV panels generally refers to the energy output per given area. Therefore, the first step is to calculate the area of the PV panels and the area of solar cells, so the PV panel efficiency and the solar cells efficiency can be found. Area calculations are as follows:

Total area PV panels = Number Panels x Area Panel

Total area PV panels = 40 x (1.2m x 0.6m) + 8 x (0.6m x 0.6m) = 31.68 m^2

Figure 136 – Equation used to calculate the total area of PV panels.

Total area Solar Cells = Number Cells x Area Solar Cell

Total area Solar Cells = [(40 x 36) + (8 x 16)] x (0.125m x 0.125m) = 24.5 m^2

Figure 137 – Equation used to calculate the total area of solar cells.

A scatter plot is shown in Figure 138 to identify the type of relationship between the hourly solar energy output from the PV panels in the Solcer House and the solar radiation incident on the 20º tilted PV panels. The graph plots hourly data collected over one year period, from August 2015 to July 2016, and shows scatter points in blue for winter and in pink for summer. The trend line shown in the graph indicates an estimative efficiency of the installed PV panels, which is around 9.71%. This means that 1m^2 of PV panel is capable of generating around 97Wh of electricity for a given incident solar radiation of 1,000Wh/m^2.

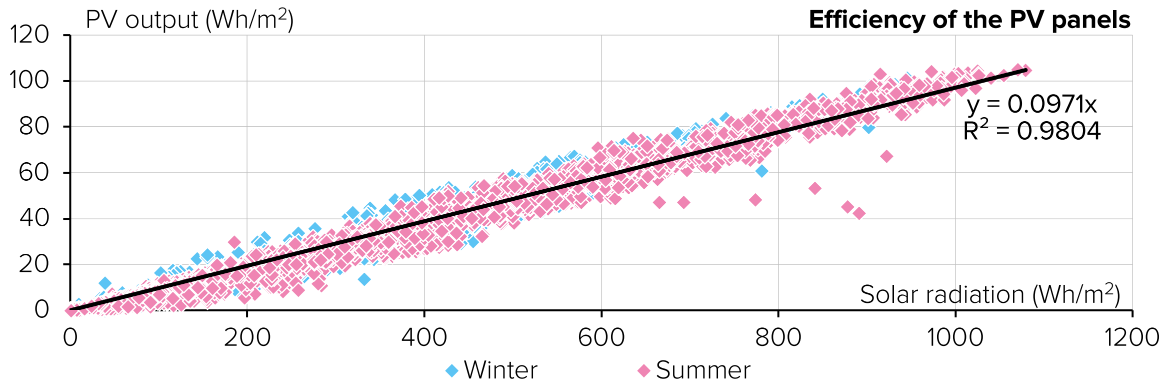


Figure 138 – Graph showing the correlation between the measured solar radiation incident on the PV panels (Wh/m^2) and the measured energy output from the PV panels (Wh/m^2).

A more detailed analysis is shown in Table 22, where the total energy output from the PV ($\sum E_{PV}$), the total solar radiation incident on the tilt of the PV ($\sum R$) and the efficiency of the PV panels (η_{PV}) are evaluated on a monthly basis. Based on the experimental data, it is found that November and December are the months when the PV is less efficient, while the summer months are the more efficient. When comparing the yearly average efficiency of 9.12%, against the efficiency claimed by the PV manufacturers of 12.9%, it is found that the installed PV panels perform slightly worse than expected. The discrepancy between the measured PV efficiency and the efficiency claimed by the manufacturers, is due to the fact that the first is measured under real outdoor operating conditions while the second is measured under laboratory standard test conditions (STC). STC is an industry-wide standard to indicate the performance of PV modules at standard conditions – i.e. cell temperature of 25°C, irradiance of 1000W/m² and an air mass 1.5 spectrum – which correspond to the irradiance and spectrum of sunlight incident on a clear day upon a sun-facing 37° tilted surface with the sun at an angle of 41.81° above the horizon. However, these conditions are rarely encountered in the real world.

Table 22 – Calculation of the monthly and annual efficiency rate of the PV, by dividing the monthly electrical energy output from the PV against the monthly solar radiation incident on it (Wh/m²).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
$\sum E_{PV}$ (kWh/m²)	2.95	6.27	12.10	14.97	17.45	14.50	14.74	13.74	14.20	8.46	2.41	1.57	122.7
$\sum R_{PV}$ (kWh/m²)	41.2	69.2	126.1	157.7	183.2	152.3	161.3	146.6	149.3	95.15	35.24	27.58	1345
η_{PV}	7.16%	9.06%	9.60%	9.49%	9.53%	9.52%	9.14%	9.37%	9.51%	8.89%	6.83%	5.69%	9.12%

A scatter plot is shown in Figure 139 to identify the relationship between the hourly solar energy output from the PV cells and the solar radiation incident on the 20º tilted PV panels. The graph plots hourly data collected over one-year period, from August 2015 to July 2016, and shows scatter points in blue for winter and in pink for summer. The trend line shown in the graph indicates an estimative efficiency of the solar cells of around 12.55%, which is much less than the 18.2% efficiency claimed by the manufacturers under laboratory STC.

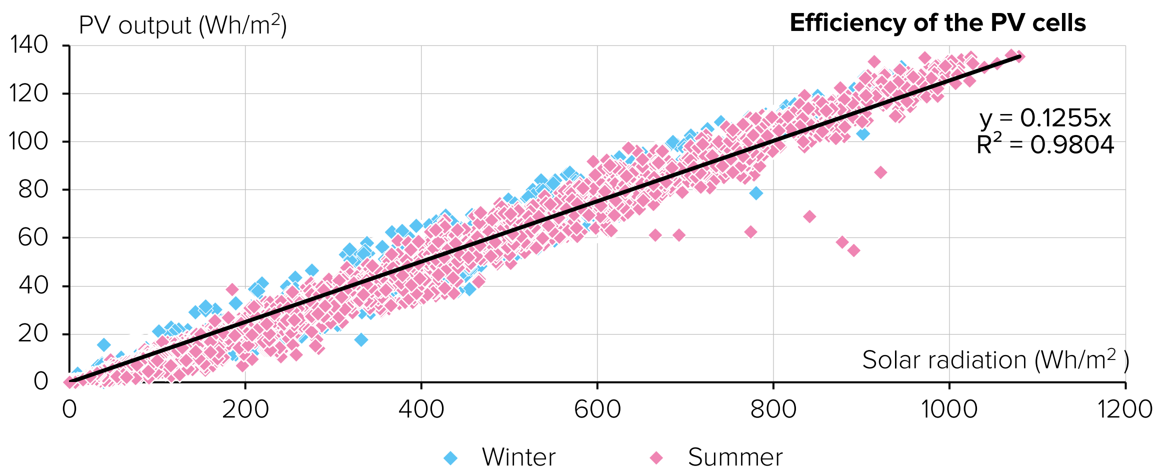


Figure 139 – Graph showing the correlation between the measured solar radiation incident on the PV cells (Wh/m²) and the measured energy output from the from the PV cells (Wh/m²).

It is important to highlight that the efficiency of the PV panel is not the same than the efficiency of the solar cell. While solar cell efficiency depends on the quality and typology of the cell, the PV panel efficiency depends on the panel construction and the density of solar cells in it. In the case of the PV panels at the Solcer House, the solar cells are separated by 24mm gap on the X-axis to let the light go through the PV panels. Results from this study have proved that the space between solar cells has a significant negative impact on the performance of the PV panels.

7.2.1.2 Battery

The performance of the LFP battery system is analysed over two years, from July 2015 to July 2017. Figure 140 shows the state of charge (SoC) of the batteries, in other words the complement of the depth of discharge of the batteries. The graph quickly demonstrates two critical issues. First, the 80% depth of discharge claimed by the manufacturers is in reality much less than that, being the average 25%. Second, the batteries failed in several occasions during the study period and a significant amount of data is missing.

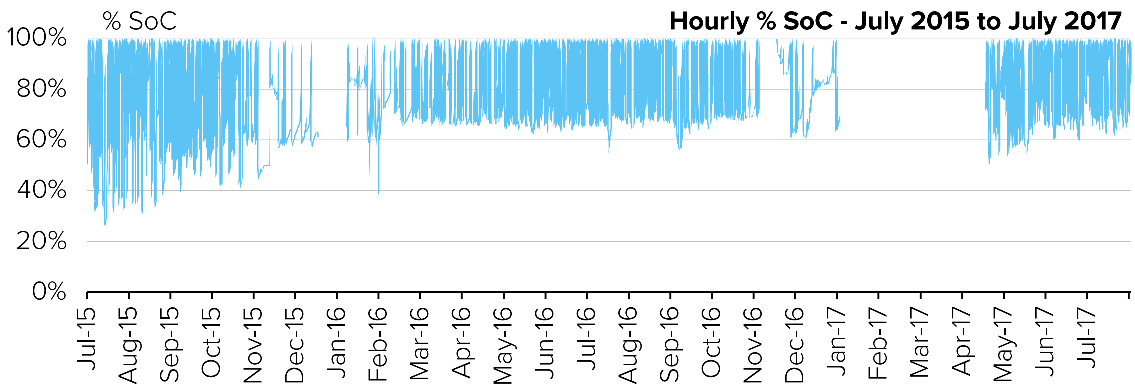


Figure 140 – Graph showing the hourly %SoC of the battery from July 2015 to July 2017. Data source: Measured data from the Solcer House.

To fully investigate the batteries poor performance, a deeper analysis of the discharge rate is done in Figure 141, which shows the frequency of the SoC rates. The main findings are:

- During 17% of the time the batteries where at full capacity. This may indicate the time when the EPH system is exporting energy.
- During 18% of the time the batteries SoC was between 70 to 75%. This indicates that the depth of discharge is around 25% instead of the 80% claimed by manufacturers.
- The lowest state of charge is 30% and only for 0.17% of the time, which indicates that the batteries have never ever reached the 20% claimed by manufacturers.

- During 19% of the time the batteries where not operating or not sending data to the server. This is a significant amount of time and raises concerns.

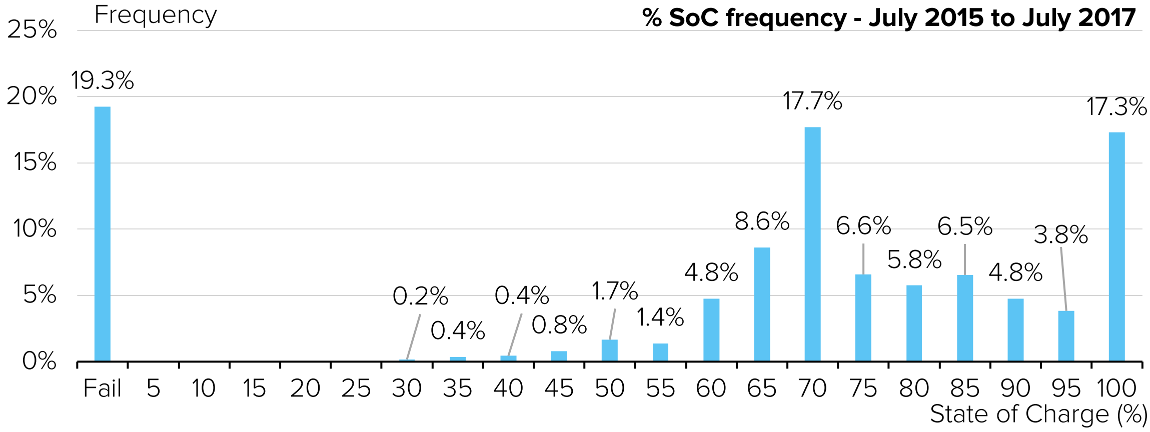


Figure 141 – Graph showing the frequency of the hourly %SoC of the battery from August 2015 to July 2017. Data source: Measured data from the Solcer House.

Monthly energy supply contribution from batteries is shown in Figure 142. There are several points to highlight. First, the contribution from batteries was much higher during the first months after the installation was completed when the state of charge was going down to 40% (see Figure 140). Second, it is found that the batteries failure spotted in Figure 140, occurred in December 2015 and from January to March 2017 when the contribution from the batteries is null or almost null. Finally, the energy supply contribution from batteries is calculated over one year period, from January to December 2016, and is found that total contribution was 575kWh, which represents a 9.8% of the annual demand of 5,860kWh during the same period. However, if this calculation is done for the first months when state of charge was going down to 40% – i.e. July to Oct 2015 – the contribution is much higher representing 36% of the energy demand during these months. This indicates that if depth of discharge could be the 80% claimed by the manufacturers instead of the measured 25%, contribution from batteries would be much higher and could meet initial expectations.

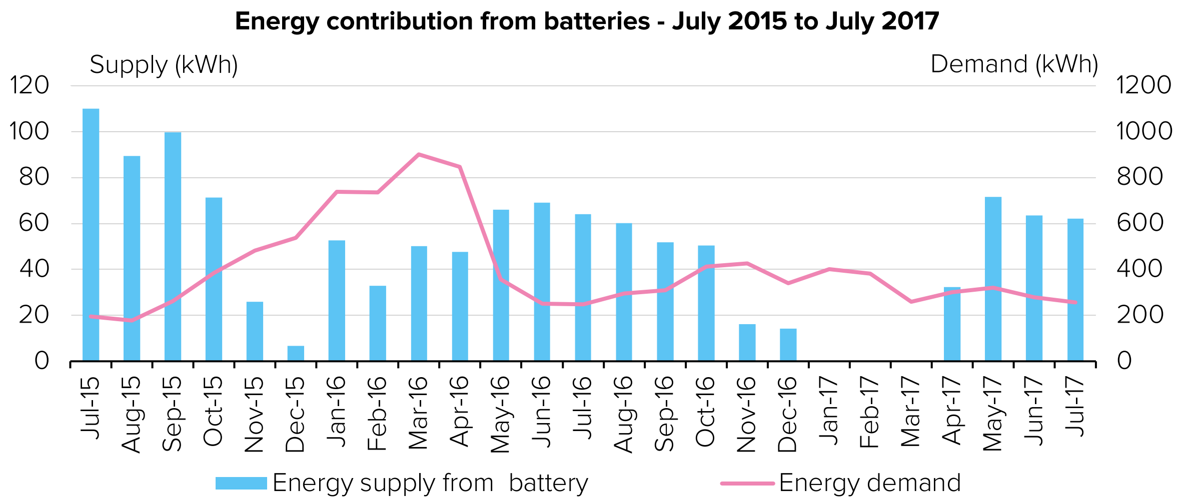


Figure 142 – Graph showing monthly energy supply contribution from batteries and monthly energy demand from July 2015 to July 2017. Data source: Measured data from the Solcer House.

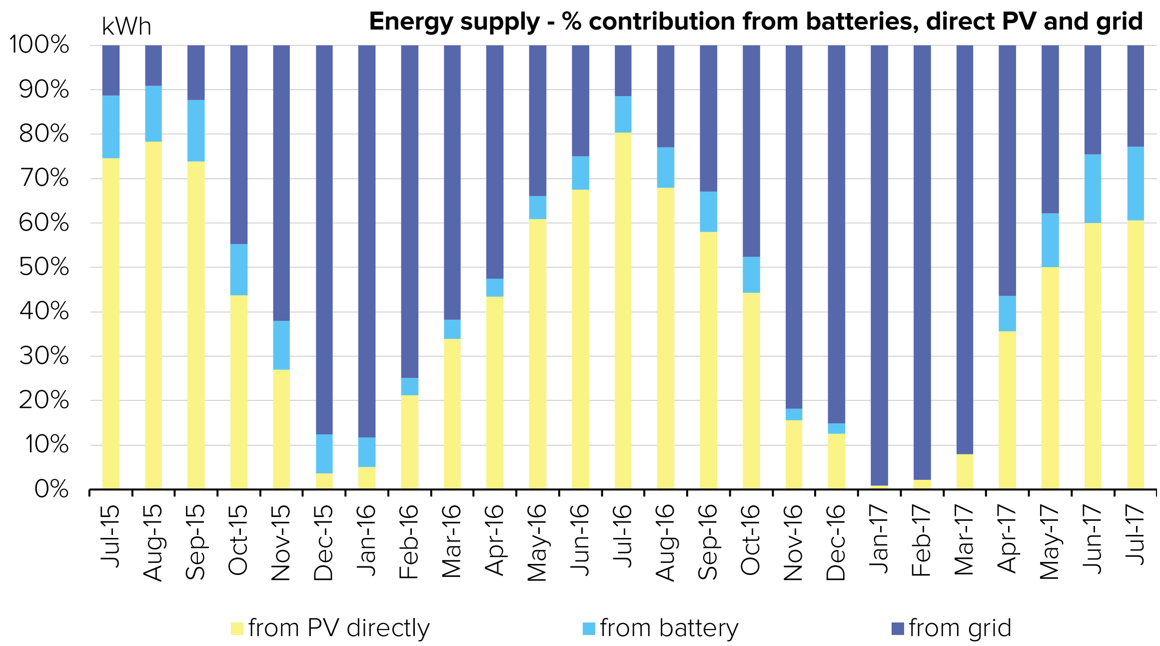


Figure 143 – Graph showing monthly energy supply contribution from batteries, direct PV and grid from August 2015 to July 2017. Data source: Measured data from the Solcer House.

In conclusion, batteries performance does not meet modelled predictions because the measured depth of discharge is much higher than manufacturer's claims, which means that the EPH system only uses 25% of the battery capacity instead of the 80% expected. After conversations with the batteries' manufacturer, it is found that the solar charge controller of the battery system uses an intelligent management algorithm that protects the battery's life by limiting the depth of discharge. Accordingly, when the solar charge controller is not able to recharge the battery to its full capacity within one day, the result is often that the battery will continually be cycled between a 'partially charged' state and the 'end of discharge' state.

This mode of operation (no regular full recharge) will destroy a lead-acid battery within weeks or months. The Battery Life algorithm will monitor the state of charge of the battery and, if needed, day by day slightly increase the load disconnect level (i.e. disconnect the load earlier) until the harvested solar energy is sufficient to recharge the battery to nearly the full 100%. From this point onwards, the load disconnect level will be modulated so that a nearly 100% recharge is achieved about once every week. However, this life-prolonging strategy reduces the energy capacity dramatically from 80% to 25% in the case of the EPH system.

It is clear that batteries deployment in the market is happening very quickly and failures and errors still need to be explored. LFP batteries have not yet fully matured and are improving. Important advancements have been made in longevity and safety, while the capacity is still an issue but increasing incrementally. However, if these barriers could be overcome, the potential of batteries to increase energy savings and self-sufficiency would be even more.

7.2.1.3 Systems approach: Annual performance of electrical system

The energy performance of the Solcer House and its electrical energy technologies is evaluated with a systems approach to the house's energy balance by considering how the energy demand from the house is covered either with renewable energy used directly or stored in the batteries, or with the grid. To guarantee a good performance of the overall systems approach, it is important to maintain always an energy balance between the energy going into the system and the energy going out, as shown in the following equation.

$$\mathbf{Ei = Eo}$$
$$\mathbf{I_r + I_g = O_d + O_g}$$

Where:

E_I = Energy input or energy from outside the house. That being:
- Ir = Energy from renewable sources
- Ig = Energy input from the grid at times when renewables or batteries are not sufficient.

E_O = Energy output or energy to the house. That being:
- Od = Energy to the house's appliances, lighting, heating and cooking devices.
- Og = Energy output to the grid that is exported when there is an excess of renewables generation and the batteries are already full.

Figure 144 – Equation used to calculate the EPH design's energy balance.

The EPH design's annual and monthly energy balance is shown in Figure 145, which is based on measured hourly data at the Solcer House from July 2015 to July 2017. On one hand, when considering the bar chart, it is clear that during the first period of analysis, energy demand was very high in winter at around 800kWh per month due to the problems experienced in the heating system described in sections 7.1.1 and 7.2.2; but as soon as the issue was corrected during the second period of analysis, energy demand was halved. Consequently, energy from the grid, which is imported when renewables do not meet demand, was much higher in the first period of analysis than in the second period; while energy to the grid, which is exported when renewables exceed demand, was much lower in the first period of analysis than in the second period. On the other hand, when considering the monthly data in more detail, it is found that during the first period of analysis, the Solcer House was energy positive for 5 months: August to September 2015, and May to July 2016. A significant improvement is seen on the second period, when the Solcer House was energy positive for 7 months: August 2016 to September 2016 and March to July 2017. Generally, it can be concluded that the Solcer House is energy positive for more than half of the year, from March to September, when the energy systems perform correctly.

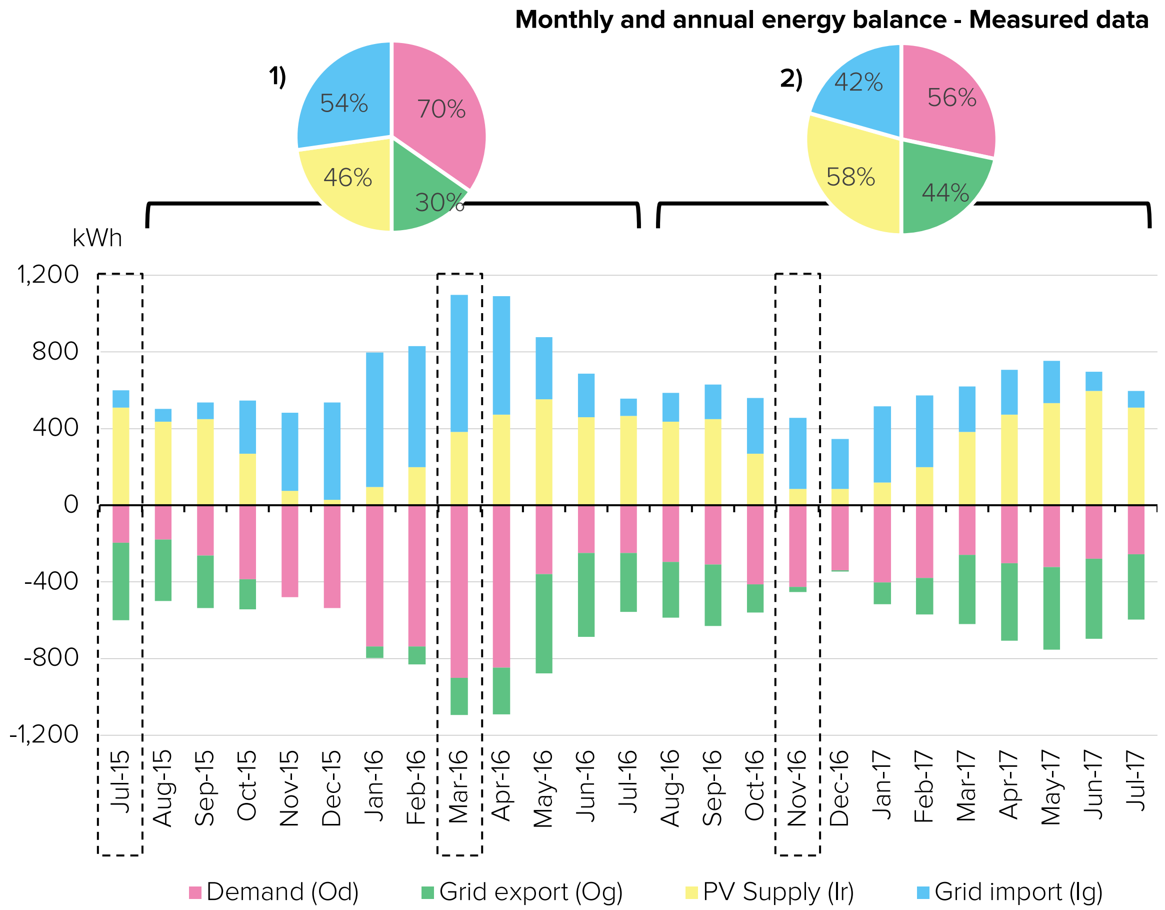


Figure 145 – Bar chart: Measured monthly energy demand and supply from July 2015 to July 2017. Pie Charts: Annual energy demand and supply from August 2015 to July 2016 and from August 2016 to July 2017. Data source: Measured data from the Solcer House.

The pie charts in Figure 145 compare the annual energy balance for the two periods that were analysed. Owning to the house's energy balance, the pie charts are divided into two exact parts, which represent energy input and output. The left half of the pie is energy input to the house –i.e. from the grid or PV generation–, while the right half is energy output from the house –i.e. export to the grid or house demand–. By comparing the percentages of energy contribution from each of the elements, it can be concluded that:

- During the first period of analysis (see pie chart 1), the energy demand from the house was 24% more than the energy generated from renewables; hence the house was not energy positive. The house energy demand was met with 46% from renewables and 54% from the grid.
- During the second period of analysis (see pie chart 2), the energy demand from the house was 2% less than the energy generated from renewables, hence the house was energy positive. The house energy demand was met with 58% from renewables and 42% from the grid. This shows that, even though the house is energy positive, it is just 58% self-sufficient, hence still needs to be connected to the grid because demand from the house occurs at times when there is no supply from renewables or batteries.

Finally, Table 23 presents annually ordered numerical data for monthly energy demand, supply and import-export balance from August 2016 to July 2017, and is graphically summarised in Figure 146. The monitoring data indicates that the Solcer House generates 3% more energy than it uses over one year, especially in summer months when its capable to export about 1,357kWh. However, in winter months when renewables generation is lower the Solcer House imports about 1,204kWh of its energy needs from the grid.

Table 23 – Annual summary of energy demand, supply and carbon dioxide emissions

	Demand			Supply	Energy balance		Energy bill		
	Heating (kWh)	**Applian. & cooking (kWh)**	**Lighting (kWh)**	**From PV use/store (kWh)**	**Import from grid**	**Export to grid (kWh)**	**Import (-£)**	**Export (+£)**	**Total (£)**
Jan	219.1	143.5	39.5	117.9	284.2	-	£63.99	£18.19	-£45.80
Feb	199.4	152.9	28.7	198.6	182.4	-	£60.35	£30.63	-£29.72
Mar	78.2	154.9	26.6	383.5	-	123.8	£43.52	£59.15	£15.63
Apr	125.2	158.9	17.9	474.2	-	172.2	£49.40	£73.15	£23.74
May	120.1	179.9	21.1	531.1	-	210.1	£52.35	£81.92	£29.58
Jun	61.9	194.7	21.4	594.7	-	316.7	£45.95	£91.73	£45.78
Jul	58.8	177.4	20.1	510.8	-	254.5	£43.04	£78.79	£35.76
Aug	151.6	120.4	24.3	435.3	-	139	£48.78	£67.15	£18.36
Sep	160.3	127.2	20.7	449.7	-	141.5	£50.29	£69.37	£19.07
Oct	281.8	107.5	23.1	268.0	144.4	-	£65.47	£41.34	-£24.13
Nov	273.1	116.7	35.4	84.8	340.4	-	£67.11	£13.08	-£54.03
Dec	206.3	101.2	32.2	86.5	253.2	-	£55.02	£13.34	-£41.68
Year		3,982		4,135	1,204	1,357	£645	£638	-£7.43

(1) Notes on costs of electricity import (Energy Saving Trust, 2017):
Electricity standard average rate = 14.37p/kWh; Electricity standing charge = £73.06/year.

(2) Notes on costs of electricity export (Ofgem, 2017):
FIT tariff Feb 2015 (4-10kW) = 13.04p/kWh; Export tariff Feb 2015 (50% gen.) = 4.77p/kWh

When analysing the resulting energy bills, Table 23 shows the money paid for the energy imported from the grid, the money received from the feed in-tariff and the export tariff and the total money balance. On one hand, the annual money spent for the energy consumed by the house is £645, which is half of the average energy bill of a typical house in the UK (OVO energy, 2014). This indicates that the energy demand reduction strategies applied in the Solcer House have successfully achieved 50% energy demand reductions. On the other hand, the annual money earnings for the energy generated and exported by the house is £638, considering the FIT and export tariff rates from 2015, which is when the commissioning of the PV system was completed. However, since 2015 solar energy tariffs have persistently been reduced, which indicates that money income from solar generation in future housing projects is likely to be less than the calculated in Table 23. At the end of the year, the energy bill is £7.43, compared against the average £1,344 (OVO energy, 2014).

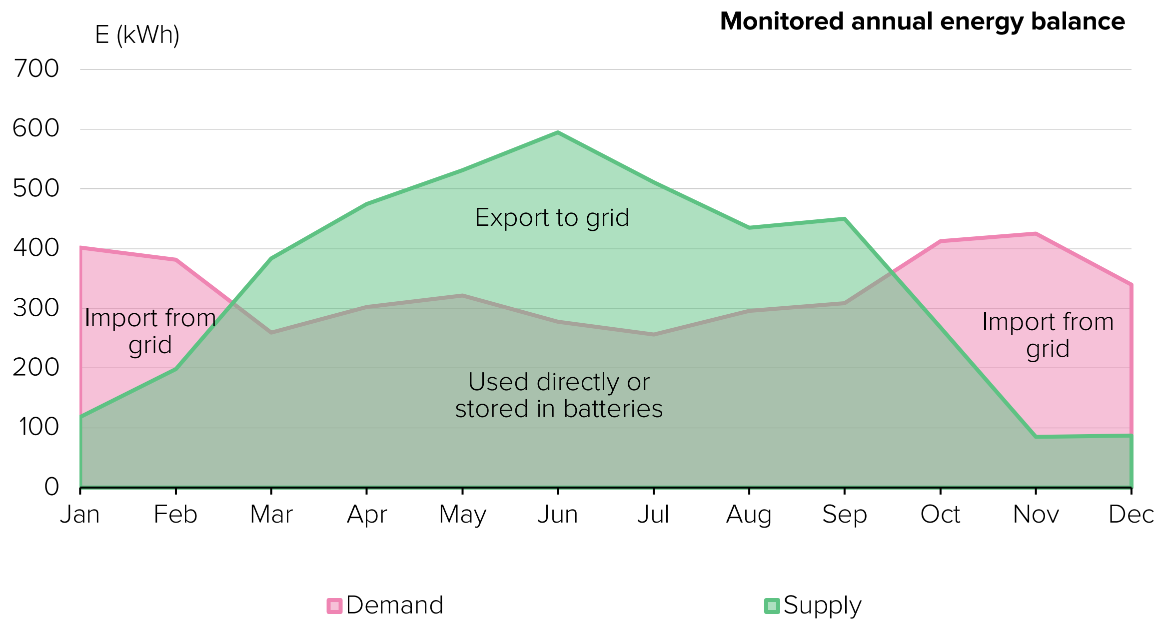


Figure 146 – Graph showing monthly energy demand and supply. Data source: Measured data from Solcer House.

Overall, across one year the house exports 13% more energy than it imports, hence it is energy positive. Figure 146 presents the monthly values of energy supply from the PV and battery system, plotted against the monthly values of energy demand from the house. It shows import of energy from the grid peaking during winter, and export of PV energy to the grid peaking in summer. It also shows that the surplus power exported to the grid in summer significantly exceeds the power imported from the grid, mainly in winter.

7.2.1.4 Systems approach: Seasonal performance of electrical system

This section considers the performance of the electrical system in more detail, by analysing a typical month in winter and in summer. The months selected to represent each season were shown earlier in Figure 145: March 2016 for winter and July 2015 for summer.

In winter, see Figure 147, the Solcer House is not energy self-sufficient as it does not meet its energy demand with the supply from the PV system and the battery system, thus solar energy is not sufficient. Over the whole month, direct energy from the PV system represents 34% of the total, while energy from batteries and the grid represent 4% and 62% respectively. In regard to energy surplus, the import to export ratio is 1:0.08, which indicates that the Solcer House is not energy positive. For example, for each 1kWh of energy that is needed from the grid at times when renewable energy is not available, only 80Wh of energy are exported at times when renewable energy is generated in excess. In order to understand better when the import and export occur during the day, a zoom to hourly data is done in Figure 148. Finally, it should not be dismissed the relevance of energy losses of the system, which represent around 5% of the energy output and tend to be higher when there is energy surplus.

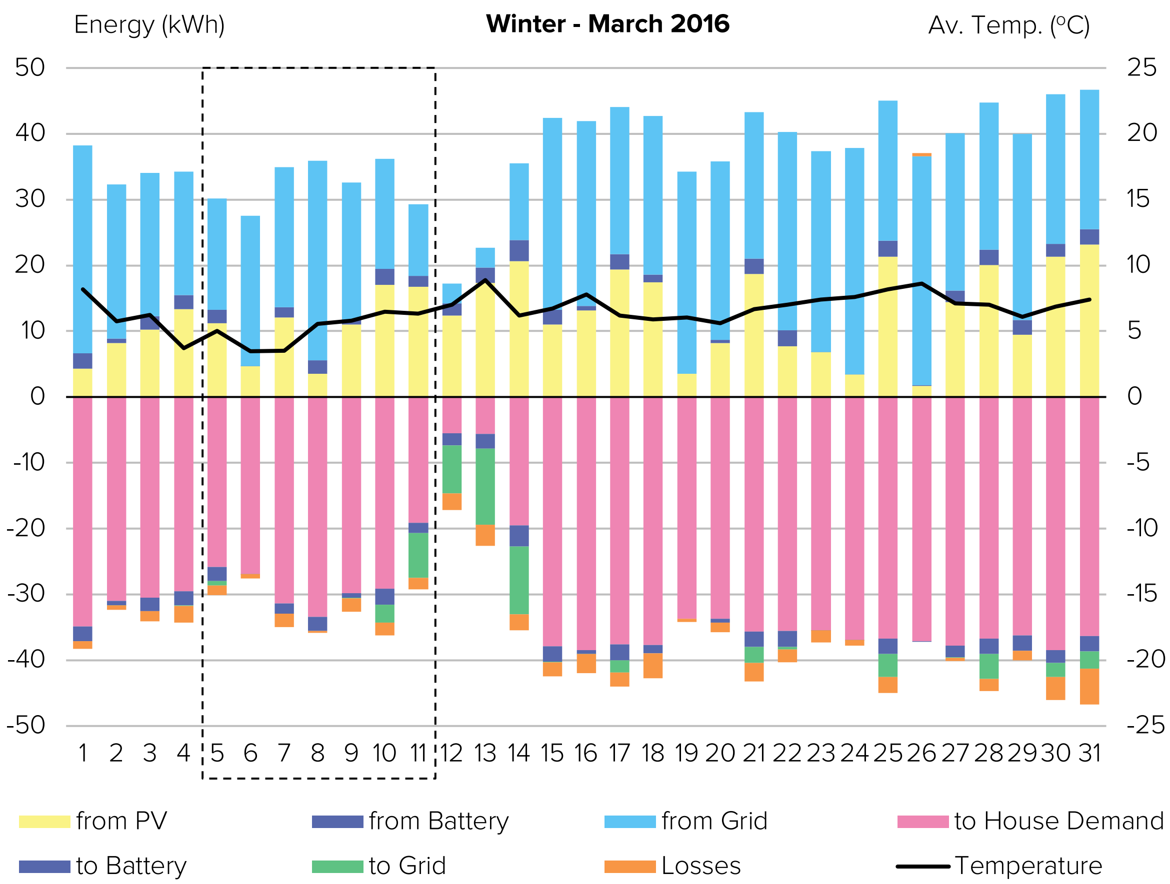


Figure 147 – Graph showing measured daily energy input and output of the electrical system at a component level in March 2016. Data source: Measured data from Solcer House.

For a more detailed analysis, Figure 148 shows a zoom to a week with different types of winter weather conditions. The graph shows that the Solcer House is almost self-sufficient during sunny winter days when solar energy can be used not only directly during the day but also to charge the batteries that can cover the demand until midnight, but not during the morning when the heating system is switched on again. However, during cloudy winter days, the energy from the solar system is not sufficient to charge the batteries, which were already emptied on the night before. The graph shows that the energy capacity of the battery is not sufficient to cover the energy demand during the night from one day to the next day, which confirm the battery problems already described in section 7.2.1.2.

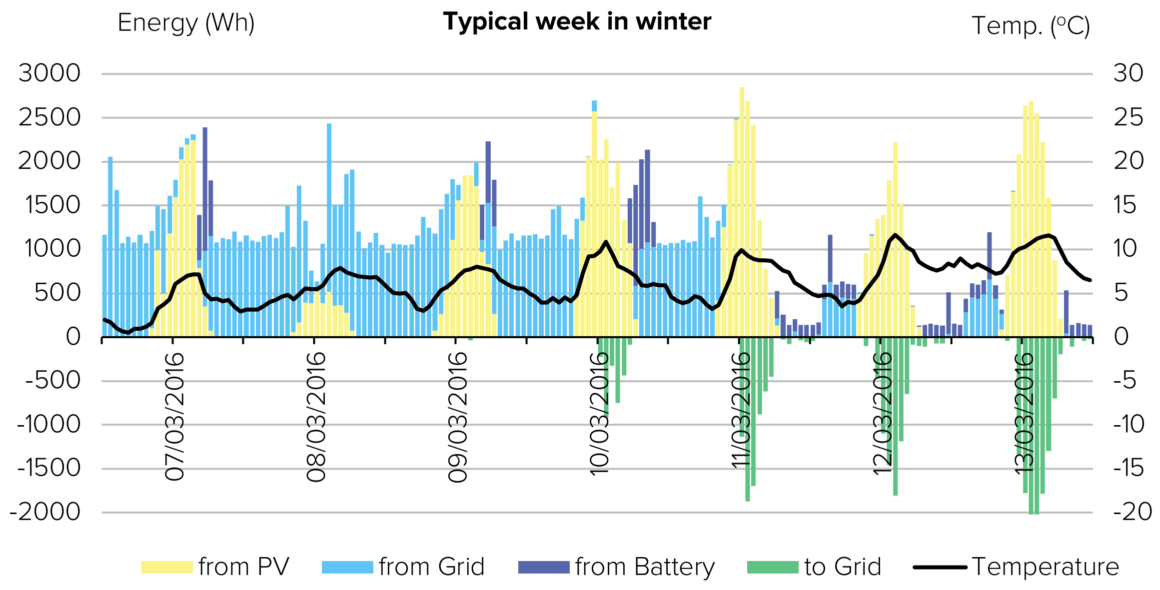


Figure 148 – Graph showing measured hourly energy input and output of the electrical system at a component level during one week in March 2016. Data source: Measured data from Solcer House.

In summer, see Figure 149, the Solcer House is most of the time energy self-sufficient covering its energy demand with solar energy from the supply of the PV and battery systems. Over the whole month, direct energy from the PV system represents 70% of the total, while energy from batteries and the grid represents 15% each. In regard to energy surplus, the import to export ratio is 1:1.52, which indicates that the Solcer House is energy positive. For example, for each 1kWh of energy that is needed from the grid at times when renewable energy is not available, 1.52kWh of energy is exported at times when renewable energy is generated in excess. During this period, as the PV power is able to supply all the building energy needs, no power is imported from grid. Also, a large amount of electricity from the PV system is exported to the grid. In order to understand better when the import and export occur during the day, a zoom to hourly data is done in Figure 150. Finally, it should not be dismissed the relevance of energy losses of the system, which represent around 15% of the energy output and tend to be higher when there is energy surplus.

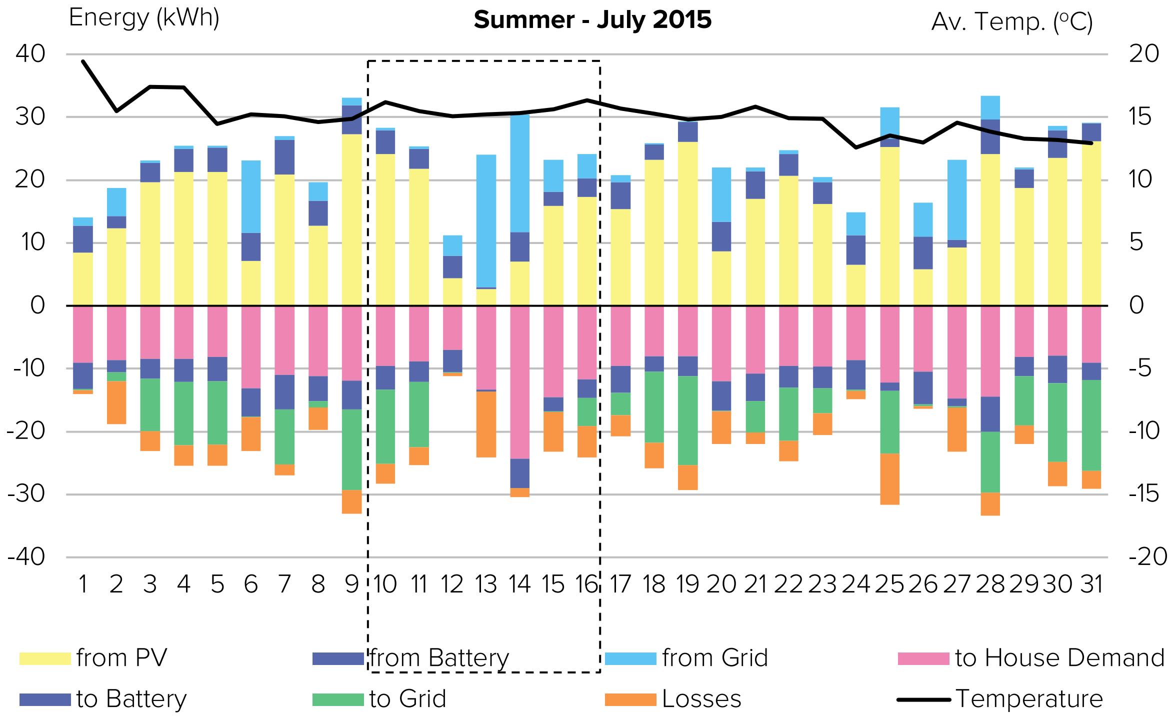


Figure 149 – Graph showing measured daily energy input and output of the electrical system at a component level in July 2015. Data source: Measured data from Solcer House.

For a more detailed analysis, Figure 150 shows a zoom to a week with different types of summer weather conditions. The graph shows that the Solcer House is self-sufficient during sunny summer days when solar energy can be used not only directly during the day but also to charge the batteries that can cover the demand overnight. However, during cloudy summer days, the energy from the solar system is not sufficient to charge the batteries, which were already emptied on the night before. The graph shows that the energy capacity of the battery is not sufficient to cover two consecutive overcast days, which confirm the battery problems already described in section 7.2.1.2.

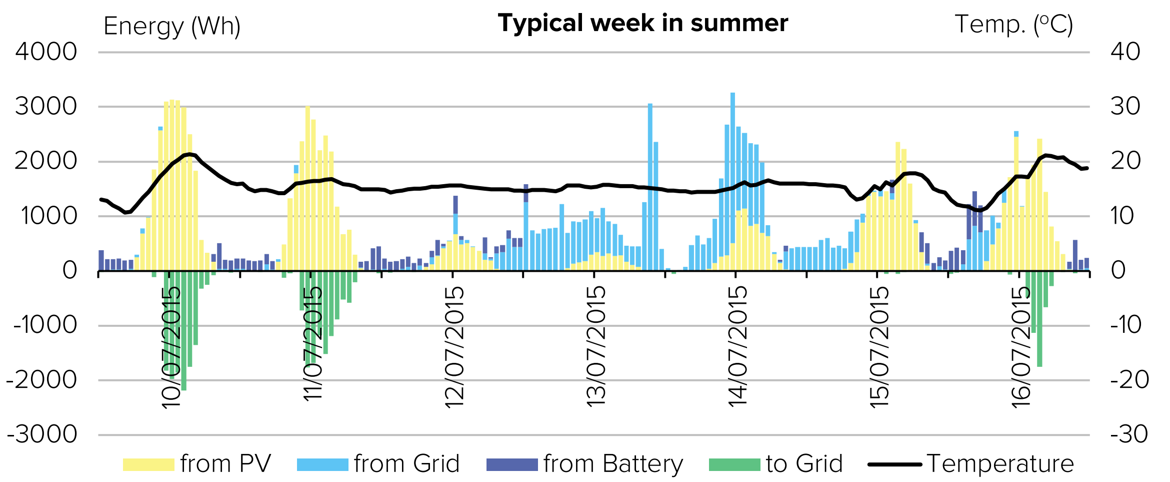


Figure 150 – Graph showing measured hourly energy input and output of the electrical system at a component level during one week in July 2015. Data source: Measured data from Solcer House.

7.2.2 THERMAL ENERGY TECHNOLOGIES

First, this section investigates the performance of each technology component that is part of the thermal energy system from July 2016 to June 2017. Afterwards, an overall evaluation of the whole thermal system is done. Accordingly, monthly and annual values are presented for heating supply and demand, and variations on the energy loads. Also, typical daily temperature profiles for a week are presented for the main stages of the thermal system, together with energy supply and demand. These are presented for sunny and overcast periods in winter and summer.

The location of the temperature sensor points is presented in Figure 151, with a number given to each sensor in order to identify them more easily in the following sections.

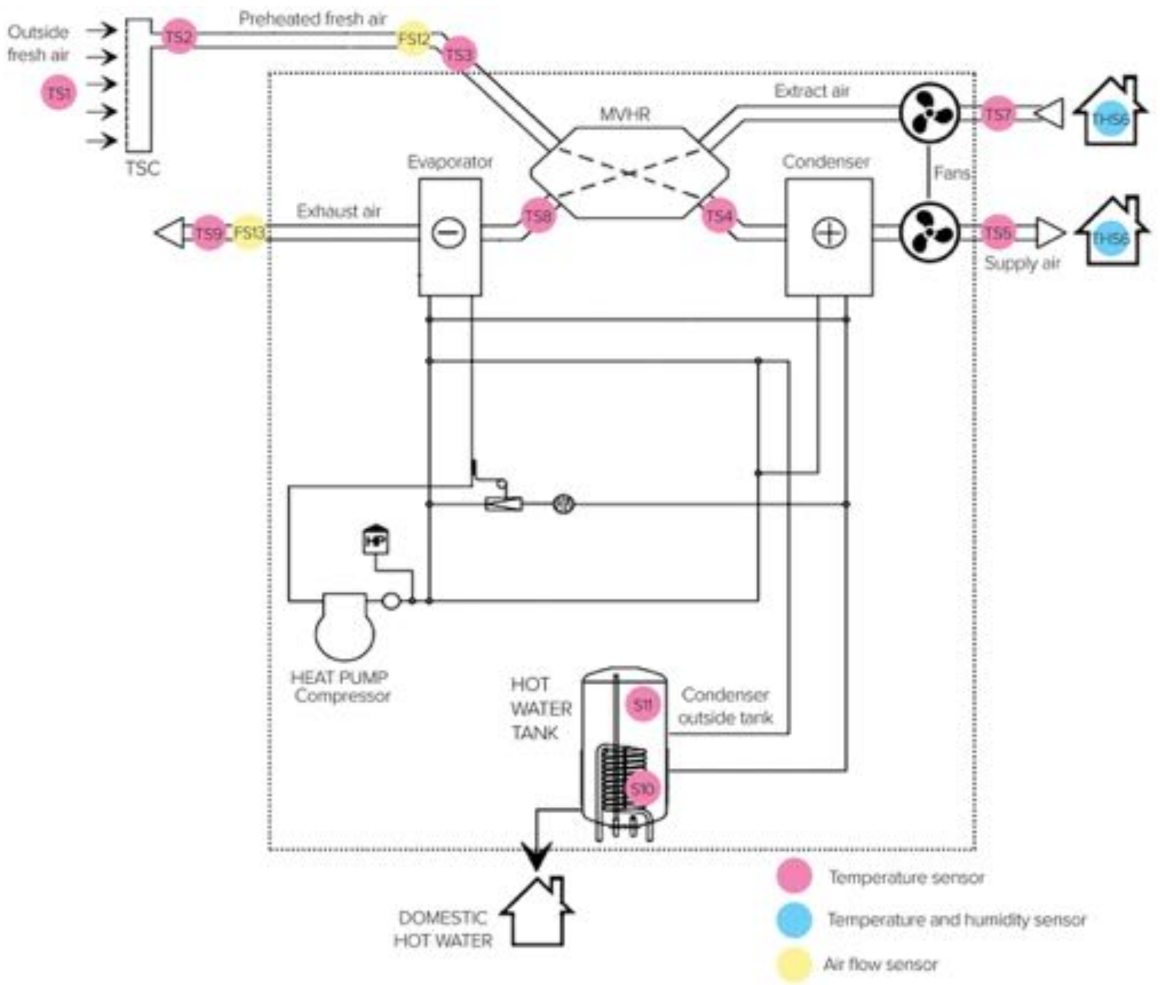


Figure 151 – Schematic showing the location of the monitoring sensor in the Solcer House thermal system.

Regarding the specifications of the sensors, these are:

- TS1, TS2, TS3, TS4, TS5, TS7, TS8 and TS9: Temperature sensors type 4-wire Class A PT100. Resolution ±0.1°C and accuracy ±0.3°C.

- THS6: Temperature and RH sensors Eltek GD11. Resolution ±0.1°C and accuracy ±0.3°C.
- TS10 and TS11: Temperature sensors installed within the Genvex Unit. Resolution ±0.1°C.
- FS12 and FS13: TPVPMP multi point velocity probe and TPDPT7 low differential pressure sensor. Accuracy +/- 0.5% FSS typical.

7.2.2.1 Transpired Solar Collectors (TSC)

Literature suggests that the external air boundary layer of the TSC provides a useful contribution to the overall energy performance, in addition to the solar heat transferred from the hot metal cladding to the air in the TSC cavity (Shukla, et al., 2012). First, the performance of the TSC system is evaluated by considering the temperature difference between the ambient air temperature (T_{AMB}) and the outflow TSC air temperature (T_{TSC}). The TSC seasonal performance is presented in Figure 152 and Figure 153, for summer (April to September) and winter (October to July). For example, with an incident solar radiation of 600W/m², TSC delivers about 16°C rise to external air temperature in summer and around 12°C rise in winter. Also, an important observation from the graphs is that there is a slight temperature drop through the TSC in some occasions, this occurs at night time or in very overcast days when solar radiation is very low. Therefore, this means that in these occasions the TSC is having a negative impact on the overall system causing some temperature losses.

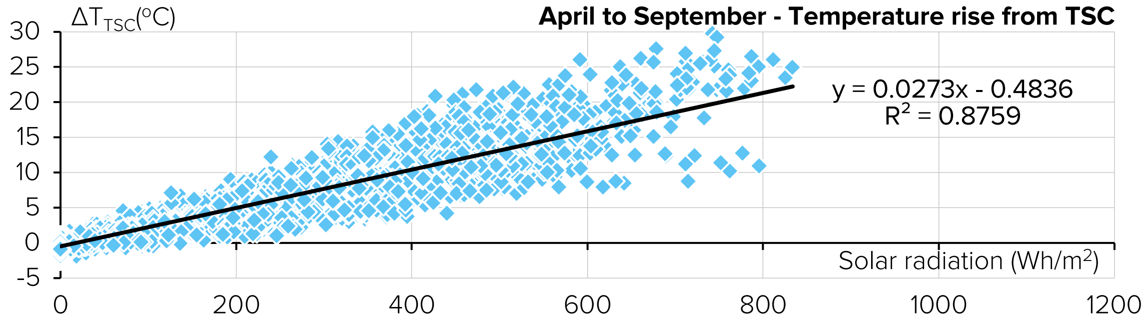


Figure 152 – Graph showing the correlation between solar radiation incident on the TSC (Wh/m²) and temperature rise (ΔT) from the TSC (°C) during the summer season. Data source: Measured data from Solcer House.

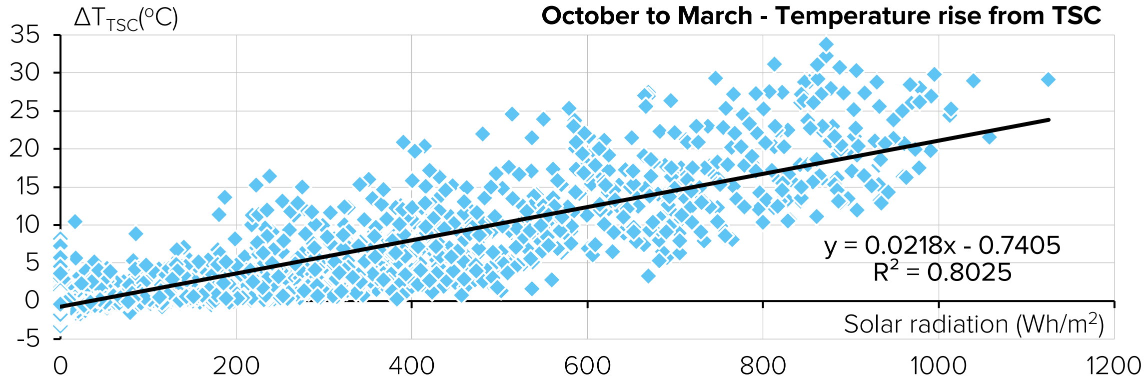


Figure 153 – Graph showing the correlation between solar radiation incident on the TSC (Wh/m²) and temperature rise (ΔT) from the TSC (°C) during the winter season. Data source: Measured data from Solcer House.

However, the temperature difference analysis does not consider the area of the TSC, which is 14 m² for the Solcer House. It also does not consider the airflow of the ventilation system, which varies significantly across the year from 0m³/h to 300m³/h. For this reason, another evaluation of the TSC performance is done, this time considering the amount of thermal energy or heat that the TSC delivers. Equation in Figure 154 is used.

$$\mathbf{Q_{TSC} = (\Delta T_{TSC}) \cdot m \cdot C_P = (T_{TSC} - T_{AMB}) \cdot m \cdot C_P}$$

Where:

T_{TSC} = Temperature fresh air after TSC measured with TS2 (ºC)
T_{AMB} = Temperature ambient fresh air measured with TS1 (ºC)
m = Mass flow measured with FS12 (m^3/h)
C_P = Volumetric specific heat capacity of air = 0.335 Wh/m^3·K

Figure 154 – Fundamental equation for fluid heat transfer used to calculate the energy delivered by the TSC.

Scatter plots are shown in Figure 155 and Figure 156 to identify the type of relationship between the hourly energy output from the TSC and the solar radiation incident on the vertical TSC area. The graphs show hourly data for the summer season in Figure 155 and the winter season in Figure 156. By comparing the two graphs, it is clear that the TSC delivers more heat during the winter months when the heat pump is on and the airflow rates are higher, rather than during summer when the thermal/ventilation system just needs to meet the ventilation needs, hence airflow is much lower.

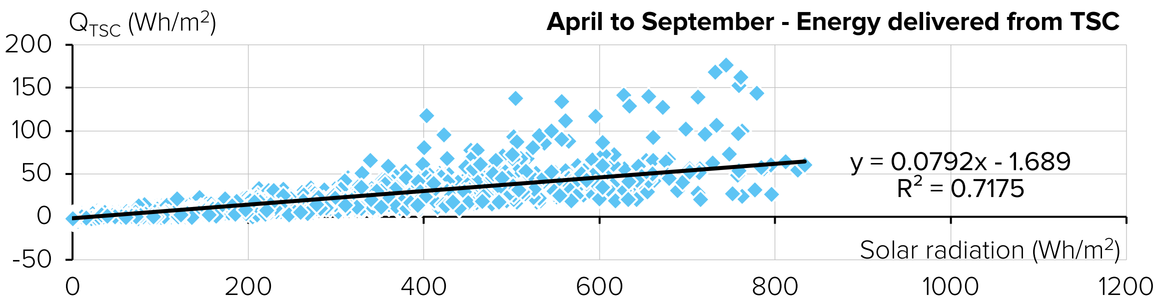


Figure 155 – Graph showing the correlation between solar radiation incident on the TSC (Wh/m²) and energy delivered (Q) by the TSC (Wh/m²) during the summer season. Data source: Measured data from Solcer House.

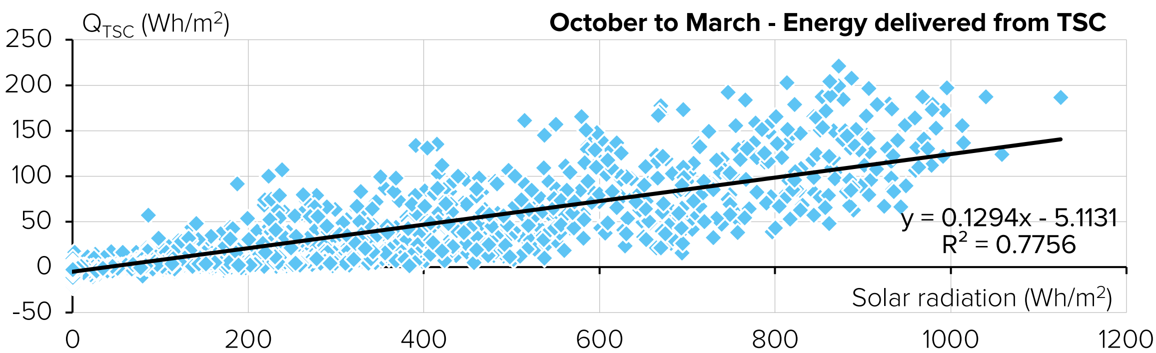


Figure 156 – Graph showing the correlation between solar radiation incident on the TSC (Wh/m²) and energy delivered (Q) by the TSC (Wh/m²) during the winter season. Data source: Measured data from Solcer House.

Table 24 – Measured monthly and annual total heat gains and heat losses through the TSC (kWh) and resulting energy contribution of the TSC in the thermal energy system (kWh).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
$\sum Q_{TSC\ Gain}$ (kWh)	110.8	82.0	100.9	149.0	107.0	74.6	79.4	79.2	82.7	182.6	168.8	70.0	1,287
$\sum Q_{TSC\ Loss}$ (kWh)	-24.9	-18.0	-9.2	-4.7	-3.5	-3.0	-2.0	-3.3	-5.1	-22.5	-26.7	-23.6	-147
$\sum Q_{TSC}$ (kWh)	86.0	64.0	91.7	144.3	103.5	71.6	77.5	75.8	77.7	160.1	142.0	46.4	1,140
$\sum R$ (kWh/m²)	70.5	65.0	91.4	113.6	100.5	76.4	83.0	95.7	97.9	113.3	91.4	61.5	1,060
η_{TSC}	**8.8%**	**7.1%**	**7.3%**	**9.2%**	**7.5%**	**6.8%**	**6.8%**	**5.7%**	**5.7%**	**10.2%**	**11.3%**	**5.5%**	**7.8%**
$\eta_{TSC + BYPASS}$	**11.4%**	**9.1%**	**8.0%**	**9.5%**	**7.7%**	**7.1%**	**6.9%**	**6.0%**	**6.1%**	**11.7%**	**13.4%**	**8.2%**	**8.8%**

Figures 139 and 140 confirm that the TSC can cause some heat losses when there is no solar radiation – i.e. night or overcast. Although the amount of heat loss is very small in an hourly basis, less than 10Wh/m², this can have a substantial impact on a monthly basis as shown in Table 24. Heat gains and heat losses results from Table 24 are calculated with the equation shown in Figure 154 using measured hourly data at the Solcer House and indicate the total amount of heat delivered by the TSC on a monthly and annual basis. This data is then used to calculate the TSC monthly efficiency using the equation shown in Figure 157.

$$\eta_{TSC} = Q_{TSC} / R \cdot A$$

Where:

Q_{TSC} = Energy delivered by the TSC as calculated in Figure 154 (Wh)
R = Solar radiation incident on the TSC (Wh/m²)
A = Area of TSC = 13.8 m²

Figure 157 – Equation to calculate the efficiency of the TSC.

The efficiency of the TSC is the ratio of the useful heat delivered by the TSC to the total solar energy incident on the collector surface (Leon & Kumar, 2007). Table 24 shows the monthly solar radiation incident on the vertical TSC and the monthly and average annual efficiency of the TSC. Two scenarios are given. First, η_{TSC},, shows the monthly TSC efficiency considering both gains during daytime and losses during night time. In this case, the average TSC efficiency is 6.9% in summer and 8.3% in winter. Second, $\eta_{TSC + BYPASS}$, only accounts for the gains as it considers that a control strategy could be added in order to optimise the system. In this case, the average TSC efficiency is 7.2% in summer and 10.3% in winter. By comparing the two efficiency scenarios, it is clear that the heat losses that occur when there is no solar radiation falling onto the TSC have a significant negative impact on the TSC efficiency, especially in winter months when the heating needs are higher. This finding indicates that a potential improvement of the thermal system performance could be achieved by enhancing the control strategy of the system with an air bypass, hence allowing to take air directly from outside rather than from the TSC during night time or overcast days.

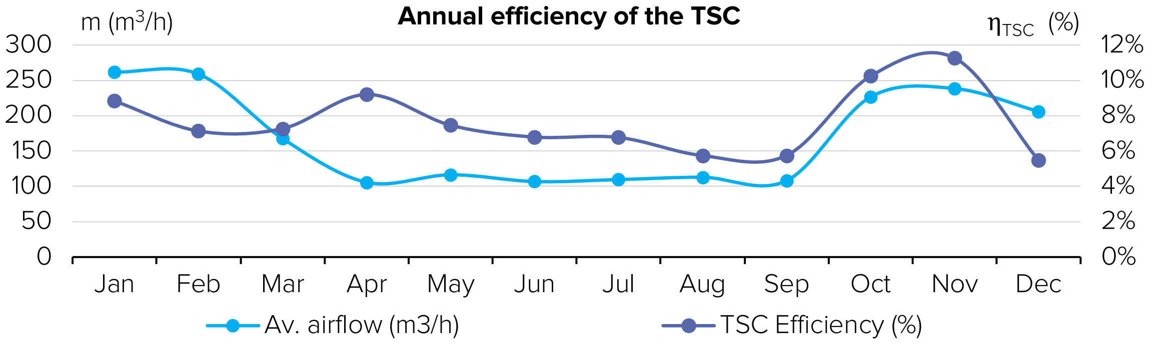


Figure 158 – Graph showing monthly average airflow delivered through the thermal energy system (m^3/h) and monthly average efficiency of the TSC (%). Data source: Measured data from Solcer House.

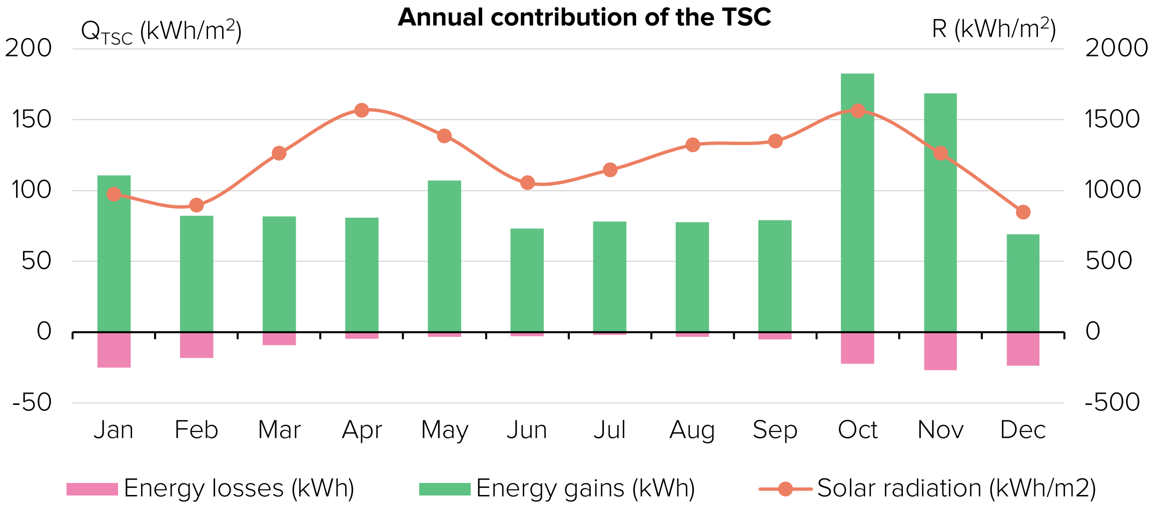


Figure 159 – Graph showing monthly energy gains and losses through the TSC (kWh/m^2) and monthly solar radiation incident on the TSC (kWh/m^2). Data source: Measured data from Solcer House.

A summary of the TSC efficiency and energy contribution is shown in Figure 158 and Figure 159. The main findings regarding the TSC performance are as follows:

- Annual efficiency of the TSC – The average efficiency is 7.8%, but varies significantly throughout the year mainly depending on:
    - Solar radiation – More solar radiation incident on the TSC surface results on more solar gains, hence higher efficiency values.
    - Airflow rate of the system – Higher airflow rates of the system result on more energy delivered, hence higher efficiency values.
    - TSC Area – The measured efficiency is lower than the predicted 20% from the manufacturer's design guidance (Tata Steel, 2016) because the designed TSC area is much larger than the minimum required (see section 5.1.2).
- Annual energy delivered by the TSC – This is around 1,060kWh. However, if energy losses during the night could be reduced with the installation of a bypass control unit, the system will significantly improve and could deliver around 1,140kWh.

7.2.2.2 Ductwork

This section evaluates the heat exchanged across the duct that delivers the air from the TSC intake located in the loft area, to the compact unit located in the ground floor of the Solcer House. The duct is made of galvanized steel with a diameter of 160mm and has 50mm of Rockwool insulation around it. It runs 10.2m horizontally across the loft area and 3m vertically through the services void.

To evaluate the heat exchanged across the duct, the hourly temperature difference from the beginning to the end of the duct is calculated and applied to the energy equation shown earlier in Figure 154. Then, scatter graphs are plotted to identify the type of relationship between the hourly energy gains or losses across the ductwork and the solar radiation incident on the glazed PV roof. The graphs show hourly data collected over one-year period, from August 2016 to July 2017, with summer in Figure 160 and winter in Figure 161. By comparing the two graphs, it is found that the duct has more heat gains than losses, especially in winter when the solar radiation incident on the glazed roof is low or zero. It seems that the greenhouse effect caused in the loft area by the glazed roof, which heats the loft space during the day, is having a big positive impact on the ductwork performance, especially in winter.

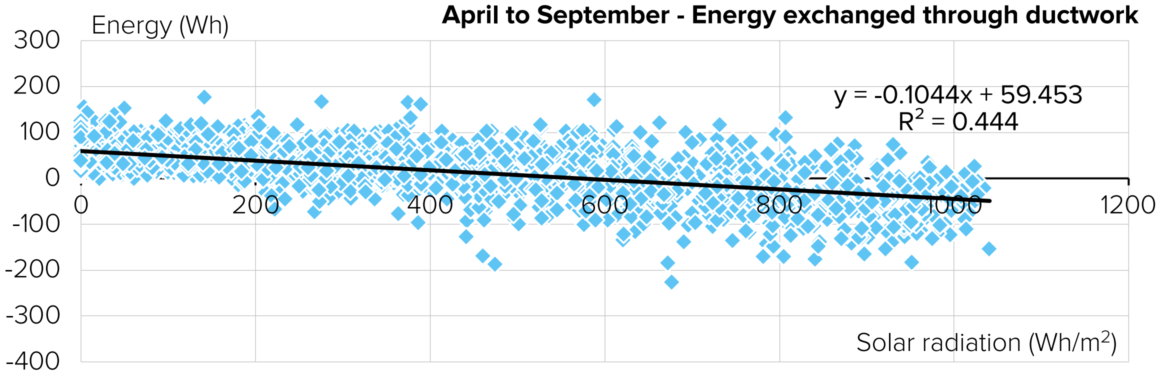


Figure 160 – Graph showing the correlation between solar radiation incident on the PV (Wh/m²) and energy exchanged through the TSC duct during the summer season. Data source: Measured data from Solcer House.

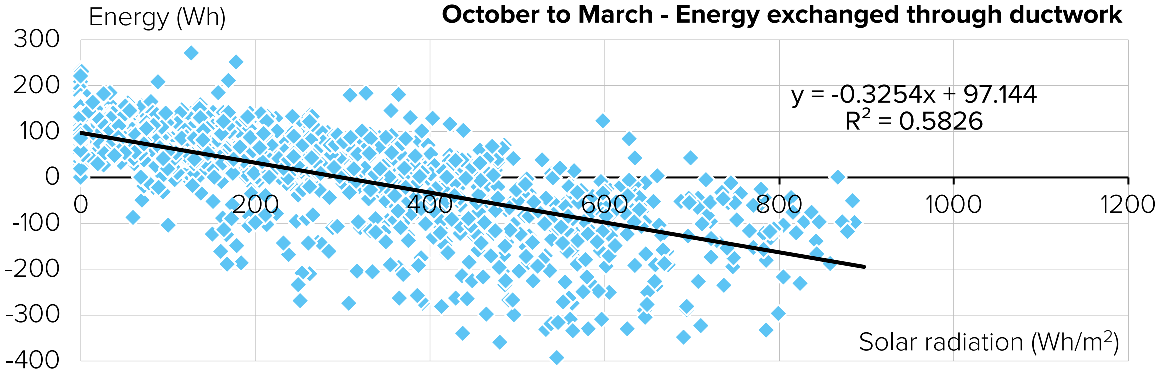


Figure 161 – Graph showing the correlation between solar radiation incident on the PV (Wh/m²) and energy exchanged through the TSC duct during the winter season. Data source: Measured data from Solcer House.

Hourly heat gains and losses across the ductwork as well as the solar radiation incident on the glazed roof for a winter month are shown in Figure 162. It is clear that heat gains occur when the solar radiation is very low or zero – i.e. cloudy days and from sunset to sunrise – because the TSC is not preheating the supply air, which is then colder than the loft space that has been heated by the sun during the day. Instead, heat losses occur when the solar radiation is at its peak –i.e. noon hours of sunny days – because the TSC preheats the supply air, which is then warmer than the loft space temperature.

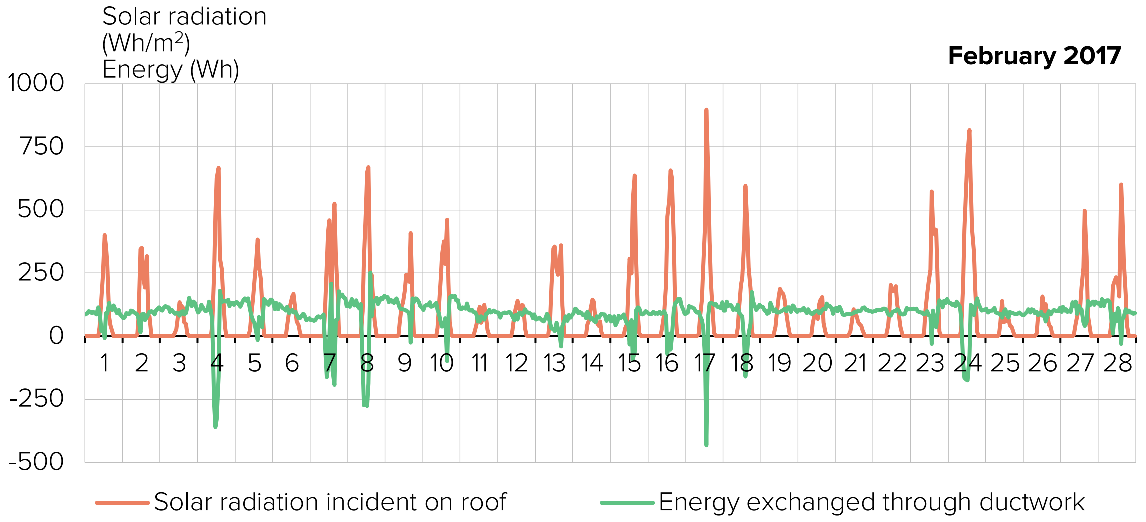


Figure 162 – Graph showing hourly solar radiation incident on the PV (Wh/m²) and hourly energy exchanged through the TSC duct (ºC) in February 2017. Data source: Measured data from Solcer House.

In conclusion, the contribution of the ductwork in the thermal energy system is positive throughout the year, whit the higher heat gains during winter. Figure 163 gives an idea of the main factors that influence the duct performance: air flow and solar radiation. For example, higher airflow rates in winter months result in higher heat gains through the duct, while solar radiation and higher outside temperatures seem to have the opposite effect and reduce the heat gains through the duct.

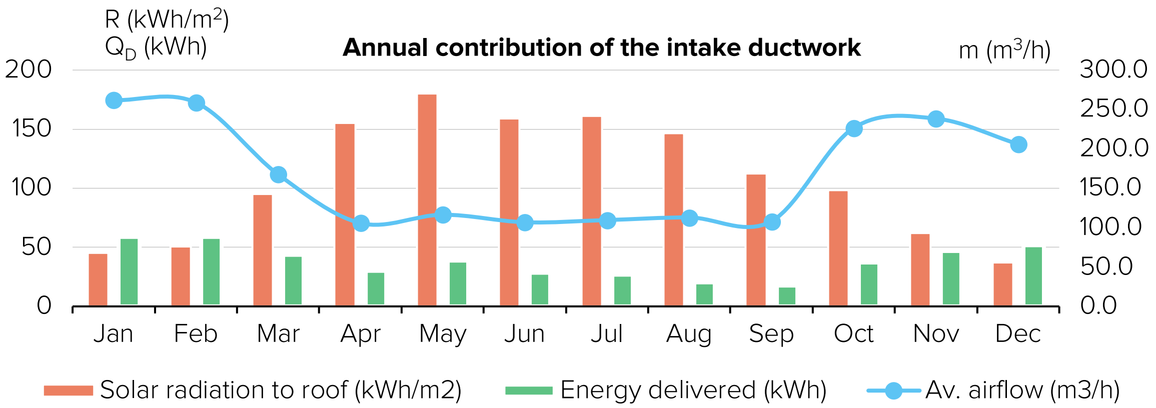


Figure 163 – Graph showing monthly energy contribution of the intake ductwork (kWh), solar radiation incident on the PV (kWh/m²) and average airflow delivered through the thermal energy system (m³/h). Data source: Measured data from Solcer House.

Table 25 – Measured monthly and annual total heat gains and heat losses through the intake duct (kWh) and resulting energy contribution of the ductwork in the thermal energy system (kWh).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
$\sum Q_{D\ Gains}$ (kWh)	66.2	63.7	49.6	39.9	42.8	32.9	31.4	25.3	24.0	49.6	59.9	56.6	541.7
$\sum Q_{D\ Loss}$ (kWh)	-7.2	-4.9	-5.8	-9.7	-3.8	-4.2	-4.5	-4.7	-6.3	-12.2	-13.2	-4.6	-81.2
$\sum Q_D$ (kWh)	**58.9**	**58.9**	**43.8**	**30.1**	**39.0**	**28.7**	**26.9**	**20.5**	**17.6**	**37.4**	**46.7**	**52.0**	**460.5**

Generally, to reduce heat losses, manufacturers and installers recommend reducing the length of the intake duct of a compact unit following Passivhaus standards (PHI, 2015). However, in the case of the Solcer House, the proposed integration of the TSC and the solar gains of the glazed loft space, turn the ductwork into a heat absorber capable to deliver around 460 kWh over one year (Table 25). This is a significant energy saving, over a third of the contribution of the TSC, easily achieved by designing and integrating the ductwork as part of the energy system and for just the small added cost of the extra duct length.

7.2.2.3 Mechanical ventilation heat recovery (MVHR)

There are two different methods to calculate the heat recovery rate (η_{HR}) of MVHR units. For the purpose of this thesis, the two methods are used and compared.

First method is the accurate methodology used for the Passivhaus certification, which calculates the heat recovery rate based on the temperatures of the exhaust (T_{EXH}) and intake air from the TSC (T_{TSC}) in relation to the extract air (T_{EXT}). For this method, equation shown in Figure 164 is used to calculate the efficiency (η_{HR1}) of the MVHR of the Solcer House.

$$\eta_{HR1} = [T_{EXT} - T_{EXH} + (P_{MVHR} / m \cdot c_P)] / (T_{EXT} - T_{TSC})$$

Where:

T_{EXT} = Temperature extract air measured with TS7 (ºC)
T_{EXH} = Temperature exhaust air measured with TS8 (ºC)
T_{TSC} = Temperature intake air from the TSC at TS3 (ºC)
P_{MVHR} = Electrical power fans and control (W)
m = Mass flow measured with FS12 (m^3/h)
c_P = Volumetric specific heat capacity of air = 0.335 $Wh/m^3 \cdot K$

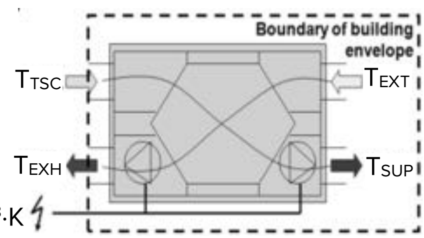


Figure 164 – Equation to calculate the heat recovery efficiency according to Passivhaus standards (PHI, 2015).

With the equation shown above and using measured hourly data at the Solcer House, the heat recovery rate is calculated hourly for every month over one year, as shown in Table 26. Following this method, the annual average heat recovery rate of the MVHR system is about 84%, a significantly higher value than the 76% claimed by the manufacturer in the 'Passive House suitable component' certificate approved by the PHI (2015).

Table 26 – Measured average monthly heat recovery rate (η_{HR}) calculated using the Passivhaus method.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
ΣP_{MVHR} (kWh)	39.5	35.6	38.9	25.3	21.4	23.4	25.1	34.4	36.4	39.6	38.2	39.4	397.1
Av. [T_{EXT}-T_{EXH}] (°C)	8.9	9.4	6.1	4.2	4.4	2.8	2.8	3.2	3.3	5.9	8.3	9.1	5.7
Av.[T_{EXT}-T_{TSC}] (°C)	10.9	11.4	6.8	5.0	5.2	3.4	3.4	4.0	4.3	7.1	10.1	10.6	6.9
$\eta_{HR\,1}$ (PHI, 2015)	**82.5%**	**82.3%**	**86.4%**	**86.0%**	**86.0%**	**80.7%**	**84.2%**	**85.2%**	**81.0%**	**83.7%**	**84.2%**	**86.6%**	**84.1%**

Figure 165 and Figure 166 represent the MVHR efficiency equation following the Passivhaus method and plot the hourly relation between the air temperature difference between extract and exhaust and between extract and intake, for winter and summer respectively. The trend lines' slopes clearly reflect the efficiency from Table 26 and indicate that the performance of the MVHR system is similarly efficient throughout the year, with minimal seasonal differences.

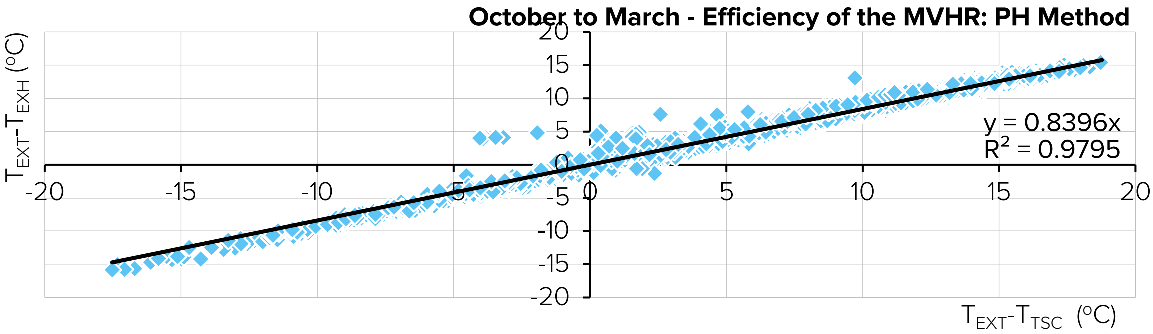


Figure 165 – Graph showing the correlation between measured hourly temperature difference between extract and exhaust air (°C) and measured hourly temperature difference between extract and intake air from TSC (°C) during the winter season. Data source: Measured data from Solcer House.

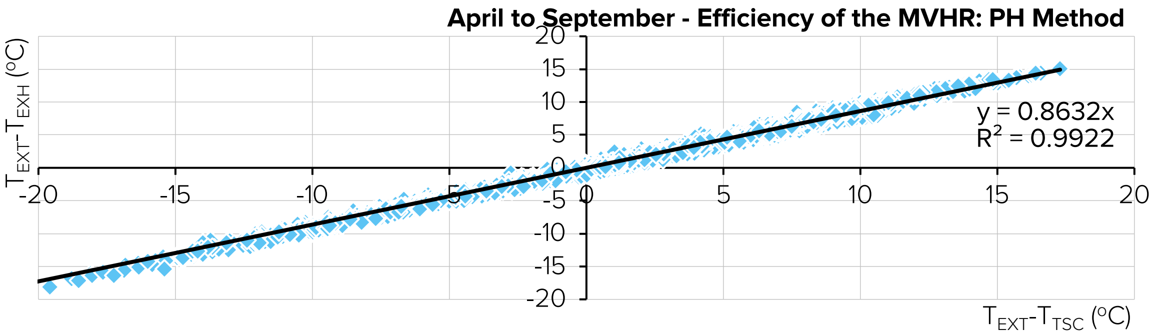


Figure 166 – Graph showing the correlation between measured hourly temperature difference between extract and exhaust air (°C) and measured hourly temperature difference between extract and intake air from TSC (°C) during the summer season. Data source: Measured data from Solcer House.

The second method is commonly used by manufacturers and engineers and is also the basis for the values that are taken into the SAP calculations (BRE, 2016). Heat recovery rate (η_{HR}) is based on the hourly temperature rise of the intake fresh air from the TSC (T_{TSC}) as it travels through the heat exchanger and is supplied to the rooms (T_{SUP}), in relation with the hourly temperature difference between the air extracted from the house (T_{EXT}) and the intake fresh air from the TSC (T_{TSC}). For this method, equation shown in Figure 167 is used to calculate the efficiency (η_{HR2}) of the MVHR of the Solcer House.

$$\eta_{HR2} = (T_{SUP} - T_{TSC}) / (T_{EXT} - T_{TSC})$$

Where:

T_{EXT} = Temperature extract air measured with TS7 (ºC)
T_{SUP} = Temperature supply air measured with TS4 (ºC)
T_{TSC} = Temperature intake air from the TSC at TS3 (ºC)

Figure 167 – Equation to calculate the heat recovery efficiency according to SAP Apendix Q (BRE, 2016).

With the equation shown above and using measured hourly data at the Solcer House, the heat recovery rate is calculated hourly for every month over one year, as shown in Table 27. Following this method, the annual average heat recovery rate of the MVHR system is about 75%, very close to the 76% claimed by the manufacturer in the 'Passive House suitable component' certificate approved by the PHI (2015).

Table 27 – Measured average monthly heat recovery rate (η_{HR}) calculated using the BRE method.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Av. [T_{SUP}-T_{TSC}] (ºC)	8.2	8.6	5.5	4.0	4.0	2.8	2.9	3.0	3.4	5.3	7.5	7.8	5.7
Av.[T_{EXT}-T_{TSC}] (ºC)	10.9	11.4	6.8	5.0	5.2	3.4	3.4	4.0	4.3	7.1	10.1	10.6	6.9
$\eta_{HR\,2}$ (BRE, 2016)	**74.7%**	**75.6%**	**72.4%**	**71.1%**	**76.2%**	**81.2%**	**82.1%**	**73.4%**	**79.9%**	**73.3%**	**73.0%**	**72.7%**	**75.5%**

Figure 168 and Figure 169 represent the MVHR efficiency equation following the SAP method and plot the hourly relation between the air temperature difference between extract and exhaust and between extract and intake, for winter and summer respectively. The trend lines' slopes closely reflect the efficiency from Table 27 and indicate that the performance of the MVHR system is similarly efficient throughout the year, with minimal seasonal differences.

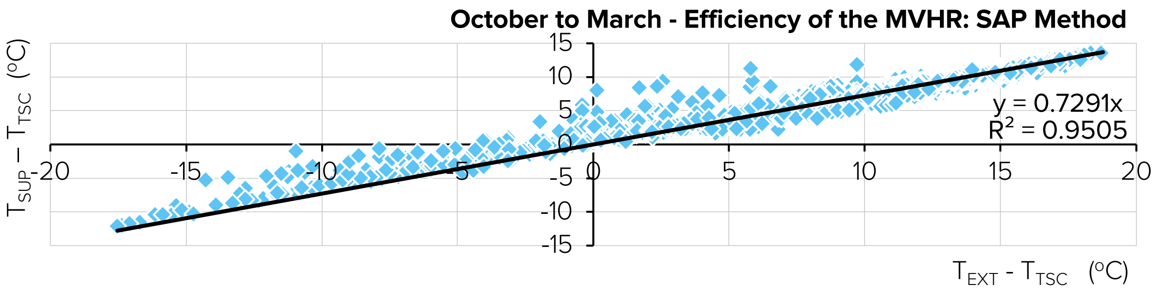


Figure 168 – Graph showing the correlation between measured hourly temperature difference between supply and outside air (ºC) and measured hourly temperature difference between extract and intake air (ºC) during the winter season. Data source: Measured data from Solcer House.

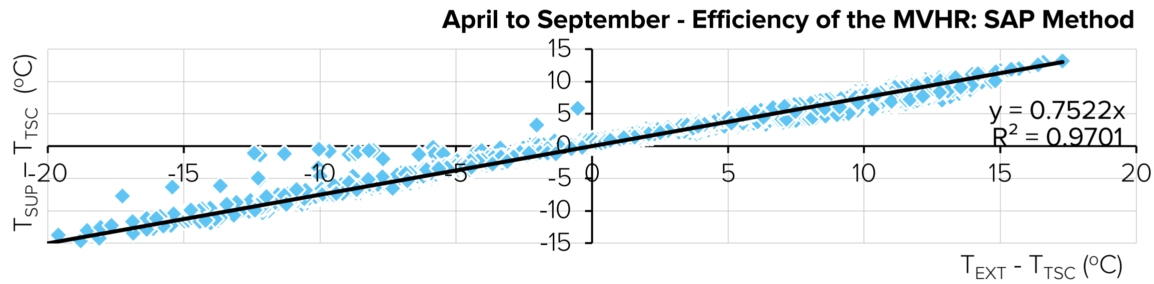


Figure 169 – Graph showing the correlation between measured hourly temperature difference between supply and outside air (ºC) and measured hourly temperature difference between extract and intake air (ºC) during the summer season. Data source: Measured data from Solcer House.

Usually, manufacturers' method results in more optimistic efficiency rates because is highly influenced by the air temperature of the test room. For this reason, the Passivhaus uses its own method, which tends to show a lower and more realistic result, especially for units with very little insulation that will result in a lower heat recovery rate (PHI, 2015). However, this is not the case when comparing the results from the two methods applied to the Solcer House monitored data. The reasons behind this finding are investigated.

It is found that the location of the temperature sensors has a big impact on the calculation. Exhaust (T_{EXH}) and supply (T_{SUP}) air temperature after the MVHR are respectively measured with sensors TS8 and TS4 that are located within the compact unit, while extract (T_{EXT}) and intake (T_{TSC}) air temperature before the MVHR are respectively measured with sensors TS7 and TS3 placed on the ducting located outside the compact unit (see Figure 151). However, sensors that are placed inside the compact unit are influenced by the waste heat produced by the fans, heat losses from the heat pump unit and heat losses from induced infiltration (PHI, 2015). For this reason, Passivhaus tests for heat recovery efficiency are always measured with the compressor and pumps switched off (PHI, 2015).

Following the same criteria from the Passivhaus test, the efficiency of the MVHR is calculated again for the Solcer House, but only when heat pump is off. In this way, monitored data used for the calculations is from the temperature sensors that are outside of the compact unit, because TS9 data can replace TS8, while TS5 can replace TS4 (see Figure 151). Results of these calculation are presented in Table 28 using both the SAP and the Passivhaus methods. Accordingly, it is clear that without the influence of the heat losses from the heat pump the heat recovery rate of the MVHR has very different results. Efficiency with the Passivhaus method goes down to 67% and with the SAP method goes up to 86%.

Table 28 – Measured average monthly heat recovery efficiency (%) calculated using the BRE method.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Time HP off	0%	0%	0.7%	1.4%	35.2%	47.4%	55.8%	48.6%	25.8%	16.0%	5.1%	0%	19.7%
$\eta_{HR\,1}$ (PHI, 2015)	-	-	**64.2%**	**66.2%**	**63.7%**	**63.4%**	**63.7%**	**70.4%**	**66.1%**	**71.8%**	**71.8%**	-	**66.8%**
$\eta_{HR\,2}$ (BRE, 2016)	-	-	**90.5%**	**77.6%**	**88.0%**	**89.4%**	**90.3%**	**84.1%**	**88.6%**	**83.4%**	**84.1%**	-	**86.2%**

Therefore, it can be concluded that many factors – i.e. location of monitoring sensors, residual heat losses, location of the unit, etc. – can influence the heat recovery rate of heat exchangers that are part of a compact unit. It is difficult to compare monitored efficiency against manufacturer's efficiency because the second is calculated under specific conditions in the laboratory. For the case of the Solcer House four different results have been found. But out of the four, the 67% heat recovery rate of the MVHR calculated with the Passivhaus method when the heat pump is off is the least influenced by external factors.

Table 29 – Measured monthly and annual total heat gains and heat losses through the MVHR (kWh) and resulting energy contribution of the MVHR in the thermal energy system (kWh).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
$\sum Q_{MVHR\ Gains}$ (kWh)	544.0	506.1	288.5	126.8	131.8	97.9	101.0	110.1	113.0	327.6	458.4	416.0	3221.0
$\sum Q_{MVHR\ Loss}$ (kWh)	-10.0	-7.3	-5.1	-15.4	-16.5	-22.7	-22.3	-18.2	-19.9	-25.8	-18.1	-5.2	-186.6
$\sum Q_{MVHR}$ (kWh)	**534**	**498.8**	**283.4**	**111.4**	**115.3**	**75.2**	**78.7**	**91.9**	**93.1**	**301.8**	**440.3**	**410.8**	**3034.3**

To evaluate the heat exchanged across the MVHR, the hourly temperature difference between the TSC intake (T_{TSC}) and the outlet (T_{SUP}) of the MVHR unit is calculated and then applied to the energy equation shown earlier in Figure 154. Results in Table 29 show that the contribution of the MVHR as part of the thermal energy system is positive throughout the year with total heat gains of around 3,034 kWh. Regarding seasonal performance, in winter heat gains are high and heat losses are low, while in summer heat gains are much lower and heat losses are slightly higher (see Figure 170). This happens because the difference between external and internal temperatures is bigger in winter than in summer. A summary of the MVHR efficiency and energy contribution is shown in Figure 170 and Figure 171.

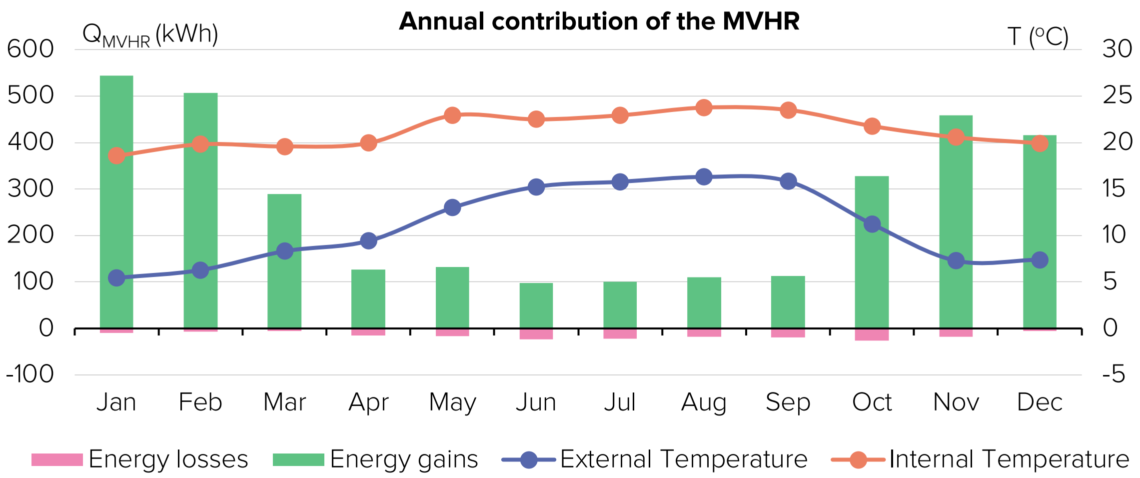


Figure 170 – Graph showing monthly energy gains and losses through the MVHR (kWh) and monthly average internal and external temperatures (ºC). Data source: Measured data from Solcer House.

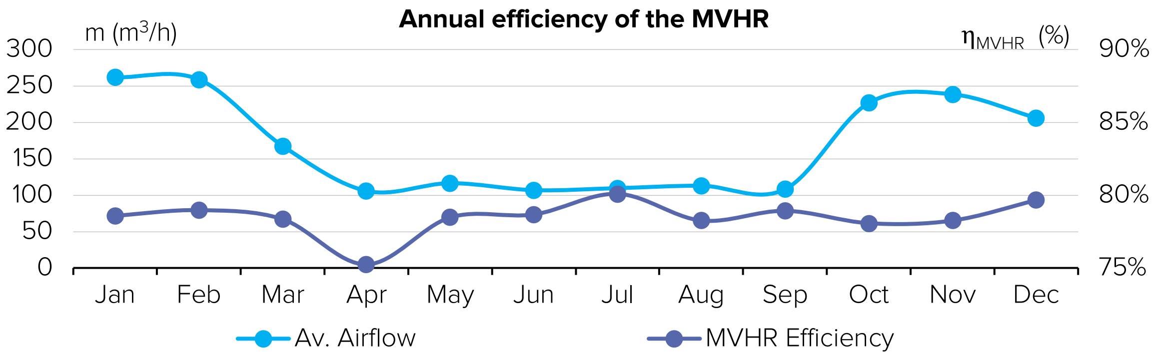


Figure 171 – Graph showing monthly average airflow delivered through the thermal energy system (m³/h) and monthly efficiency of the MVHR (%), as the average from the efficiency rates in Table 26, Table 27 and Table 28. Data source: Measured data from Solcer House.

The main findings regarding the MVHR performance are as follows:

- Annual efficiency of the MVHR: The average efficiency from the various efficiency rates calculated with different methods (see Table 26, Table 27 and Table 28), is relatively constant over the year and is about 78%. Monitored results are slightly higher than the manufacturer's claims of 76%, which is measured at a constant airflow rate of 200m³/h.
- Airflow rate of the system: Higher airflow rates of the system result on less time to exchange heat through the MVHR, hence lower efficiency values.
- Influence from TSC: When comparing the MVHR performance at night – i.e. no solar gains from TSC – and at daytime – i.e. solar gains from TSC –, Figure 172 shows that the efficiency of the MVHR is similar, but slightly better at night time, especially during the shoulder months. This happens when, during very sunny hours, the incoming air from the TSC (T_{TSC}) reaches very high temperature that is above the temperature of internal air extracted from the house (T_{EXT}). Then, heat exchange through the MVHR generates a heat loss and preheated air from TSC gets colder through the MVHR (see Figure 173).

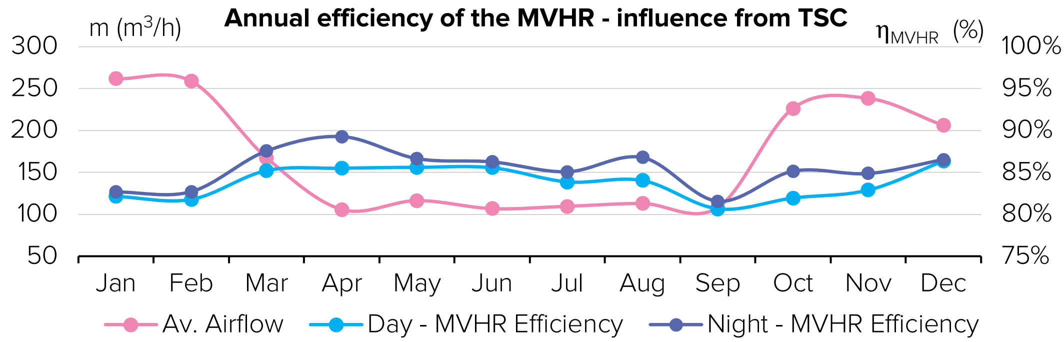


Figure 172 – Graph showing monthly average airflow delivered through the thermal energy system (m³/h) and monthly average efficiency of the MVHR (%) at night and daytime. Data source: Measured data from Solcer House.

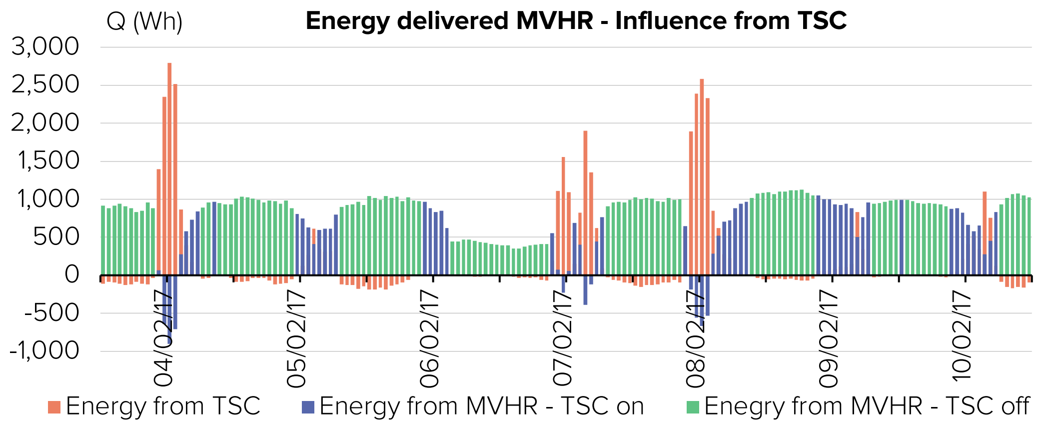


Figure 173 – Graph showing hourly energy delivered from the MVHR and the TSC during a week in February 2017. Data source: Measured data from Solcer House.

7.2.2.4 Heat pump

When it comes to evaluating heat pumps, two different parameters are considered: The Coefficient of Performance (COP) and the Seasonal Coefficient of Performance (SCOP). Understanding what these terms mean is absolutely essential since they reveal the efficiency of a heat pump.

The COP is a simple ratio of the heating provided by a heat pump to the electricity consumed. For example, where an electric heater converts 1kW of electricity into 1kW of heat or a heat pump converts that 1kW of electricity into 3 or 4 kW of heat. The COP equation for a heat pump is shown in Figure 174.

$$COP_{HP} = Q_{HP} / E_{HP}$$

Where:

Q_{HP} = Thermal energy or heat delivered by the heat pump for space heating (kWh)
E_{HP} = Electric energy input to run the heat pump and the fans only for space heating (kWh)

Figure 174 – Equation to calculate the COP of a heat pump.

Table 30 – Measured monthly and annual total heat gains from the heat pump (kWh). Data: Solcer House.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Time ON heating	92.7%	94.1%	68.8%	12.6%	22.3%	1.9%	11.0%	17.9%	15.4%	50.1%	84.3%	93.5%	48%
$\sum Q_{HP}$ (kWh)	1075.9	1011.8	788.3	202.9	253.2	36.6	136.7	148.9	128.0	611.0	950.7	965.6	6,310
$\sum E_{HP}$ (kWh)	199.3	189.0	186.8	62.0	61.0	30.2	68.0	117.6	110.4	233.8	254.3	198.3	1,711
COP_H	**5.26**	**5.41**	**4.60**	**4.58**	**5.50**	**2.40**	**2.68**	**1.54**	**1.61**	**2.70**	**4.22**	**4.88**	**3.78**

With the equation shown above and using measured hourly data at the Solcer House, the average COP is calculated for each month for the whole year. Table 30 shows the results of these calculations, which indicate that the annual average COP of the heat pump is about 3.78, a slightly higher value than the 3.21 claimed by the manufacturer (Genvex, 2010). However, it is problematic to compare monitored COP against manufacturer's COP because the second is calculated under specific instantaneous conditions in the laboratory. On the other hand, there is a significant seasonal variation of the COP, which indicates that using the average annual COP as the sole measure of heat pump efficiency is not ideal. However, the calculation of an annual average efficiency of the heat pump over a year is useful to be able to compare different heat pump units.

Alternatively, the SCOP evaluates how well the heat pump works at both low and high temperatures and is a far better reflector of how efficient the heat pump will be throughout the year. The SCOP describes the performance of the unit over a typical season where the source temperature varies considerably. To obtain the SCOP values for the Solcer House case, the average SCOP is calculated for winter (October to March) and for summer (April to September). As a result, it is found that in winter the heat pump is on over 80% of the time to provide space heating to guarantee comfortable room temperature, so the SCOP is relatively high with an average value of 4.51. In summer, the opposite happens; since the temperature of outside air is warm already, the heat pump requires less operating time and switches on and off to deliver a comfortable temperature, so the SCOP is lower with an average of 3.05.

To summarise, the main findings regarding the heat pump performance are as follows:

- Annual energy contribution of the heat pump: The heat pump delivers around 6,242kWh per year of space heating and varies significantly through the year, with more heat delivered during winter. This is calculated with the hourly temperature difference between the air from the MVHR (TS4) and the air after the condenser (TS5), which is then applied to the energy equation shown earlier in Figure 154.

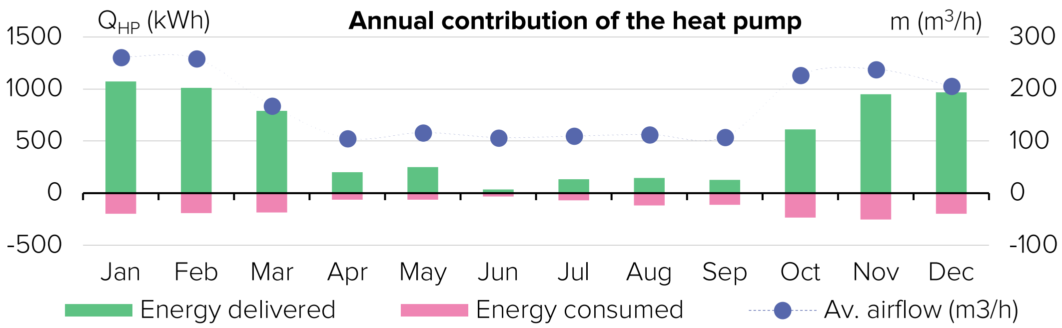


Figure 175 – Graph showing monthly energy delivered and consumed by the heat pump (kWh), and average airflow through the thermal system (m³/h). Data source: Measured data from Solcer House.

- Annual COP of the heat pump: The average annual COP of the heat pump is 3.78 but varies significantly through the yea. Monitored results are slightly higher than the manufacturer's claim of 3.23, which is measured at a constant airflow rate of 200m³/h.

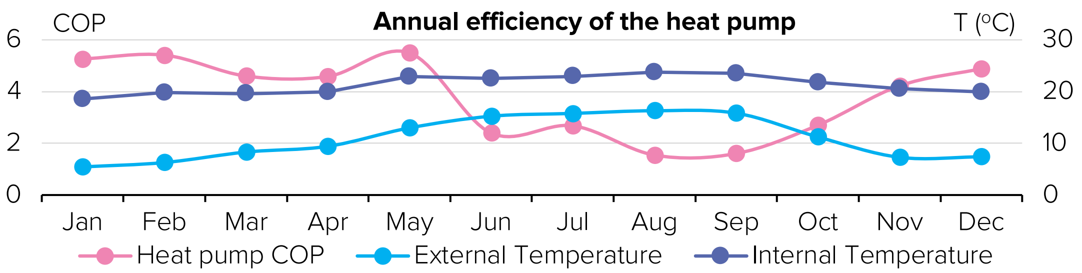


Figure 176 – Graph showing monthly calculated COP of the heat pump and monthly average internal and external temperatures (ºC). Data source: Measured data from Solcer House.

- Seasonal performance of the heat pump: Figure 176 shows how the COP varies significantly through the year, with better performance levels during winter months. This large variation of the COP of the heat pump is investigated. According to the fundamental equation for fluid heat transfer (see Figure 154) the energy delivered through the heat pump (Q_{HP}) depends on the temperature rise (ΔT_{HP}) and the mass flow (m). Therefore, these two factors are investigated:

- Temperature rise from the heat pump (ΔT_{HP}): Figure 177 and Figure 178 plot the hourly relationship between the air temperature rise and the COP, for summer and winter respectively. The graphs confirm the findings from literature that the COP of a heat pump is higher with less temperature rise between the source temperature and the output temperature (ICAX, 2018). However, the coefficient of correlation in both graphs is extremely low, hence the variables have a very weak linear relationship.

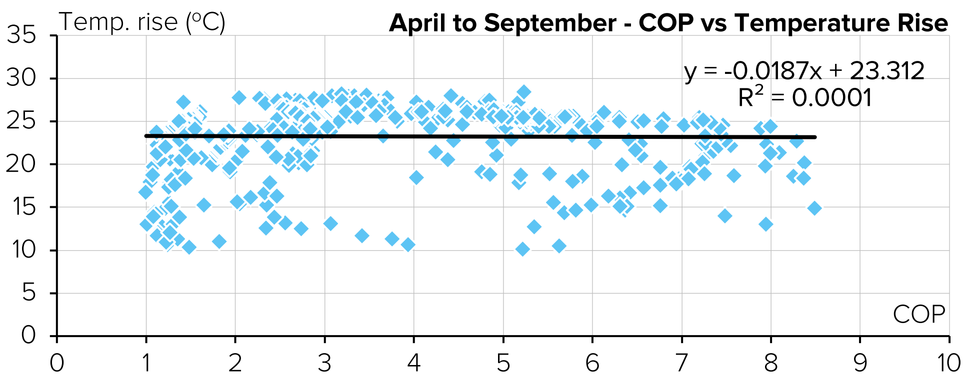


Figure 177 – Graph showing the correlation between the measured hourly temperature rise through the heat pump (ºC) and the calculated hourly COP factor during the summer season. Data source: Measured data from Solcer House.

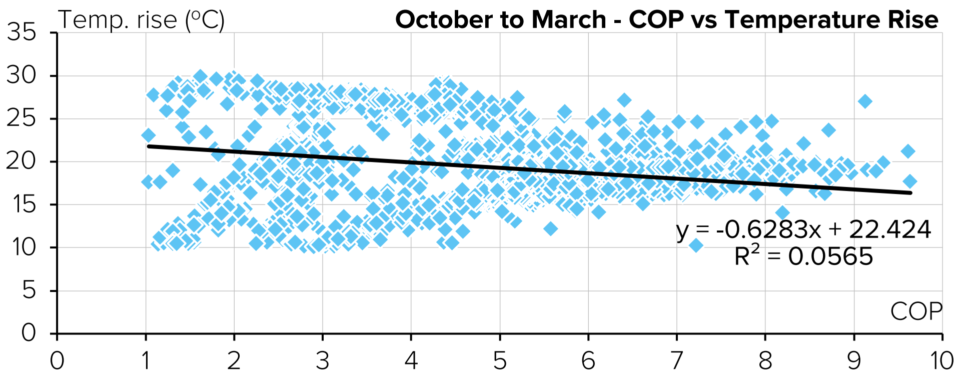


Figure 178 – Graph showing the correlation between the measured hourly temperature rise through the heat pump (ºC) and the calculated hourly COP factor during the winter season. Data source: Measured data from Solcer House.

- Mass flow rate through the heat pump (m): In winter, the heat pump needs to deliver more heat to meet comfort levels, while in summer it needs to deliver much less (see Figure 175). The airflow has a strong influence on the amount of heat delivered from the heat pump. For example, higher airflow rates in winter months result in higher heat delivered.

Figure 179 and Figure 180 plot the hourly relationship between the mass flow rate and the COP, for summer and winter respectively. The graphs indicate that the COP of a heat pump is higher when more airflow goes through the system. This could explain why winter months with higher airflow rates have a higher COP than summer months with lower airflow rates. However, the coefficient of correlation in both graphs is not high enough to confirm that these two variables have a strong linear relationship. Further investigations on these findings could be relevant and useful.

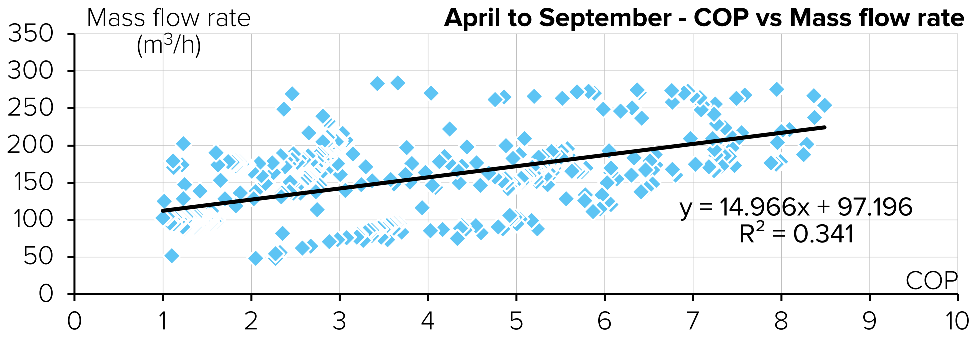


Figure 179 – Graph showing the correlation between the measured hourly mass flow rate through the heat pump (m³/h) and the calculated hourly COP factor during the summer season. Data source: Measured data from Solcer House.

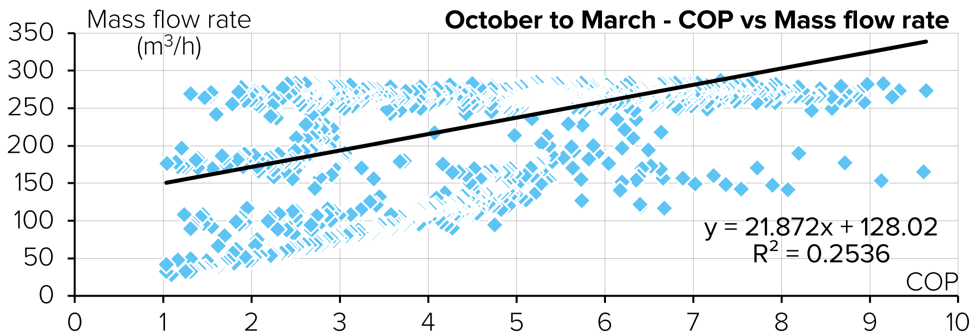


Figure 180 – Graph showing the correlation between the measured hourly mass flow rate through the heat pump (m³/h) and the calculated hourly COP factor during the winter season. Data source: Measured data from Solcer House.

7.2.2.5 Thermal store

The compact unit integrated air source heat pump prioritises the production of domestic hot water (DHW) and provides space heating when the 185 litres DHW cylinder has been fully heated. According to the manufacturers, the heat pump is able to produce about 380 litres of DHW every day at a temperature of 55°C (Genvex, 2010). To evaluate the performance of the DHW cylinder, different scenarios are tested on a weekly basis and shown from Figure 181 to Figure 185, which represent the temperature of hot water inside the DHW cylinder. The scenarios are as follows:

- Scenario 1: Heat pump and immersion heater ON & DHW setup at 55ºC.
- Scenario 2: Heat pump and immersion heater ON & DHW setup at 52ºC.
- Scenario 3: Heat pump OFF, immersion heater ON & DHW setup at 52ºC.
- Scenario 4: Heat pump OFF, immersion heater OFF & DHW setup at 52ºC.
- Scenario 5: Heat pump and immersion heater ON & DHW setup at 52ºC.

The first aspect to test is how the system performs at different temperatures when the DHW is not being used. Although the compact unit manufacturers recommend setting the DHW temperature at 52ºC, it is important to consider what happens if the set temperature is increased a few degrees. Scenario 1 (see Figure 181) shows the performance of the DHW system with the default settings from the manufacturer, while scenario 2 (Figure 182) shows what happens when the temperature is set at 55ºC. It is found that to mitigate the heat losses through the DHW tank and to maintain the DHW at the desired temperature, the heat pump is on twice a day in both scenarios, but it works harder, at about 75% of its full power, when the temperature is set at 55ºC. Regarding the performance of the immersion heater, Figure 181 and Figure 182 show that once a week the 1kW immersion heater is on at full power to heat the DHW up to 65ºC and protect the system from legionella. However, the immersion heater is on for two hours when the base temperature is at 52ºC, instead of just one hour when the temperature is set at 55ºC.

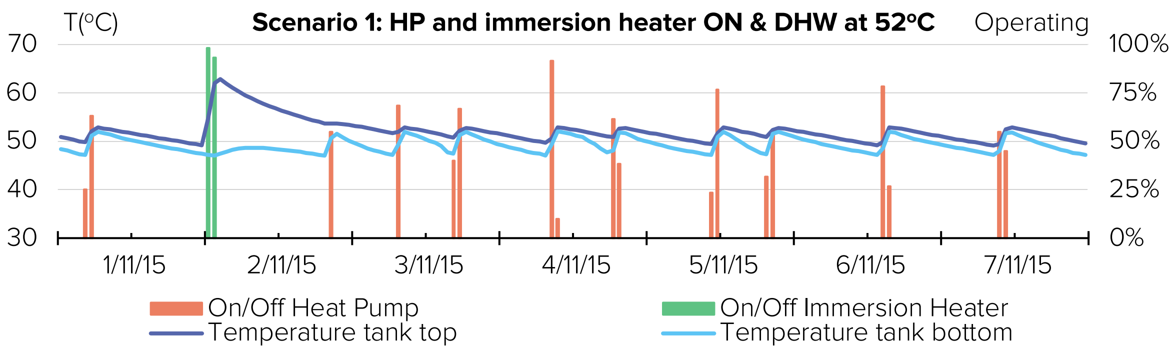


Figure 181 – Graph showing measured hourly temperature of hot water inside the DHW cylinder for one week. Scenario 1: Heat pump and immersion heater ON, DHW temperature setup at 52ºC.

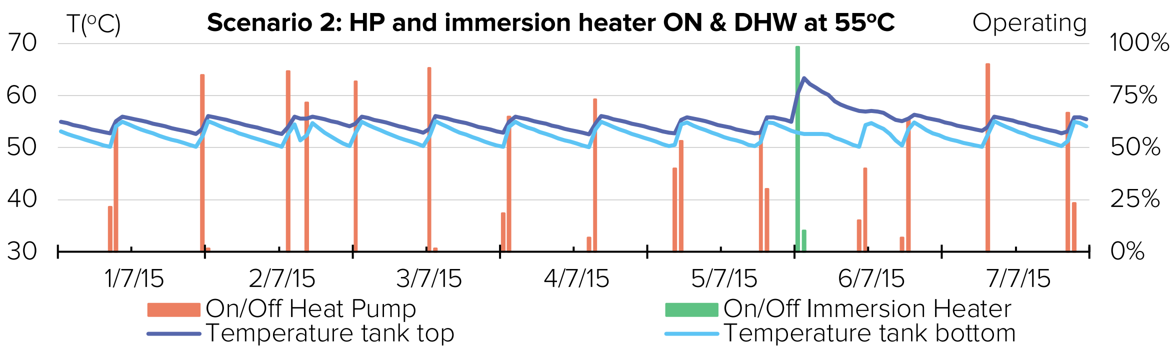


Figure 182 – Graph showing measured hourly temperature of hot water inside the DHW cylinder for one week. Scenario 2: Heat pump and immersion heater ON, DHW temperature setup at 55ºC.

The second aspect to test is how the system performs when the heat pump's priority is space heating during a cold week in winter. Scenario 3 (see Figure 183) shows that when heat pump is used to provide space heating all the time, DHW is heated with the immersion heater, which needs to be on about 5 hours per day at about 30% of its power. However, the immersion heater is only capable to maintain the DHW temperature at the top of the tank, thus the bottom water gets gradually colder, down to 35ºC, by the end of the week.

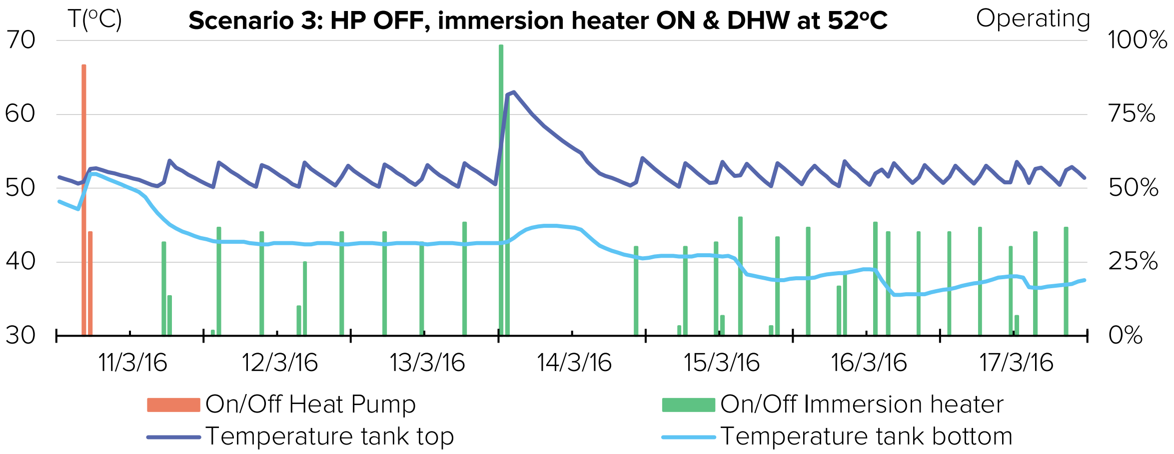


Figure 183 – Graph showing measured hourly temperature of hot water inside the DHW cylinder for one week. Scenario 3: Heat pump OFF, immersion heater ON, DHW temperature setup at 52ºC.

The third aspect to test is how the system performs when it is switched off, thus to evaluate the heat losses through the DHW tank when heat pump and electric resistive heater are not operating. It is found that DHW goes from 52ºC down to 25ºC after 4 days of system's inactivity. Another relevant finding refers to the legionella cycling, which for health and safety operates automatically even if the system is turned off. Figure 184 shows that the 1kW needs to be on at full power for 6 hours to heat the water from 28ºC to 65ºC.

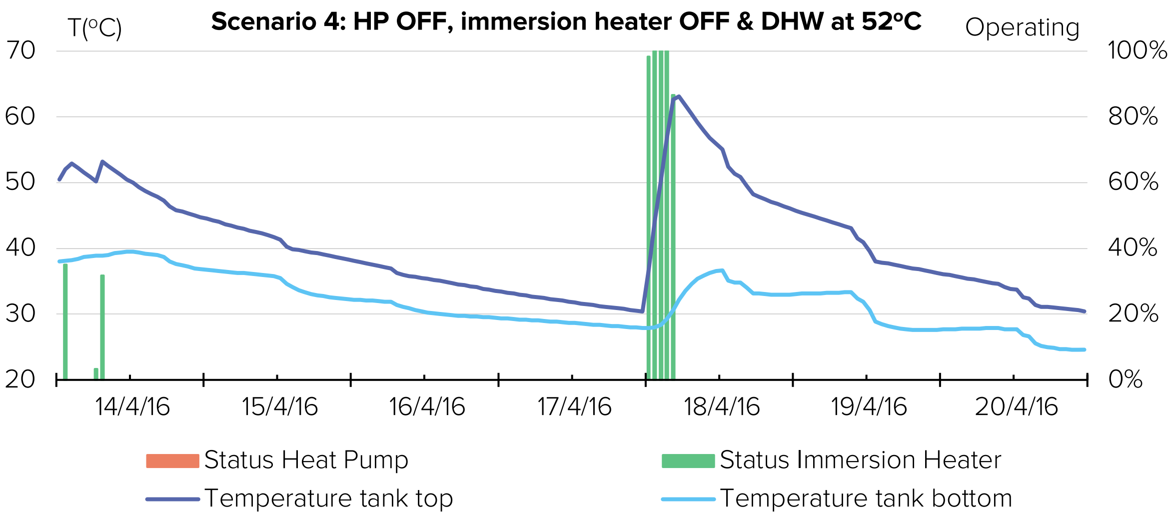


Figure 184 – Graph showing measured hourly temperature of hot water inside the DHW cylinder for one week. Scenario 4: Heat pump and immersion heater OFF, DHW temperature setup at 52ºC.

The last aspect to test is how long does it take to heat the 185 litres DHW tank from 25ºC back to 52ºC using only the heat pump. Figure 185 shows that the 325W heat pump needs to be on at full power for 6 hours to heat the water from 25ºC to 52ºC. This indicates that the immersion heater has a slightly more rapid response when DHW temperature needs to have a boost, however it consumes three times more energy than the heat pump to achieve that.

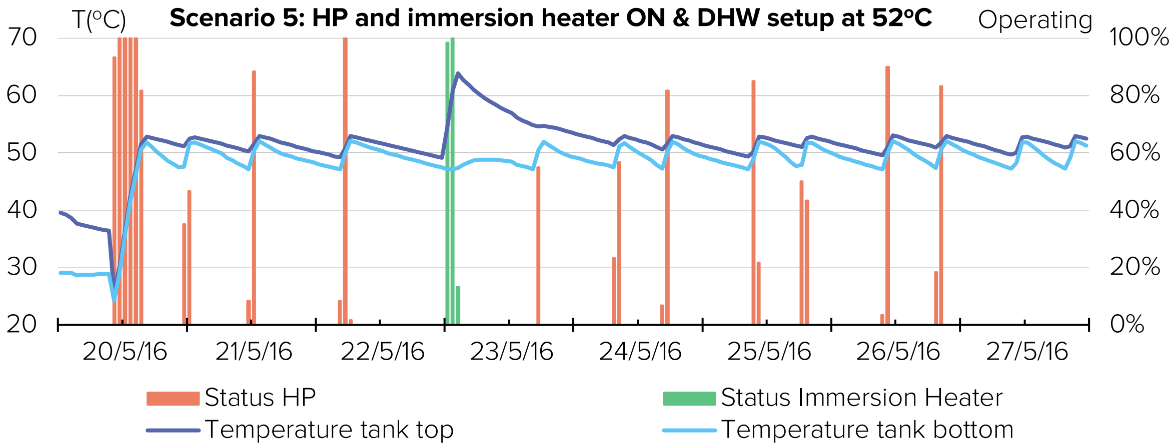


Figure 185 – Graph showing measured hourly temperature of hot water inside the DHW cylinder for one week. Case 2: Heat pump and immersion heater ON, DHW temperature setup at 52ºC.

To summarise, the DHW thermal store operates between a temperature of 52ºC and 65ºC. Usually, the heat pump raises the temperature to 52ºC when the water storage tank requires heat input. But once a week to disinfect the tank, the electrical heating element will increase the water temperature to 65°C. A potential improvement of the thermal system performance could be achieved if a better control strategy was implemented. The strategy should link the weekly legionella cycle with the times of the day that there is solar energy excess, therefore the immersion heater should heat water up to 65ºC before energy from excess generation from PV was exported.

7.2.2.6 Systems approach – Energy analysis of the annual performance

This section evaluates the holistic energy performance of all the components that are part of the whole thermal energy system. By adding the energy contribution of each technology together, it is found that total energy delivered by the system over one year is 10,945kWh. Then, this total delivered energy is divided by the energy consumption of 2,147kWh from the compact unit over the same year, to find the annual average COP value for the whole thermal system, which is a significant 5.15. Table 31 shows this calculation in a more detailed monthly basis, which proves that the system performs much better in winter.

Table 31 – Measured monthly and annual total energy delivered (Q) and consumed (E) by the whole thermal energy system and calculated monthly COP.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
$\sum Q_{SYSTEM}$ (kWh)	1755	1633	1207	489	511	212	320	337	316	1110	1580	1475	10,945
$\sum E_{SYSTEM}$ (kWh)	219	199	100	261	120	64	98	155	168	282	273	208	2,147
COP_{SYSTEM}	**8.00**	**8.19**	**12.05**	**1.87**	**4.26**	**3.33**	**3.28**	**2.18**	**1.88**	**3.94**	**5.78**	**7.08**	**5.15**

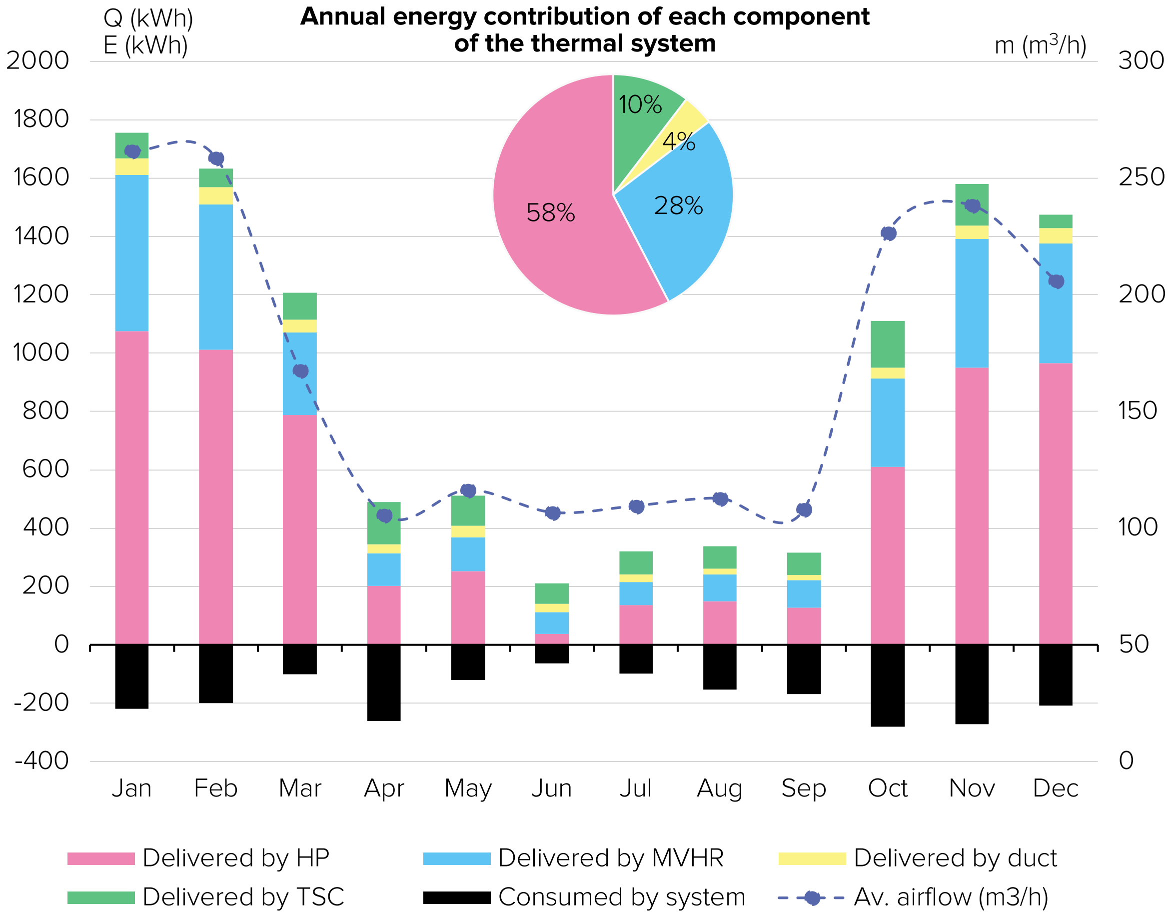


Figure 186 – a) Pie chart: percentage of the annual delivered energy contribution of each technology. b) Bar chart: monthly distribution of the delivered energy (kWh) from each technology plotted against the monthly average airflow (m³/h) through the system. Data source: Measured data from Solcer House.

The monthly energy contribution of each technology into the total delivered energy is compared against the energy consumed (negative values) by the whole compact unit system in Figure 186. It is clear that during winter, the heat pump is the component that delivers the most, around 60% of the energy; while, the combination of the TSC, ductwork and MVHR is capable to provide the rest of the heat needed with no extra energy consumption required. In summer time, when the heating demand is much lower and solar radiation is much higher, the contribution of the TSC is much more significant, being around 30%. When considering the overall contribution across the whole year, the heat pump provides 58% of the heating demand; the heat recovered through the MVHR represents 28% of the heating demand, while the solar gains from the TSC and its ductwork meet 14% of the heating demand. On the other hand, regarding the electrical energy consumed by the whole system, in winter its monthly consumption is around 200kWh while in summer it is just about 100kWh. Finally, by dividing the total electrical consumption of 2,147kWh by the 100m^2 area of the Solcer House, this results in an annual heating consumption of 21kWh/m^2.

The monthly average airflow through the heating system is also shown in Figure 186. As mentioned in previous sections, it is clear that the airflow has a big impact on the system's performance and efficiency. For this reason, a more detailed analysis of the airflow's frequency is done in Figure 187 and Figure 188, which show the histogram of hourly airflows for both summer and winter respectively. In summer time, the system operates most of the time with an airflow of around 110m^3/h; while in winter, the airflow needs to be much higher to guarantee comfortable room temperature, thus the system operates most of the time at about 270 to 290m^3/h. On the other hand, Figure 187 and Figure 188 help recognising the times that the system has been down for technical problems due to air filters not being replaced on time. For example, during March and April the system was down for 162 and 375 hours respectively, these represent 22% and 52% of these months, which explains why March and April figures are slightly out of place in some of the earlier graphs.

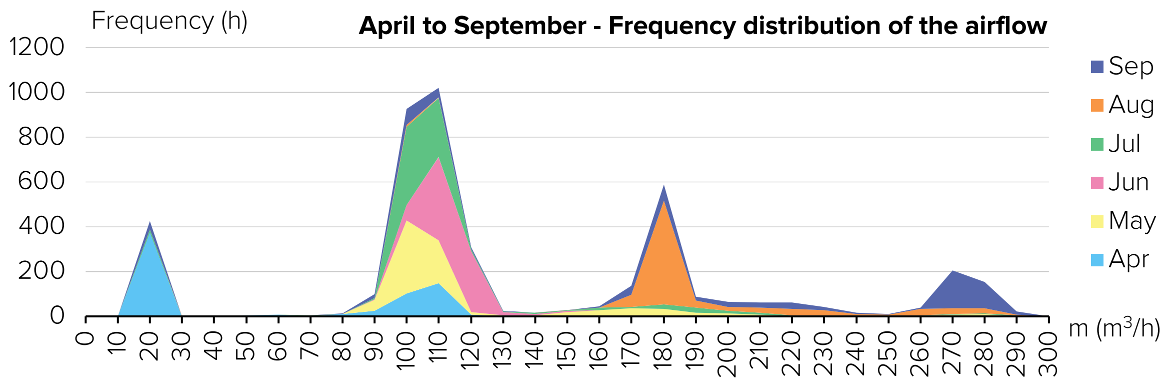


Figure 187 – Histogram showing the measured frequency hourly distribution of the airflow during summer. Data source: Measured data from Solcer House.

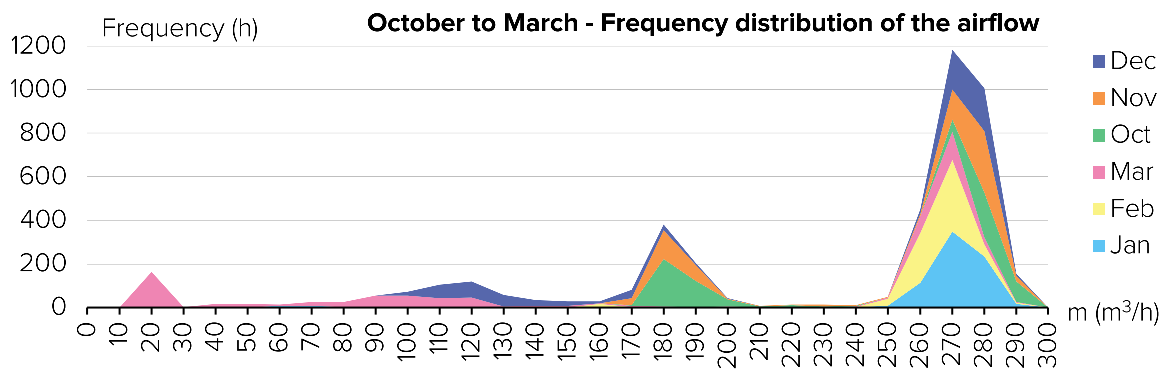


Figure 188 – Histogram showing the measured frequency hourly distribution of the airflow during winter. Data source: Measured data from Solcer House.

On the other hand, Figure 189 and Figure 190 show the histogram of hourly temperature rise for both summer and winter respectively. In summer time, to guarantee comfortable room temperatures, the system lifts the outdoor air temperature by about 6 to 10ºC; while in winter, the temperature rise needs to be much higher, between 26 to 30ºC, most of the time.

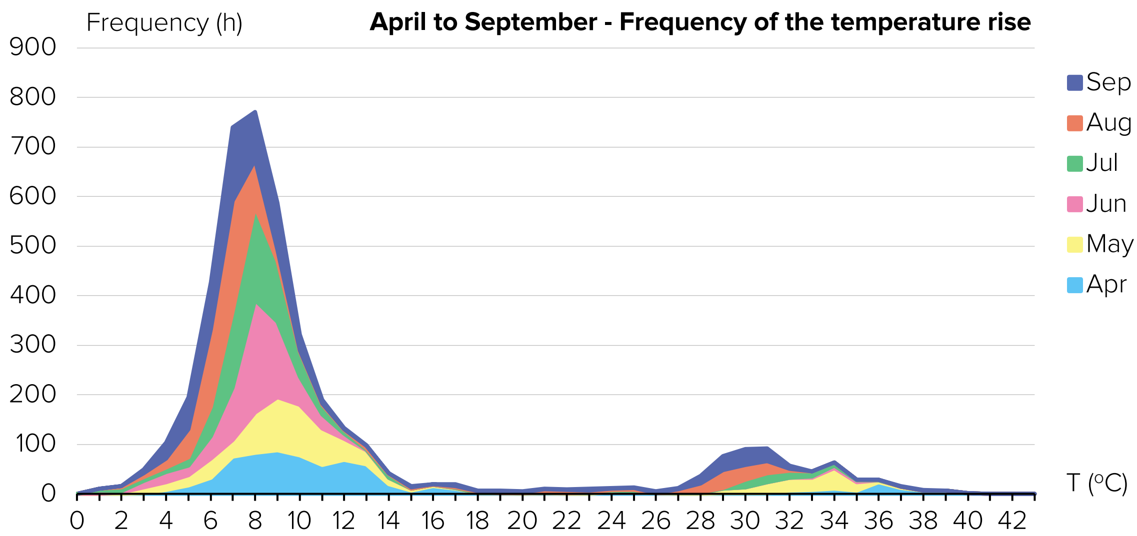


Figure 189 – Histogram showing measured frequency hourly distribution of temperature-rise during summer. Data source: Measured data from Solcer House.

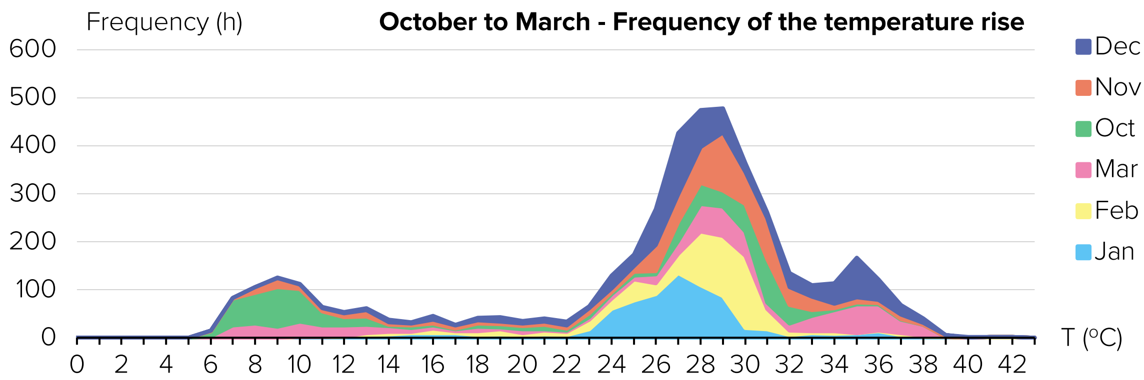


Figure 190 – Histogram showing measured frequency hourly distribution of temperature-rise during winter. Data source: Measured data from Solcer House.

Finally, when comparing the trend of the histogram of hourly distribution of the airflow against the trend of temperature-rise, it is found that the temperature is more stable than the airflow. Therefore, even though the airflow varies depending on the chosen fan speed settings of the compact unit, the temperature rise delivered by the system seems to be maintained stable.

To understand better how the thermal system performs, a full analysis of the increase in temperature from the system, with all the technologies working together, is shown in the next two sections.

7.2.2.7 Systems approach - Temperature analysis of the annual performance

Initially, the Solcer House monitored data was analysed for a period of two years, from July 2015 to July 2017. Figure 191 presents the results from the collected data during this period for the temperature rise of the outside air thanks to the TSC, MVHR, heat pump and electric resistive heater. The graph shows clearly that during the first year, the thermal system of the Solcer House had some issues and the 1kWh electric resistive heater was switched on permanently in March and April 2016. These issues are also discussed in section 7.1.1 and Annex 2, in regard to the energy demand. In May 2016, after the heating problem was spotted, the settings of the thermal system were corrected and brought bag to the recommended values from the manufacturers. Since then, data collection for supply air temperature presents a profile much more in line with the expected heating load of a highly insulated house.

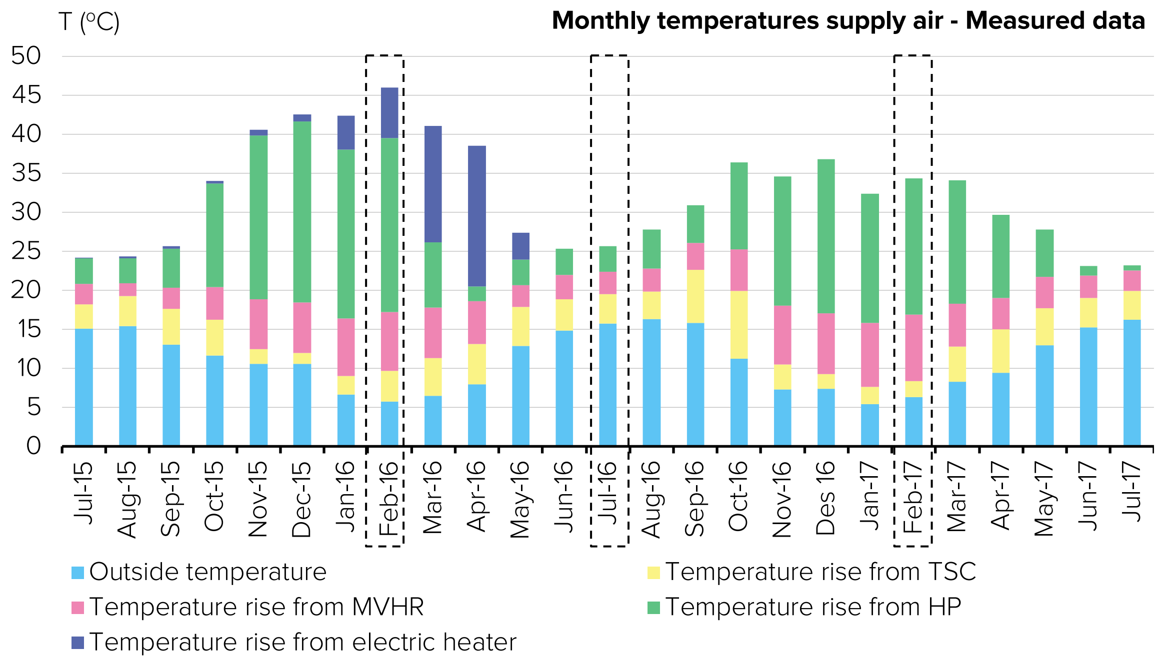


Figure 191 – Graph showing monthly average temperature rise by the supply air system at a component level from July 2015 to July 2017. Data source: Measured data from Solcer House.

Figure 191 shows the monthly average temperature performance of the thermal system considering the supply side at a component level. During the heating season, from October 2016 to March 2017, average temperature uplifts across the elements of the thermal system are 3.75°C for the TSC, 7.15°C for the MVHR, and 16.22°C for the heat pump (see Table 32). Therefore, the internal space is heated by internal power heat gains, people heat gains and through the heating/ventilation system (TSC, MVHR and heat pump). Although the heat pump temperature rise is the highest and represents 58% of the total temperature rise of 27.12°C, the benefits from the MVHR (28%) and TSC (14%) are significant. Also, it is important to highlight that the electric heater was turned off during the second year, hence the temperature rise from this is 0°C. On the other hand, during spring and summer, from April to September, the days are sunnier and less cold; hence the benefits from the TSC are much higher and represent 37% of the total 12.75°C temperature rise, the same than the heat pump. Overall, on an annual basis, the thermal system increases the temperature of the outside air by 19.94°C; of these, 53% is delivered by the heat pump, 26% by the MVHR and 21% by the TSC (see Table 32).

Table 32 – Seasonal and annual summary of system temperatures.

	Outside air (°C)	Supply air - Average temp. difference (°C)				Exhaust air - Average temp. difference (°C)	
Season	**Weather station**	**TSC + ductwork**	**MVHR**	**HP**	**Electric heater**	**MVHR**	**HP**
October to March	7.66	3.75	7.15	16.22	0	-7.95	-6.35
April to September	14.33	4.70	3.32	4.73	0	-3.39	-1.32
Annual	10.99	4.23	5.23	10.48	0	-5.67	-3.84

On the exhaust side, the temperature drop across the thermal system is obviously higher in winter than in summer, which indicates the level of heat transfer to the incoming air. On an annual basis, the temperature drop in the MVHR is 5.67°C, and across the heat pump is 3.84°C (see Table 32).

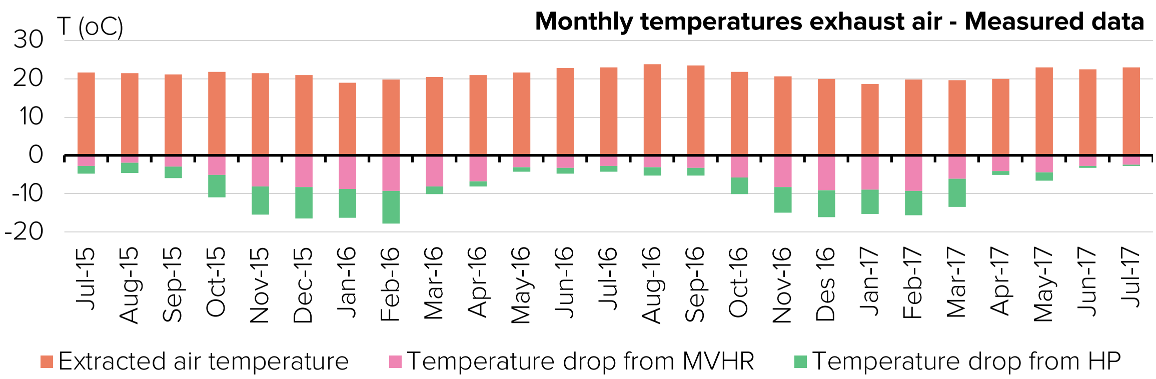


Figure 192 – Graph showing monthly average temperature drop of the exhaust air at a component level from July 2015 to July 2017. Data source: Measured data from Solcer House.

Figure 192 shows the monthly average temperature performance of the thermal system considering the exhaust side at a component level. The internal air temperature, shown in the graph as the extracted air from rooms, is generally maintained at comfort levels between 19°C and 24°C; falling during cooler non-sunny periods in winter and rising during warmer sunny periods in summer. During the heating season, from October to March, average temperature drop across the elements of the thermal system is 7.95°C for the MVHR and 6.35°C for the heat pump (see Table 32).

7.2.2.8 Systems approach – Temperature analysis of the seasonal performance

This section considers the performance of the thermal system in more detail, by analysing a typical month in winter and in summer. The months selected to represent each season are shown earlier in Figure 191: February 2016, February 2017 and July 2016. The performance of the winter season is analysed by considering two different situations – i.e. electric heater on (February 2016) and off (February 2017). Figure 193 shows measured data for February 2016, plotting the hourly temperature data for the supply air as it travels through the components of the thermal system with the electric heater on.

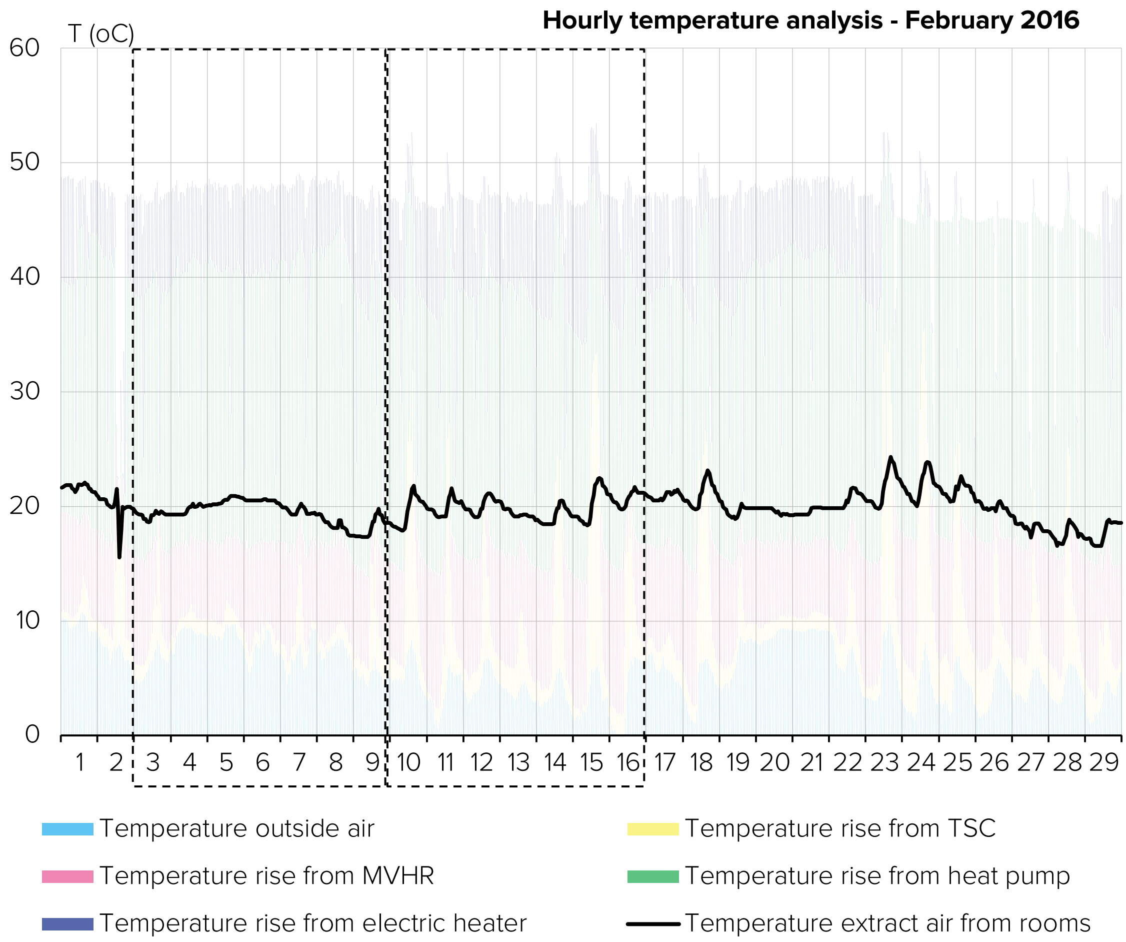


Figure 193 – Graph showing hourly temperature of the thermal system at a component level in February 2016. Data source: Measured data from Solcer House.

Two different types of weather conditions are analysed to better understand how the thermal system performs. First, a zoom to a week with mild temperature and overcast days is presented in Figure 194. Graph shows that when temperature of outside air is at about 10ºC, the TSC delivers around 1ºC rise at night time or when its cloudy thanks to its sheltering effect and can heat the air up to 20ºC when the sun is out sporadically. In the meantime, the temperature rise from the MVHR is fairly stable across time and increases the air temperature up to about 17ºC. When considering the heat pump performance, the supply air reaches temperatures around 40°C, but twice a day this temperature drops drastically for a short period of time, just when the heat pump switches its priority to DHW to keep the temperature of DHW above 52°C. Finally, the electric resistive heater installed in the ductwork raises the temperature of the supply air up to about 48°C and maintains this temperature fairly stable even when the heat pump is delivering only DHW. As a result, the air temperature inside the house is very stable at around 20°C.

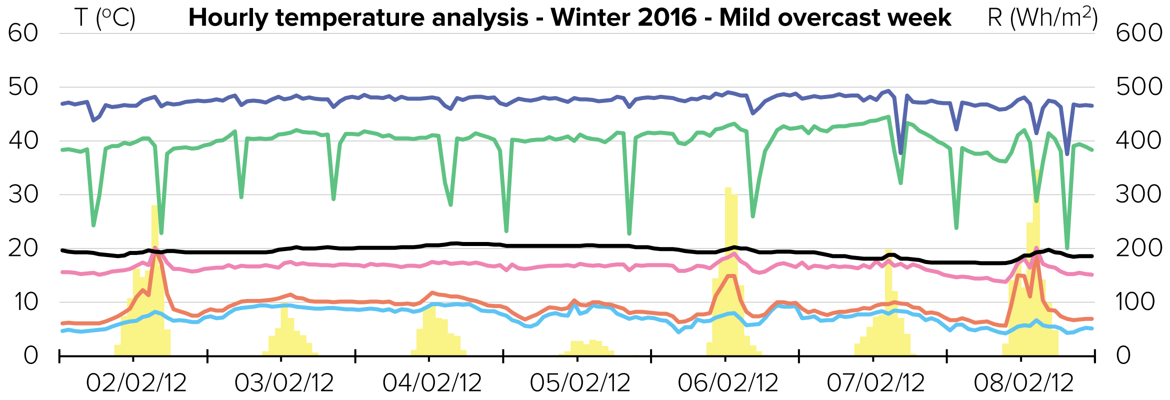


Figure 194 – Graph showing hourly temperature of the thermal system in a mild overcast week in winter 2016. Data source: Measured data from Solcer House.

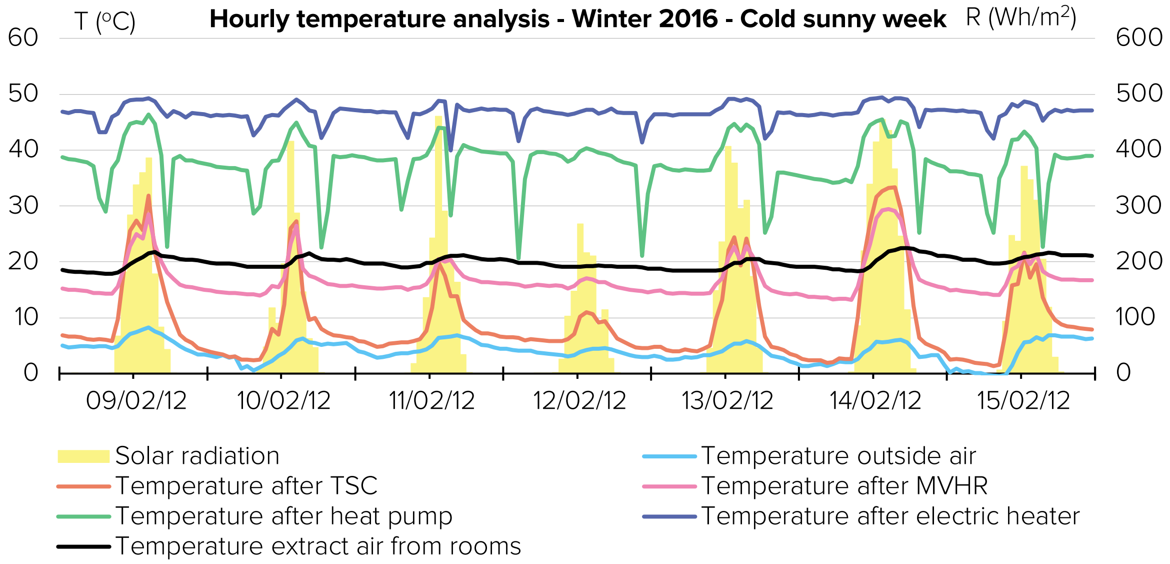


Figure 195 – Graph showing hourly temperature of the thermal system in a cold sunny week in winter 2016. Data source: Measured data from Solcer House.

Second, a zoom to a week with colder temperatures and sunny days is presented in Figure 195. Graph shows that during the day when temperature of outside air is at about 5°C and the sun is out, the TSC can heat the air up to 30°C. However, when this occurs, the MVHR seems to have a neutral or even negative effect reducing the temperature of the supply air. This happens when the temperature of the fresh supply air from the TSC is higher than the temperature of the inside air extracted from rooms, hence the heat transfer occurs on the opposite desired direction. Otherwise, when the sun goes down the MVHR increases the air temperature up to about 15ºC. When considering the heat pump performance, the supply air reaches temperatures around 40ºC when the sun is down and up to 45ºC when the sun is out, which indicates that the heat pump does not stop during sunny periods. Again, supply air temperature drops drastically twice a day for a short period of time, for DHW maintenance. Finally, the electric resistive heater raises the temperature of the supply air up to about 46ºC when the sun is down and up to 50ºC when the sun is out, which indicates that the electric heater does not stop during sunny periods. As a result, the air temperature inside the house is fairly stable at around 20ºC with a slightly increase of up to 22ºC when the solar radiation is at its peak by midday.

In May 2016, the electric resistive heater was permanently switched off to reduce the energy demand from space heating and the overheating problems during the heating season, as explained in in section 7.1.1 and Annex 2. The performance of the thermal system with the electric heater off during the winter season is analysed in Figure 196. Graph shows measured data for February 2017, plotting the hourly temperature data for the supply air as it travels through the components of the thermal system.

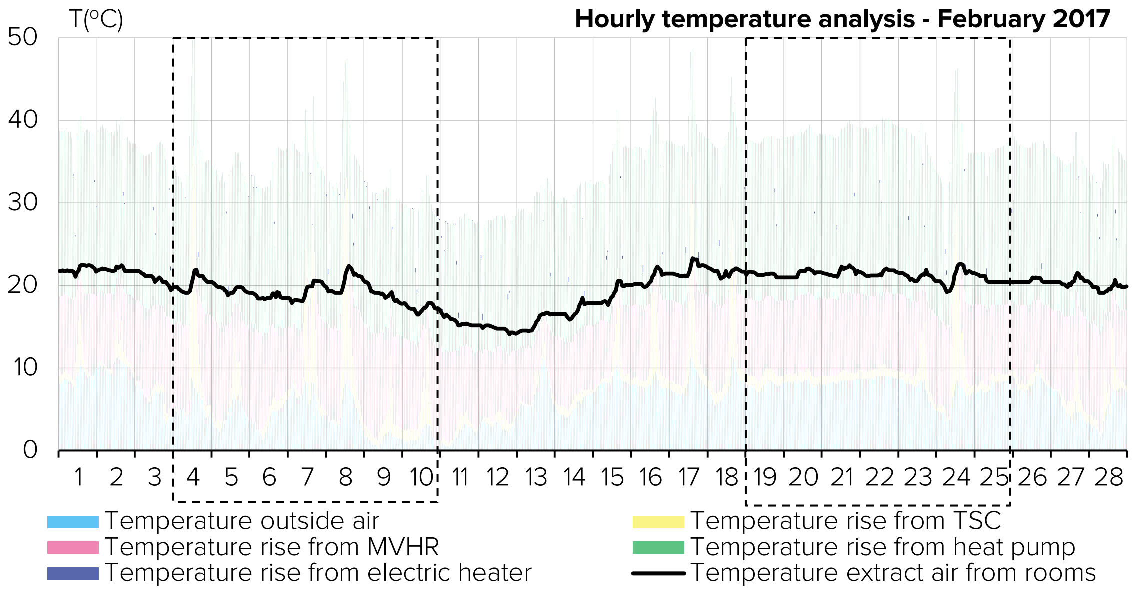


Figure 196 – Graph showing hourly temperature of the thermal system at a component level in February 2017. Data source: Measured data from Solcer House.

Again, two different types of weather conditions are analysed. First, a zoom to a week with mild temperature and overcast days is presented in Figure 197. Graph shows that when the electric resistive heater is switched off, the performance of the thermal system is still satisfactory and capable to deliver the supply air at around 40ºC. The temperature drop in the supply air caused by the use of the heat pump for DHW, has a minimum effect on the air temperature inside the house, which is still very stable at around 20ºC.

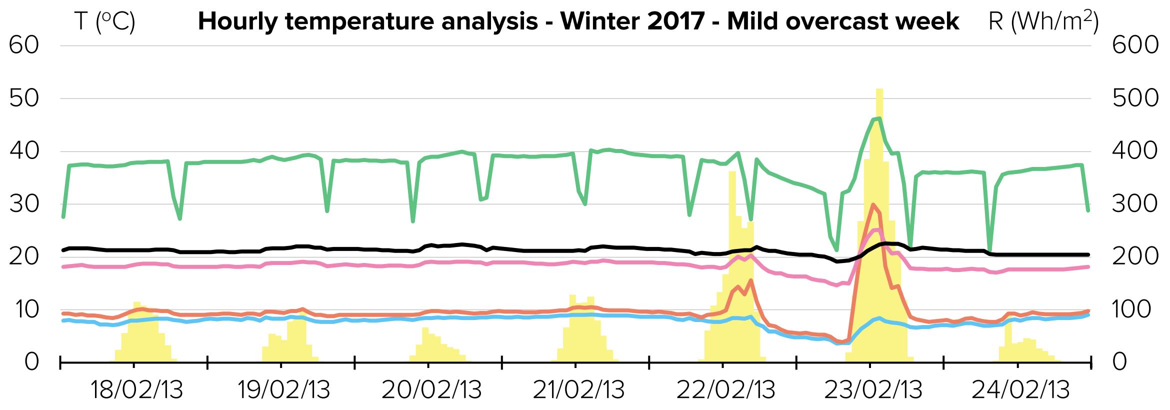


Figure 197 – Graph showing hourly temperature of the thermal system in a mild overcast week in winter 2017. Data source: Measured data from Solcer House.

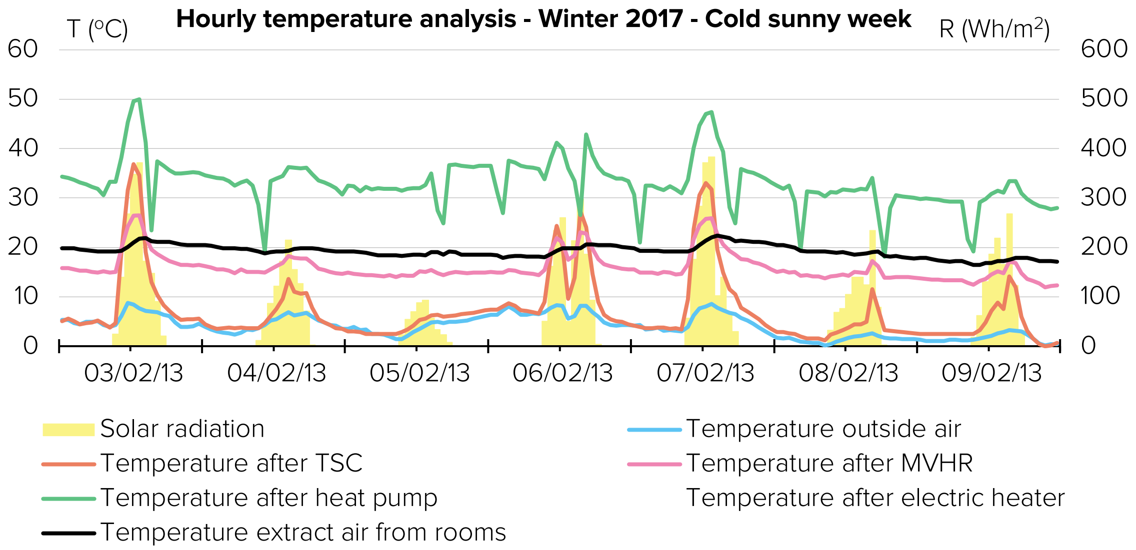


Figure 198 – Graph showing hourly temperature of the thermal system in a cold sunny week in winter 2017. Data source: Measured data from Solcer House.

Second, a zoom to a week with cold temperatures and sunny days is presented in Figure 198. Graph shows that when the electric resistive heater is switched off, the performance of the thermal system is still reasonable during very cold days and is capable to deliver the supply air at around 35°C. However, after a long period with outside temperature below 5°C, the thermal system is not capable to maintain the house temperature at the typical 20°C and the house starts to cool down to 17°C, especially during night time.

The fact that the electric resistive heater is on or off does not affect the performance of the thermal system during summer, hence only one representative month has been analysed. Figure 199 shows measured data for July 2016, plotting the hourly temperature data for the supply air as it travels through the components of the thermal system.

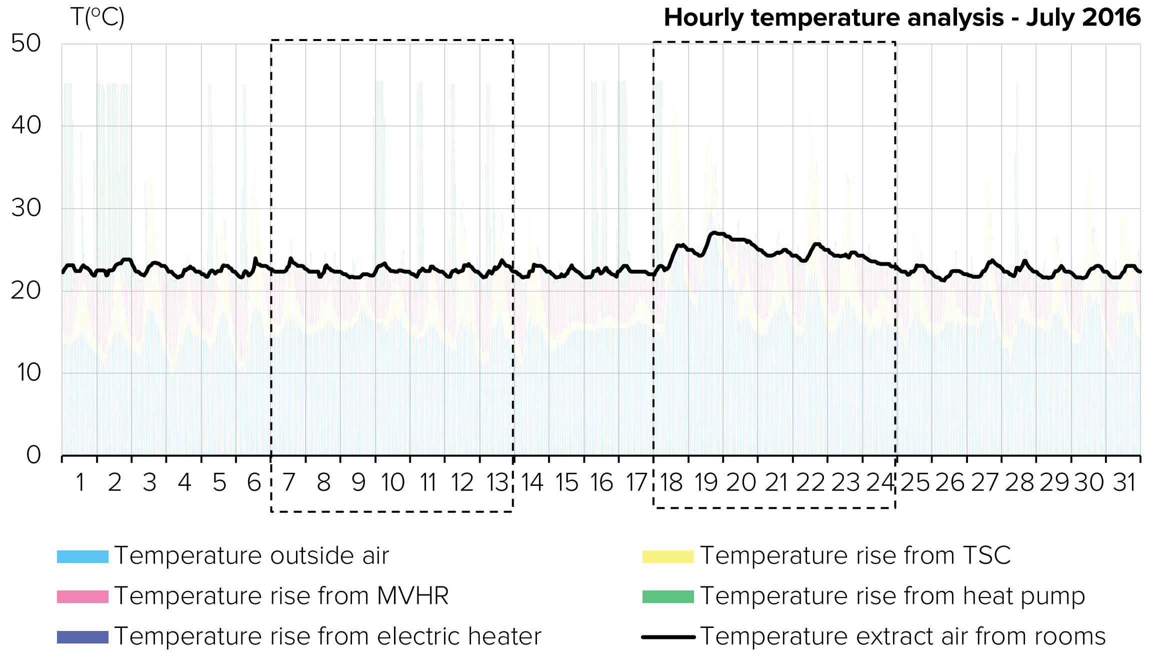


Figure 199 – Graph showing hourly temperature of the thermal system at a component level in July 2016. Data source: Measured data from Solcer House.

Again, two different types of weather conditions are analysed. First, a zoom to a week with milder temperature and overcast days is presented in Figure 200. Graph shows that after a long period of colder overcast days during summer, when the outside temperature is at about 16ºC, the heat pump switches on during a few hours at night to maintain internal temperatures more stable. However, when considering the air temperature inside the house, this is around 22ºC, which indicates that the heat pump use could be avoided.

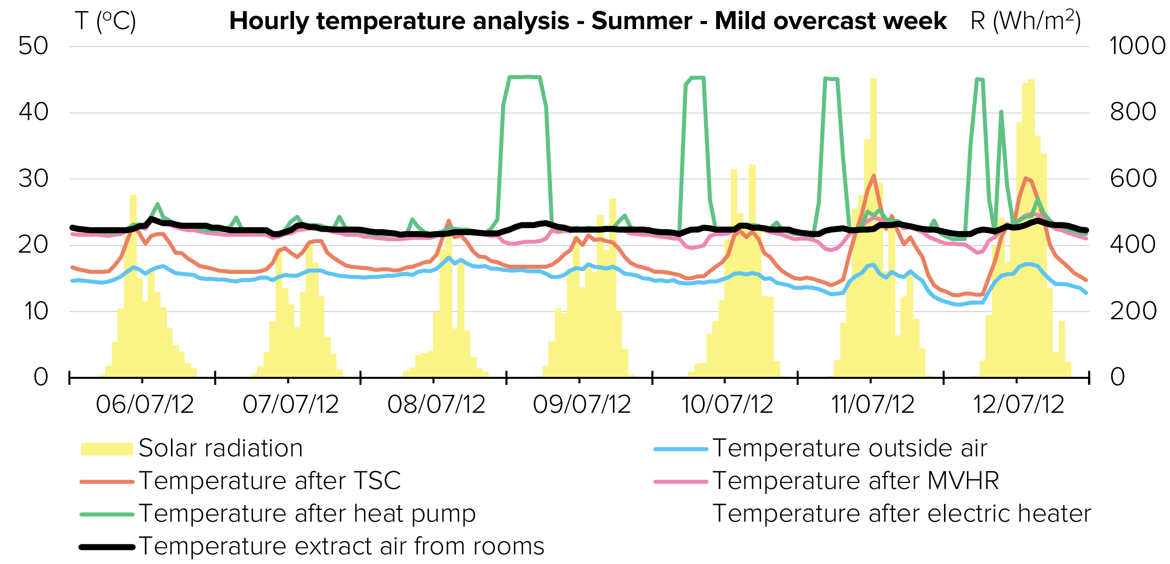


Figure 200 – Graph showing hourly temperature of the thermal system in a mild overcast week in summer 2016. Data source: Measured data from Solcer House.

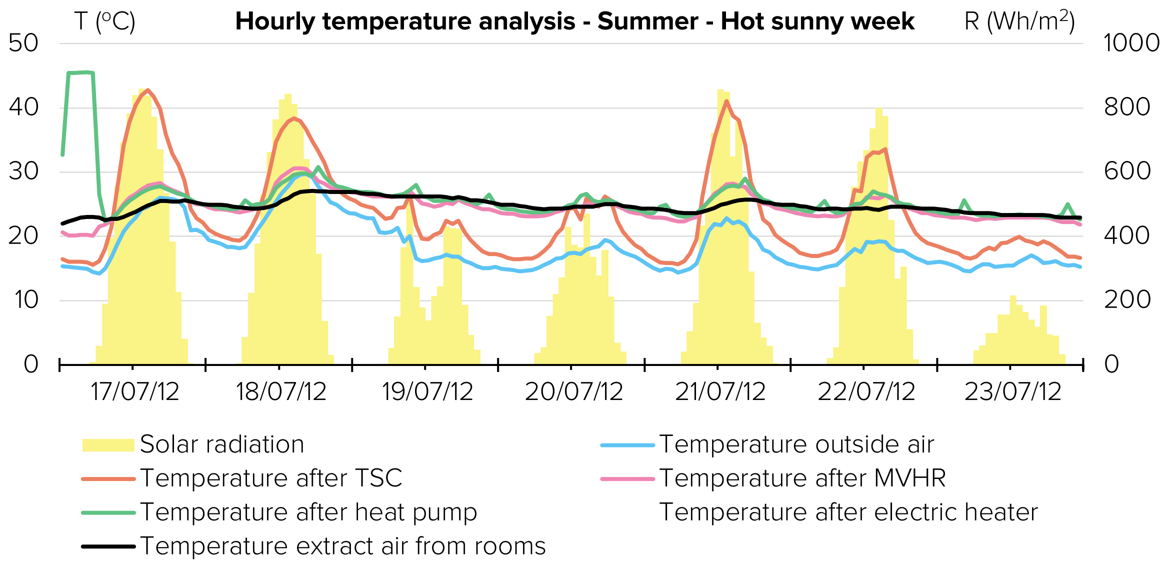


Figure 201 – Graph showing hourly temperature of the thermal system in a hot sunny week in summer 2016. Data source: Measured data from Solcer House.

Second, a zoom to a week with hot temperatures of up to 30ºC and sunny days is presented in Figure 201. Graph shows how during the day, the TSC adds a considerable amount of heat boosting the air temperature by up to 40ºC, while the MVHR absorbs this excess of heat from the TSC and helps to reduce the overheating risk by cooling the supply air temperature down to 27ºC. At night, when outside temperatures drop down to around 16ºC, the MVHR provides up to 10ºC temperature rise and helps maintaining internal temperatures more stable without the need of the heat pump. Overall, after a few days of very hot summer days, the temperature inside the house goes up to 27ºC, resulting in a slightly overheating discomfort for the occupants. This seems to indicate that the damper installed after the TSC, which should avoid overheating risk by bypassing the TSC warmer air and bringing direct outside air when temperature inside the house is at 25ºC and outside temperatures above 15ºC, is not operating properly. In conclusion, it is found that to reduce overheating risk during hot summer days, the TSC should not be used and the MVHR should change to summer mode bypassing heat recovery, and just supplying fresh air to the main living spaces.

7.3 EPH design: environmental impact

The goal of this Life Cycle Assessment (LCA) study is to estimate the environmental impact of the EPH design. The results of the LCA of the Solcer House case study are then used to estimate its full impact from cradle-to-grave with the aim of identifying hot spots and improvement opportunities along the supply chain. This LCA follows the ISO 14040/44 methodology (ISO, 2006), which is outlined in Figure 202 and focuses on three main stages:

- House construction: This stage involves extraction and manufacture of construction materials and fuels, transportation through the supply chain and construction of the house.
- Use over its lifetime: This stage includes water and energy consumption for space and water heating, cooking, lighting and domestic appliances. Maintenance activities such as replacement of windows, doors and floor covering are also considered.
- End-of-life waste management: This stage involves house demolition and waste management activities, such as reuse, recycling and landfilling of construction waste.

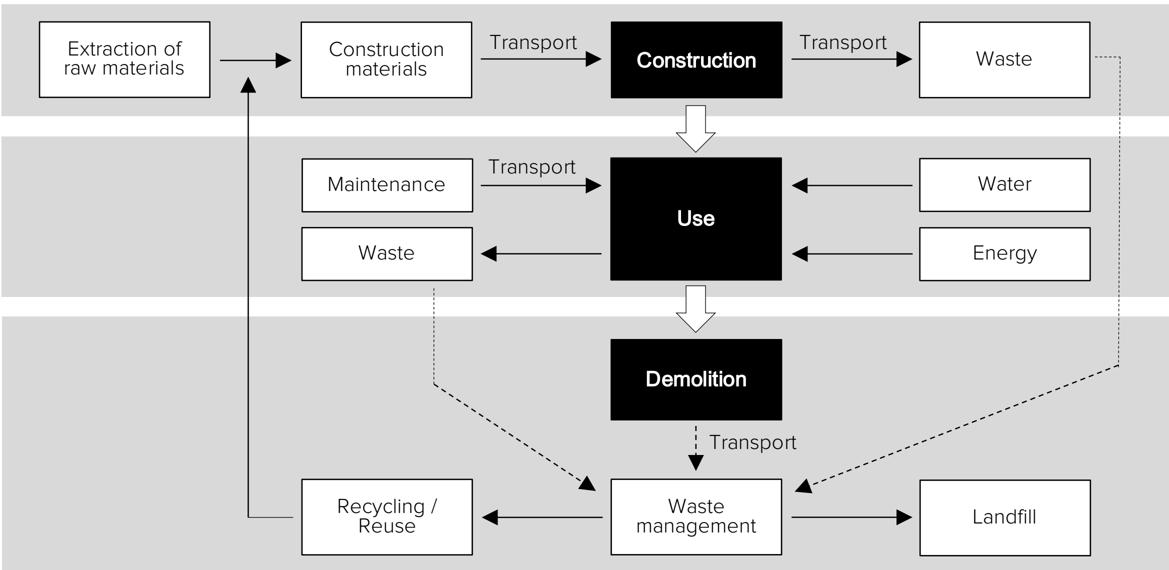


Figure 202 – Diagram showing the boundaries and life cycle stages considered for the LCA of the Solcer House.

7.3.1 CONSTRUCTION STAGE

The construction of the EPH design is presented in Chapter 6. Accordingly, the types and quantities of material for the construction of the house are calculated using construction guides and specifications, material specifications, direct information from installers and manufacturers and expert consultation. As shown in Table 33, it is estimated that 106t of materials are used in the construction of the Solcer House, with a total embodied 43.5tCO_2.

Table 33 – CO_2 emissions from the construction stage of the Solcer House. Data source: Ratio CO_2 emissions from ICE database (Hammond & Jones, 2011) and material quantities from specifications and monitored data.

Elements and components	Volume (m^3)	Density	Mass (Kg) [waste]	Ratio CO_2 emissions ($KgCO_2$/Kg)	Total CO_2 emissions ($KgCO_2$)
FOUNDATIONS					5,372.27
Mix 280	11.93		-	-	-
Cement CEM2	-		3,340 [1]	0.573	1,913.72
Stone 20-5. Virgin Stone	-		12,216 [1]	0.022	268.76
Recycled Sand & Blend (50:50)	-		9,997 [1]	0.005	47.99
Water	-		-	-	-
Slab/column foundation P330 (ST3)	6.85		-	-	-
Cement CEM2	-		2,261 [1]	0.573	1,295.04
Stone 20-5. Virgin Stone	-		6,782 [1]	0.022	149.19
Recycled Sand & Blend (50:50)	-		5,549 [1]	0.005	23.63
Water	-		-	-	-
Brickwork			-	-	-
7N Concrete Block	660 Un.		9,900 [2]	0.073	722.70
Grey facing brick	540 Un.		1,080 [2]	0.878	948.24
SLAB					248.92
Slab			-	-	-
Sand			1,000 [1]	0.005	4.80
Cement			750 [1]	0.573	429.68
Hardcore - recycled T1 aggregate			20,000 [1]	0.016	316.00
DPM – Polythene			52 [1]	8.280	430.56
Drainage			-	-	-
100/150 mm ducts – U-PVC			24 [3]	3.230	77.84
Entry bends – U-PVC			5 [3]	3.230	15.57
Insulation			-	-	-
Celotex xr400 insulation			187 [4]	2.550	477.36
500g polythene separating layer			26 [4]	2.040	53.04
Screed			-	-	-
Sand/cement fibre			5,090 [1]	0.050	254.51
DPM layer			52 [1]	8.280	430.56
EXTERNAL WALLS					4,707.41
EWI Render Parex system	-		-	-	-
Acrylic Render System	4.38		6,596 [5]	0.050	329.81
Maite adhesive layer	0.44		-	-	-
355 Mesh	0.15		-	-	-
EPS Insulation	8.15		163 [4]	2.550	415.65
Knauf Aquapanel Exterior	2.04		2,139 [5]	0.050	106.97
Dupont Tyvek Reflex	-		14 [4]	?	?
SIPS Panels	-		-	-	-
Oriented Strand Board (OSB)	1.80		1,219 [6]	0.460	560.85
Climate CE100 EPS	28.04		589 [4]	3.380	1,990.00
Oriented Strand Board (OSB)	1.80		1,219 [6]	0.460	560.85
Internal finishes	-		-	-	-
DuPont Airguard Reflective	-		24 [4]	-	?
Gyproc Wallboard	2.45		1,956 [5]	0.380	743.28
NORTH ROOF					3,452.18
Finishes	-	-	-	-	-
Aluminium sheet	0.02	2,700	56 [4]	8.240	460.53
Dupont Tyvek Reflex	-	-	2 [4]	-	
SIPS Panels	-	-	-	-	-
Oriented Strand Board (OSB)	0.25	680	172 [6]	0.460	79.14
Climate CE100 EPS	3.96	21	83 [4]	3.380	280.80
Oriented Strand Board (OSB)	0.25	680	172 [6]	0.460	79.14
Fittings	-	-	-	-	-
Flashing – Galvanized steel	0.05	7,850	424 [7]	2.800	1,186.92
Eaves – Galvanized steel	0.03	7,850	254 [7]	2.800	712.15
Gutters – Galvanized steel	0.02	7,850	170 [7]	2.800	474.77
Downpipe – UPVC	-	-	14 [3]	12.840	178.73

Elements and components	Volume (m^3)	Density	Mass (Kg) [waste]	Ratio CO_2 emissions ($KgCO_2$/Kg)	Total CO_2 emissions ($KgCO_2$)
SYSTEMS					12,266.39
PV System	-	-	-	-	-
Solar PV – Monocrystalline	-	-	-	242.000	8,252.20
Single glazing panels	0.20	2,500	512 [8]	0.850	434.78
Aluminium railing	-	-	116 [7]	8.240	952.11
TSC	-	-	-	-	-
Steel Prisma perforated planks	0.12	7,850	-	1.370	1,294.84
Flashing – Galvanized steel	0.04	7,850	-	1.370	387.16
Heating/ventilation System	-	-	-	-	-
Ducting – Aluminium	0.03	2,700	84 [7]	8.240	693.00
Ducting – Insulation Glass Wool	0.16	1,200	187 [4]	1.350	252.31
WINDOWS					6,972.06
Glazing	-	-	-	-	-
Pilkington Energycare Advantage	0.44	2,500	1,104 [8]	0.850	938.40
Frame	-	-	-	-	-
Aluminium clad timber frame	-	-	80 [6]	75.000	6,015.00
Ironmongery	-	7,870		1.910	-
Sills	-	-	-	-	-
MDF board (200mm wide)	0.04	720	26 [6]	0.720	18.66
FLOORS					3,270.37
Ground Floor	-	-	-	-	-
Laminate flooring	0.38	720	271 [6]	0.870	253.53
Vinyl	0.01	1,200	7 [10]	2.920	21.02
Foam underlay	0.09	480	45 [10]	3.480	157.02
First floor	-	-	-	-	-
Laminate flooring	0.35	720	253 [6]	0.870	220.49
Foam underlay	0.09	480	42[10]	3.480	147.00
Vinyl	0.01	1,200	14 [10]	2.920	42.05
Floor board - moisture resisting	1.10	600	660 [6]	0.460	303.60
Metal joists	-	-	270 [7]	1.370	369.90
Mineral wool insulation	0.44	12	5 [4]	1.350	7.13
Ceiling – Plasterboard	0.75	800	600 [5]	0.380	228.00
Second floor	-	-	-	-	-
Vinyl	0.06	1,200	72 [10]	2.920	210.24
Floor board - moisture resisting	1.10	600	660 [6]	0.460	706.20
Metal joists	-	-	270 [7]	1.370	369.90
Mineral wool insulation	1.50	12	18 [4]	1.350	24.30
Ceiling – Plasterboard	0.75	800	600 [5]	0.380	228.00
INTERNAL FINISHES					4,992.06
Internal walls	-	-	-	-	-
Plasterboard	3.93	800	3,144 [5]	0.380	1,194.72
Timber Stud	1.24	500	619 [6]	0.460	284.73
Mineral wool insulation	1.31	12	16 [4]	1.350	21.22
Paint	-	1,500	1,204 [10]	2.120	2,551.95
Ceramic tiles	0.22	2,000	442 [9]	0.740	327.08
Stairs	-	.-	-	-	-
Stair GF – MDF rise	-	720	47 [6]	0.720	33.53
Stair GF – ash threads	-	1,000	101 [6]	0.460	46.55
Mopstick handrail GF – softwood	0.02	510	8 [6]	0.460	3.61
Balustrade F1 - ash spindles	10.13	650	253 [6]	0.460	116.44
Stair F1 - MDF rise	-	720	43 [6]	0.720	31.14
Stair F1 - ash threads	-	1,000	79 [6]	0.460	36.43
Mopstick handrail F1 – softwood	0.02	510	8 [6]	0.460	3.61
Carpentry	-	-	-	-	-
Internal fire doors and linings	-	-	-	5.177	51.77
Stain steel ironmongery	-	-	10 [7]	6.150	61.50
MDF Skirting	0.09	720	62 [6]	0.720	44.38
MDF Architraves	0.08	720	58 [6]	0.720	41.47
Sanitaryware	-	-	-	-	-
Toilet and cistern	-	-	50 [10]	1.510	75.50
Wash hand basin	-	-	44 [10]	1.510	66.44
TOTAL			**105,661**		**43,522.6**

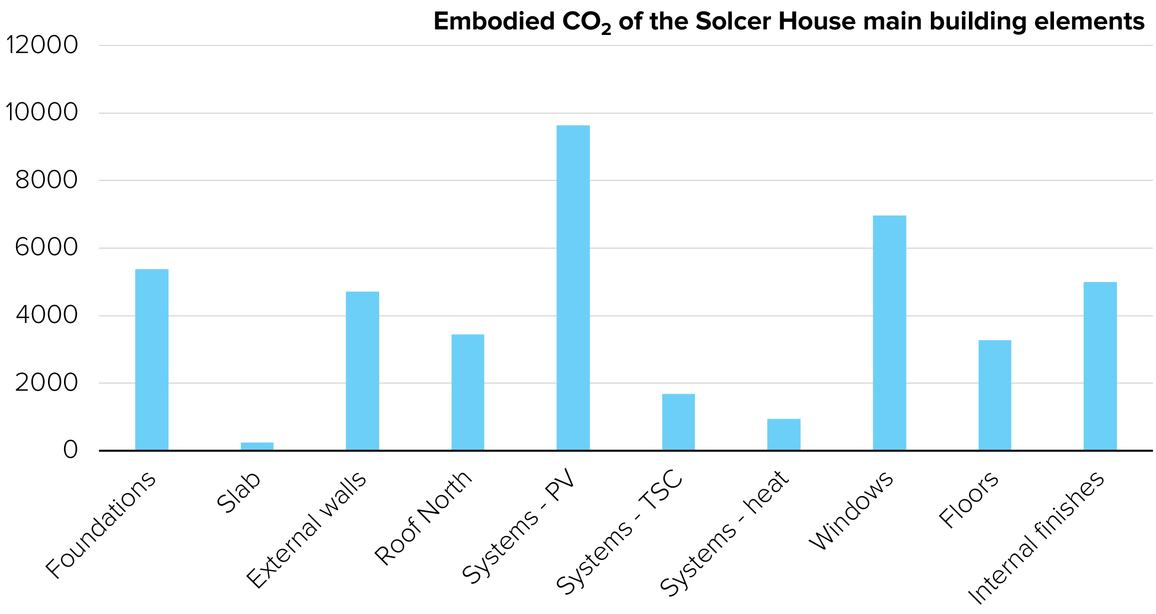


Figure 203 – Graph showing the embodied carbon emissions of the Solcer House's building elements. Data source: Table 33.

The embodied carbon emissions of the building elements have been estimated referring to the ICE database (Hammond & Jones, 2011). The overall results are presented in Figure 203, while Table 33 presents the material embodied CO_2 values used in the calculation. It should be noted that low carbon cement has been used, provided from Cenin Cement, which has an emission factor of around 1/20th of normal cement. The south facing PV roof has the largest embodied CO_2, and accounts for 22% of the total. It is then followed by the windows, foundations, external walls and internal finishes, making up 16, 12%, 11% and 11% of the total embodied emission respectively. The embodied carbon emission of the whole house construction is estimated to be 335kg/m^2. This is relatively low, compared with other studies of 403kgCO_2/m^2 (Hammond & Jones, 2008), or 492-569kgCO_2/m^2 (Hacker, et al., 2008).

The calculation in Table 33 does not consider material wastage, which is minimised as much as possible. The main strategies used to minimise the waste produced, thereby reducing the amount of waste to be removed from the project, are as follows:

- Pre-contract design team meetings were held with all subcontractors on a fortnightly basis to identify waste preventative actions and provide value engineering.
- Materials, which arrived on pallets, were unloaded and the pallets were stored neatly and removed from the site once the numbers were sufficient.
- A secure storage area was provided to protect materials from weather and accidental damage. For example, rigid insulation boards in particular can be damaged by poor storage and handling.

- Rigid insulation boards off-cuts were reused wherever possible.
- External cladding is designed to cladding panel heights to minimize waste.
- All brick / block walls are designed to brick dimensions to minimize waste.
- Building structure with SIPs was manufactured of site to reduce waste.
- Wall heights are to plasterboard sizes.

During the construction of the Solcer House, a specific area was laid out and labelled to facilitate separation of materials for potential recycling, salvage and re-use. Skips for segregation of wasted were provided and the weight removed was monitored. Table 34 shows the quantities of waste produced during the construction stage and the resulting 769.52kg equivalent embodied CO_2 emissions from this waste disposal.

Table 34 – CO_2 emissions from the waste disposal during the construction stage of the Solcer House. Data source: GHG conversion factors (BEIS, 2018) and waste quantities from monitored data.

Waste type	Quantity (t)	GHG conversion factor ($KgCO_2/t$)			Total CO_2 emissions ($KgCO_2$)		
		Reused	Recycled	Landfilled	Reused	Recycled	Landfilled
Plasterboard	1.5	-	21.3842	-	-	32.08	-
General	4.96	-	-	1.277	-	-	6.33
Timber	0.8	64.3758	21.3842	828.1303	51.5	17.11	662.50
Total					**51.5**	**49.19**	**668.83**

Finally, the energy data for the construction machinery was recorded on a weekly basis on site. During the 24 weeks of the construction stage, a total of 2,257.2 kWh of electricity, 8,503L of water and 120L of diesel (1,200kWh) were used. The total energy used in the construction of the EPH house is estimated at 3,457kWh or 12.5GJ. This is relatively low compared with other studies of 31.2 GJ for a similar size detached house (Cuellar-Franca & Azapagic, 2012), thanks to the use of pre-fabricated construction systems. Table 35 shows the equivelent CO_2 emissions from the different sources of energy used on site.

Table 35 – CO_2 emissions from the energy used during the construction stage of the Solcer House. Data source: GHG conversion factors (BEIS, 2018) and energy quantities from monitored data.

Energy source	Quantity	GHG conversion factor	Total CO_2 emissions ($kgCO_2$)
Electricity	2,257 kWh	0.283 $kgCO_2/kWh$	638.7
Diesel	120 L	3.132 $kgCO_2/L$	375.8
Water supply	8.503 m^3	0.344 $kgCO_2/m^3$	2.9
Total			**1,017.4**

7.3.2 USE STAGE

The lifetime of a house depends on many aspects; thus, it is a difficult parameter to standardise. However, for research purposes, many authors assume a life span of 50 years (Cuellar-Franca & Azapagic, 2012). Therefore, this lifetime is also assumed in this LCA. In terms of the occupancy of the Solcer House, it is assumed that the house is occupied by a family of two adults and two children. Considering the assumptions, the calculations are as follows:

- Energy: The total energy demand of the Solcer House over its lifetime during the use stage is 199,100kWh, however this is offset by the energy generated from the integrated PV roof. Therefore, as previously explained in section 7.2.1, the Solcer House is energy positive. As it can be seen in Table 36, over its lifetime the building's energy import from the electric grid is 60,200kWh and the energy fed into the grid is 67,850kWh. As a result, the Solcer House is negative carbon in terms of electricity consumption during the use stage.

Table 36 – CO2 emissions from the energy used during the use stage of the Solcer House. Data source: GHG conversion factors (BEIS, 2018) and energy quantities from Table 23.

Energy element	Quantity (kWh)	GHG conversion factor ($kgCO_2$/kWh)	Total CO_2 emissions ($kgCO_2$)
Electricity demand	199,100	-	-
Electricity supply from PV/battery	206,750	-	**-**
Electricity import from grid	60,200	0.283	**17,036.6**
Electricity export to grid	67,850	-0.283	**-19,201.6**
Total	**-**	**-**	**-2,165**

- Water: The average water use is assumed at 142L per person per day (Energy Saving Trust, 2013), so that the total consumption over 50 years for the house is equivalent to 10,366m^3 of water. Table 37 gives the equivalent CO_2 emissions from water supply and sewage treatment over the lifetime of the house.

Table 37 – CO2 emissions from the water used during the use stage of the Solcer House. Data source: GHG conversion factors (BEIS, 2018).

Energy element	Quantity (m^3)	GHG conversion factor ($kgCO_2$/m^3)	Total CO_2 emissions ($kgCO_2$)
Water supply	10,366	0.344	3,565.9
Waste water treatment	10,366	0.708	7,339.1
Total	**-**	**-**	**10,905**

- Maintenance: The maintenance activities reflected in the use stage involve replacing the windows and the PV system every 25 years, and the doors and floor coverings every 20 years.

7.3.3 DEMOLITION STAGE

The end-of-life options are analysed based on the destination of demolition waste in the UK as shown in Cuellar-Franca & Azapagic (2012). For the demolition activities, the data for the quantity of materials is calculated grouping the materials by type from Table 33. To avoid double counting, it is assumed that all the construction materials are manufactured from virgin raw materials. As shown in Table 38, the demolition of the Solcer House would generate about 110t of waste, of which 97t (88.2%) could be recycled, 6.7t (6.1%) reused and 6.3t (5.7%) landfilled. Note that the quantities of replacement components and materials used in the maintenance stage are based on the inventory data in Table 33 and the replacement intervals mentioned above.

Table 38 – End-of-life waste management for the Solcer House over 50 years. Data source: Destination of demolition waste ratio (Cuellar-Franca & Azapagic, 2012).

[ ]	Element / Material	Demolition waste (kg)	Maintenance waste (kg)	Total waste (kg)	Destination (kg)		
					Reused	Recycled	Landfilled
1	Concrete & aggregates	67,089	-	67,089	-	67,089	-
2	Bricks	10,980	-	10,980	5,600	3,953	1,427
3	U-PVC	43	-	43	-	21.5	21.5
4	Insulation	1,370	-	1,370	247	-	1,123
5	Gypsum	15,035	-	15,035	-	15,035	-
6	Timber	6,010	1,518	7,528	151	5,947	1,430
7	Metal	1,598	136	1,734	-	1,734	-
8	Glass	1,616	1,616	3,232	-	3,232	-
9	Ceramic	442	884	1,326	756	93	477
10	Others	1,478	346	1,824	-	-	1,824
	Total	**105,661**	**4,500**	**110,161**	**6,754.5**	**97,104.5**	**6,302**

The UK Government provides annual GHG conversion factors for waste disposal (BEIS, 2018), which are then used to calculate the equivalent CO_2 emissions generated from the quantities of different waste types. Accordingly, as shown in Table 39, the total carbon emissions from waste disposal would be 1,835kgCO_2, of which 65% are from landfilling, 34% are from recycling and 1% are from reusing materials.

Table 39 – CO_2 emissions from the end-of-life waste disposal for the Solcer House over 50 years.

[ ]	Element / Material	GHG conversion factors ($KgCO_2/t$)			Total CO_2 emissions ($KgCO_2$)		
		Reused	Recycled	Landfilled	Reused	Recycled	Landfilled
1	Concrete & aggregates	-	1.0192	-	-	68.38	-
2	Bricks	1.0192	1.0192	1.277	5.71	4.03	1.82
3	U-PVC	-	21.3842	9	-	0.46	0.19
4	Insulation	1.0192	-	1.277	0.25	-	1.43
5	Gypsum	-	21.3842	-	-	321.51	-
6	Timber	64.3758	21.3842	828.1303	9.72	127.17	1,184.22
7	Metal	-	21.3842	-	-	37.08	-
8	Glass	-	21.3842	-	-	69.11	-
9	Ceramic	1.0192	1.0192	1.277	0.77	0.09	0.61
10	Others	-	-	1.277	-	-	2.33
	Total				**16.45**	**627.83**	**1,190.66**

7.3.4 FULL LCA RESULTS

The results of the full impact assessment are shown in Table 40. The total CO_2 emissions over the lifetime of the Solcer House are estimated at $55.8tCO_2$. The large majority of the impact (81%) is from the construction stage, with the use contributing 16% and the demolition stage the remaining 3%. This percentage distribution is unusual when compared against a house without renewable technologies. For example, when the PV and its energy generation are removed, the Solcer House doubles its CO_2 emissions to up to $104.7tCO_2$ and then the use stage has the majority of the impact (64%). Also, the full impact is very low if compared against a traditional house, which is about 8 times more (Cuellar-Franca & Azapagic, 2012).

Table 40 – Full LCA impact assessment from cradle-to-grave for the Solcer House, the Solcer House without renewable energy generation technologies and a traditional house (Cuellar-Franca & Azapagic, 2012).

Element / Material	Solcer House	Solcer House without PV	Traditional House
Construction stage	**45,309.5**	**35,670.4**	**47,069**
Building materials (Table 33)	43,522.6	33,883.5	41,272
Waste disposal (Table 34)	769.5	769.5	560
Energy sources (Table 35)	1,017.4	1,017.4	5,237
Use stage	**8,740**	**67,250.3**	**402,556**
Electricity	-2,165	56,345.3	400,551
Water	10,905	10,905	2,005
Demolition stage	**1,835**	**1,783**	**5,437**
Waste disposal	1,835	1,783	5,437
Total	**55,884.5**	**104,703.7**	**455,062**

7.4 EPH design: economic impact

The Solcer House was built for and estimated cost of £145,000 if the extra costs from R&D works are not included, which represent an extra 30%. When considering the build cost expressed in pounds per square metre (£/m²) this equals to a cost of 1,425 £/m² if only the habitable area of the ground and first floor are considered, or 950 £/m² if the loft area is also included. Table 41 shows the breakdown of the build costs.

Table 41 – Cost of the construction of the EPH design showing the real cost of the Solcer House case study as built and without the extra costs from R&D elements. Note: Costs relate to year 2015.

Element	Solcer House as build	Solcer House without R&D
Ground Works	**£11,790**	**£10,150**
Foundations	£9,530	£8,150
Insulation and screed	£2,260	£2,000
Building fabric	**£71,025**	**£64,760**
SIPS panels	£47,125	£47,125
Facades Rendering	£14,415	£8,150
Windows and external doors	£9,485	£9,485
Roof	**£11,570**	**£11,570**
Roof Cladding	£11,570	£11,570
Systems Works	**£52,895**	**£30,190**
TSC System	£8,580	£4,290
PV System	£11,700	£6,300
Battery System	£9,060	£7,060
Electrical Installation	£12,515	£2,500
Heat/Vent/DHW System	£11,040	£10,040
Interior Works	**£38,030**	**£28,330**
Internal partitions	£7,315	£7,315
Wall and ceiling finishes	£3,660	£3,660
Floor finishes	£4,225	£4,225
Internal doors	£2,920	£2,920
Built-in cupboards	£7,050	£300
Stairs	£4,945	£2,470
Kitchen fittings	£4,475	£4,000
Sanitary fittings	£3,440	£3,440
Total	**£185,310**	**£145,000**

The analysis of the breakdown costs indicates that the building fabric is the most expensive element of the Solcer House, representing around 45% of the total cost (Figure 204); which is notably higher than the 16% of a traditional house (see Figure 205). Therefore, the building fabric of a highly insulated house with a fabric first approach is almost 30% more costly.

The second most expensive element of the Solcer House is the energy system, which represents 21% of the total cost (Figure 204); which is slightly higher than the 13% of a traditional house (see Figure 205). However, the Solcer House includes extra low carbon technologies such as the TSC, the building integrated PV, the Li-Ion battery or the combi unit for heating and ventilation; which bring significant energy savings (see section 7.2).

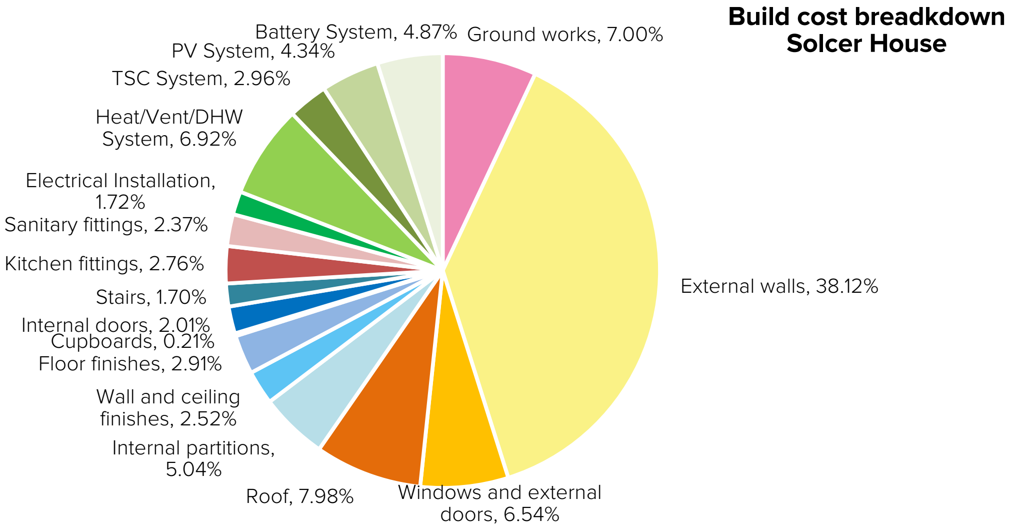


Figure 204 – Pie chart shows the breakdown of the build cost of the Solcer House. Data source: Monitored data.

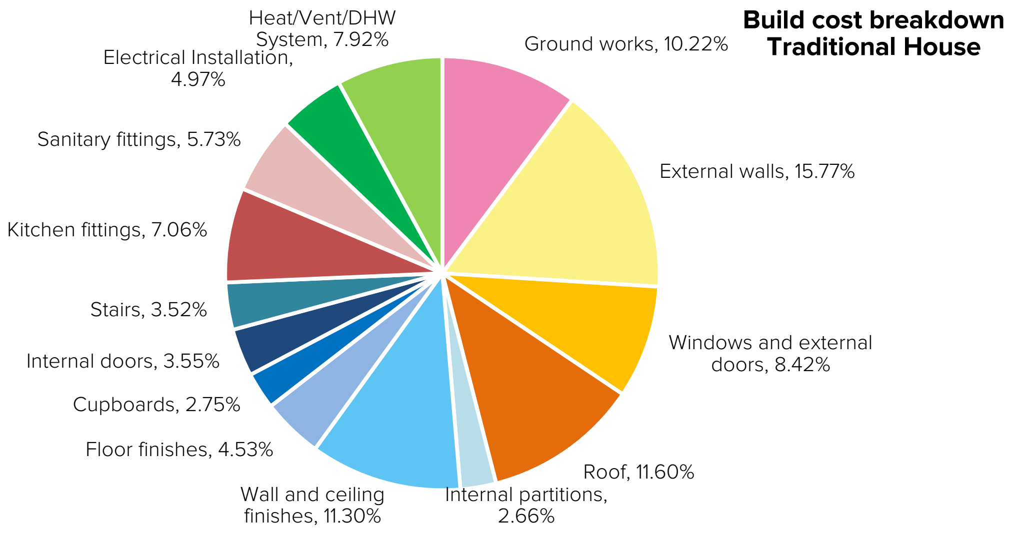


Figure 205 – Pie chart shows the breakdown of the build cost of a traditional house. Data source: (Holmes, 2012).

Finally, it is important to consider the effect of the project size on the cost of housing construction as shown in Figure 206. For example, the build cost for all residential schemes of 10 units or less is on average +6% than on large developments and this percentage is +14% for housing only schemes and -5% for flats only schemes (BCIS, 2015). Moreover, single unit projects, like the Solcer House case study, are generally bespoke houses and are significantly more expensive than units in other developments.

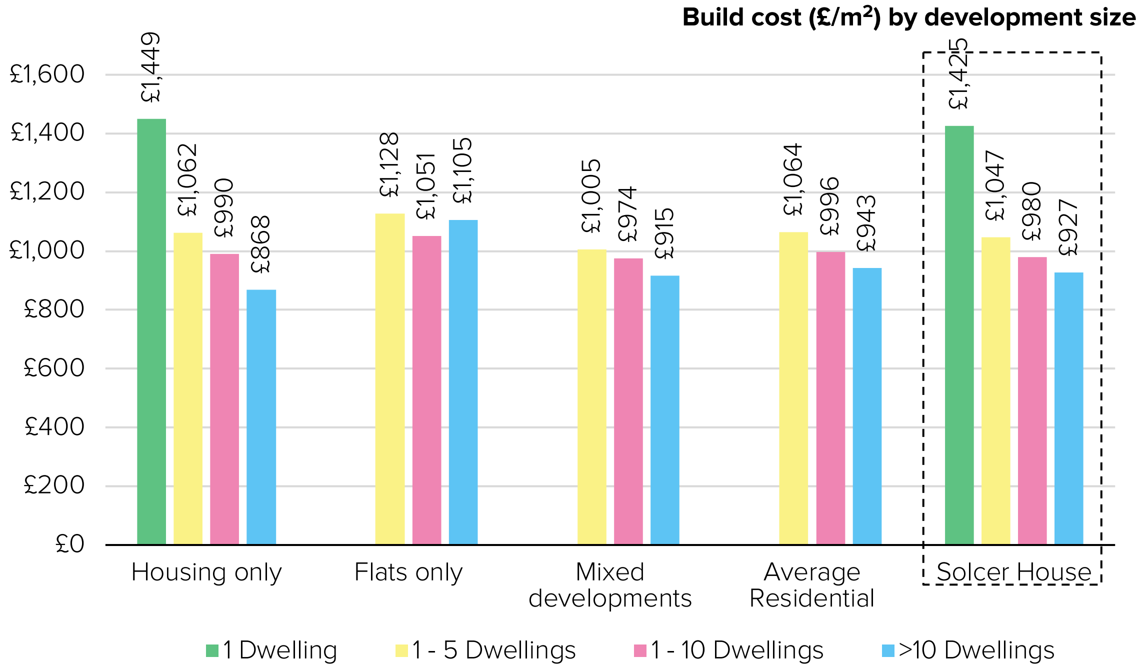


Figure 206 – Bar chart shows the UK's average build cost by development size for the BCIS Wales Location Index 92 and the cost of the Solcer House as a single unit or replicated in multiple units. Data source: (BCIS, 2015)

In Figure 202, the reduction costs due to the development size from the BCIS report are applied to the Solcer House case study to calculate the real cost that the EPH design could have when replicated in bigger size residential developments for a future low carbon built environment. Results indicate that the build cost to replicate the Solcer House project would be around 1,050 £/m² for a development of 1 to 5 dwellings, 980 £/m² for a development of 1 to 10 dwellings and 927 £/m² for a development of more than 10 dwellings. The build costs for the EPH design are almost the same than the build costs of a traditional house design, which indicate that an energy positive house model can be built for an affordable cost if low carbon technologies are integrated in the building design during the early stages of the design process.

7.5 EPH design: social impact

Following the launch of the Solcer House by the Welsh Government's Minister for Business, Enterprise, Technology and Science in July 2015, interest in the house has been significant. The house has received over 2,000 visitors from a broad range of organisations. Visitors include the Chinese Vice Premier of the People's Republic of China, Liu Yangdong, registered social landlords, architectural practices, manufacturing companies, construction institutions, a range of departments from Welsh Government and UK Government, Natural Resources Wales and other academic institutions. The visitors expressed interest in replicating the building at other locations in Wales, the UK and further afield, using the house to lobby government, to influence policy and to inform future practitioners on the incorporation of low carbon technologies into buildings.

Figure 207 – Visit to the Solcer House from the Vice Premier of the People's Republic of China, Liu Yangdong, and the Welsh Minister for Business, Enterprise and Technology, Edwina Hart.

As described in Chapter 3, an online survey was done to the visitors of the Solcer House. In total 88 people answered over one-month period with a response rate of 17%. A sample of the questionnaire can be found in Annex 1. When analysing the characteristics of the respondents, considering gender 74% of the responses were from men and 26% from women; considering location 77% of the responders were from Wales, 19% from England and 4% from other countries; while considering the age groups 34% were 46 to 55 years old, 25% were 36 to 45 years old, 20% were 56 to 65 years old and only 7% were below 25 or above 66 years old. Finally, when considering the nature of their interest on the Solcer House research project, the responders background was very broad, from researchers (17%), public sector housing (11%), manufacturers (10%), occupiers (9%), designers (9%), policy makers (6%), house builders (5%), developers (5%), etc. The main motivations to visit the Solcer House were also very wide-ranging. For example, some had a work-related interest (13%), some wanted to find out more about products and technologies used (12%), some had a general interest in sustainability (11%), while some wanted to experience the house from the inside (7%), etc. The satisfaction rates after the visit were very positive, with 72% of the visitors finding it very useful and 74% highly recommending the visit to others.

7.5.1 QUALITY AND FUNCTIONALITY

To evaluate the quality of the design of the EPH design, visitors were asked if the design was pleasant to them aesthetically, functionally, practically, spatially, externally and internally (see question 15). Responses from the survey are presented in Figure 208. Table 42 compares the average score from higher to lower. Functionality, practicality and internal aspect are the better valued with about 80% of the visitors being satisfied or very satisfied; followed by space, aesthetics and external aspect with around 55% of the visitors being satisfied or very satisfied. Generally, visitors' opinion is very positive with a 3.9 out of 5. Comments from visitors highlighted the nice aesthetics of the building integrated PV stating "I loved the transparent roof tiles and light into the attic", while others criticized the external design for being too modern and suggested to incorporate more traditional design features to achieve a conventional look to hit the mass market, for example saying "some further work needed on the aesthetics of the outside to help normalise, trick is that it looks like a normal house" or "reference to traditional design features would appeal to wider audience".

Table 42 – Average score of each design characteristic.

Functionally	Practically	Internally	Spatially	Aesthetically	Externally
4.23	4.14	3.94	3.65	3.55	3.50

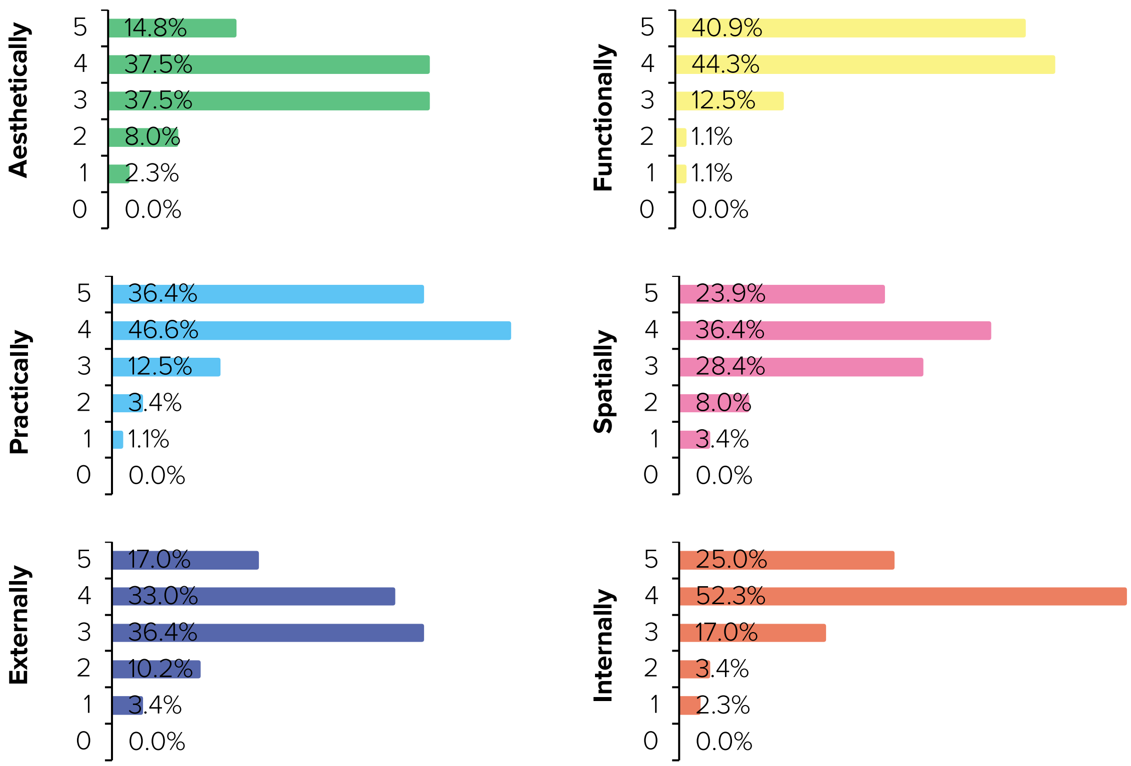


Figure 208 – Graphs showing the statistics and responses from the survey question 15: "Is the Solcer House design pleasing to you?" (0) for low value and (5) for high value.

7.5.2 ADAPTABILITY

To evaluate the EPH design adaptability potential, visitors were asked about the issues that the Solcer House might pose if they wanted to build it themselves (see question 16). Responses from the survey are presented in Figure 209. When comparing the average scores in Table 43, visitors were mostly concerned about the potential difficulties to get planning permission and to sell the house, were fairly concerned about its maintenance and operation, and were less worried about the look being too modern or too different. Nevertheless, visitors' overall opinion is optimistic with a mean level of concern of 2 out of 5. Comments from the visitors showed worries related with the adaptation of the house model to a specific site stating "other issues could be a shaded site, awkward shaded site, sloping side, etc.", or the influence of the occupants on the performance of the systems saying "I'm aware of heat pump systems which occupants have found intimidating, so open windows to release heat rather than adjust the system resulting in waste of energy". To increase the feeling of security to investors, one visitor advised that "a support package for the various systems should be offered at a reasonable price, with guaranteed performance".

Table 43 – Average score of each concern characteristic.

Planning permission	Sell	Maintenance	Operation	Different	Modern
2.63	2.43	1.93	1.92	1.68	1.60

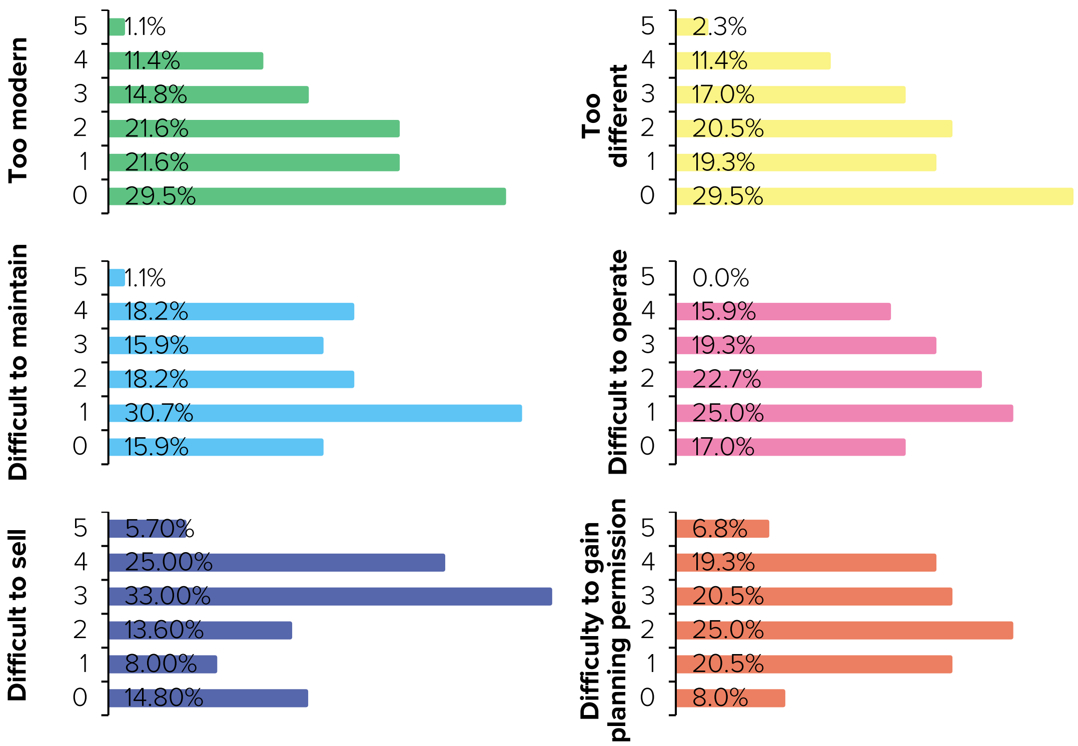


Figure 209 – Graphs showing the statistics and responses from the survey question 16: "What issues do you think the Solcer House might pose if you wanted to build it?" (0) for low concern and (5) for high concern.

7.5.3 NOVELTY

Visitors were asked to value some of the most novel building features (see question 17). Responses from the survey are presented in Figure 210. When comparing their average score in Table 44, the building integrated PV system is the most successful feature with an outstanding 4.63 out of 5, followed by the attic space, the built-in staircase to the attic space and the lack of radiators with a very good score of around 3.8 out of 5. The less valued element is the standing seam metal roof in the north façade. Comments from the visitors highlighted that in general these innovative ideas were very inspiring and attractive.

Table 44 – Average score of each architectural aspect.

PV	Attic space	Staircase	No radiators	TSC	Windows	Render	Metal roof
4.63	3.86	3.84	3.76	3.60	3.38	3.24	3.03

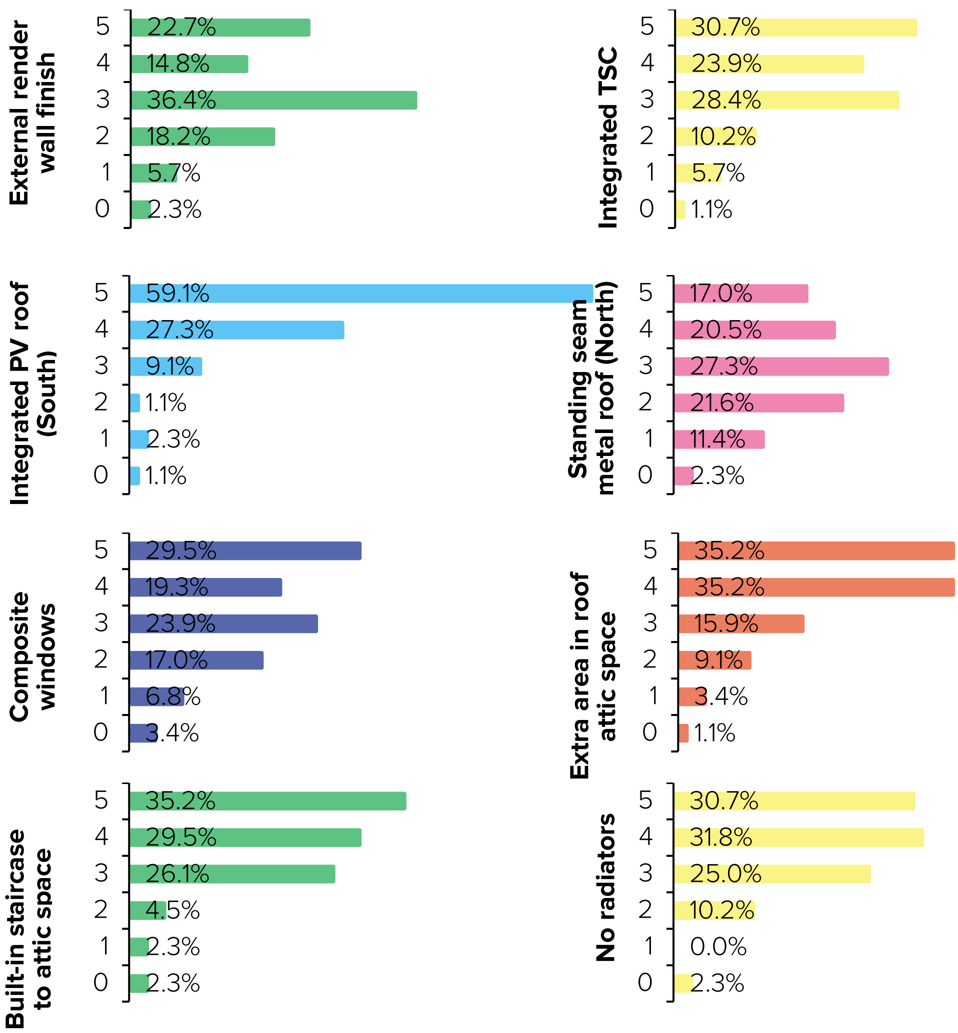


Figure 210 – Graphs showing the statistics and responses from the survey question 17: “How much do you value each of the following features of the house?” (0) for low value and (5) for high value.

Visitors were also asked to value their preference for the low carbon technologies that were installed in the house (see question 12). Responses from the survey are presented in Figure 211. When comparing their average score in Table 45, LED lights and building integrated PV system are the most successful features with an outstanding 4.6 out of 5, followed by MVHR, batteries and TSC with a very good score of around 3.8. The less valued element is the air source HP, but with a good 3.5 score. Therefore, it can be concluded that all the technologies are accepted by the public, who would happily consider installing them at home.

Table 45 – Average score of the low carbon technologies installed in the Solcer House.

LED Lights	PV	MVHR	Batteries	TSC	Air HP
4.63	4.58	3.94	3.85	3.77	3.50

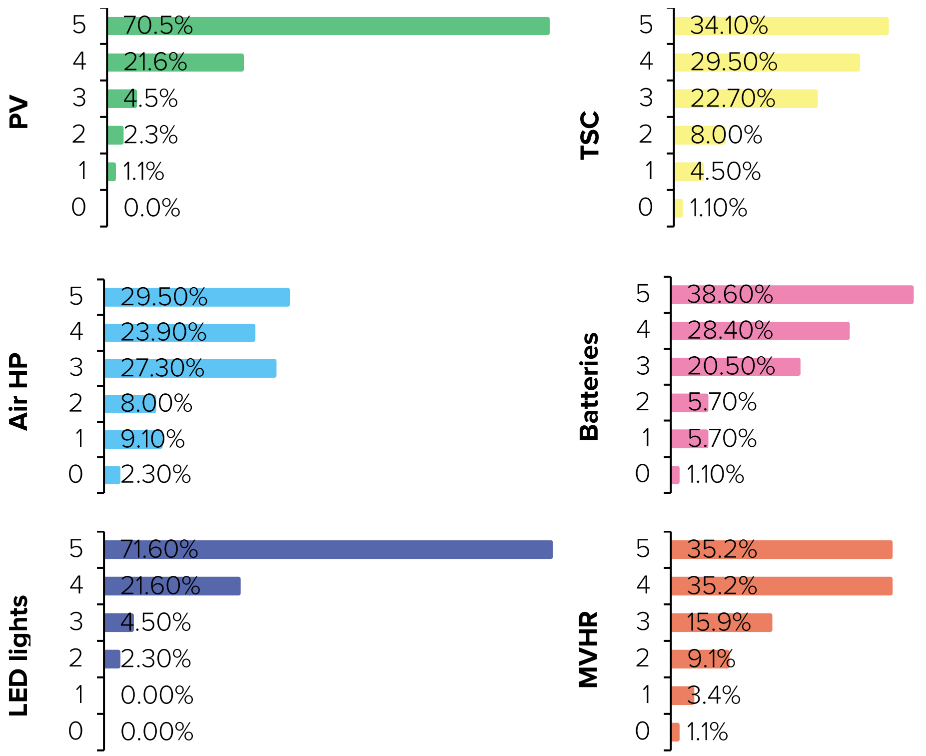


Figure 211 – Graphs showing the statistics and responses from the survey question 12: "Thinking about preference of technologies installed in the Solcer House, could you value the following if you were going to build a SOLCER type house with a limited budget?" (0) for low value and (5) for high value.

In order to have a wider view on low carbon technologies, visitors were asked to evaluate their preference for the technologies that were not part of the EPH system. Table 46 shows that solar thermal and underfloor heating are accepted, while ground source heat pumps and biomass boilers are less accepted, and radiators and wind turbines are not popular.

Table 46 – Average score of the low carbon technologies not installed in the Solcer House.

Solar Thermal	Underfloor heating	Ground HP	Biomass Boiler	Radiators	Wind Turbine
3.64	3.48	2.78	2.46	1.97	1.78

7.6 Summary

In this chapter, an energy performance monitoring and analysis framework is proposed for the EPH design, and the Solcer House is analysed as a case study. The aim of the evaluation framework of monitoring, analysis and modelling of the Solcer House is to provide future feedback for the EPH design's operation and to establish improvements and information for future designs and implementation.

In the first section, the EPH tool is validated and calibrated using the monitored data from the real case study of the Solcer House. It is found that the modelled results predicted with the tool are accurate and reliable in terms of energy demand, supply and storage. Therefore, the use of the EPH tool as an early-stage guidance for EPH design is recommended.

In the second section, the performance of each technology component of the EPH system is investigated individually using monitored data from the Solcer House. First, considering the electrical energy system, and then the thermal energy system. This allows comparing the real performance against the predicted performance claimed by manufacturers specifications.

First, the study of the electrical energy system indicates that an energy positive house can be achieved through an integrated systems approach. The measured annual electricity demand is 3,982kWh/year, so around 39kWh/m^2/year, with an annual grid import of 1,204kWh and grid export of 1,357kWh. Therefore, the building imports about 30% of its energy needs from the grid, but over the year its import to export ratio is 1:1.13. This positive outcome is achieved despite the fact that the efficiency of PV panels is significantly lower than expected and that batteries only use 25% of their full capacity.

Second, the study of the thermal energy system indicates that the TSC efficiency is about 8%. Thanks to TSC's contribution, the efficiency of the MVHR is slightly increased from 76% to 78% and the COP of the heat pump is significantly improved from 3.21 to 3.78. Also, DHW tanks performs well meeting expectations. By adding the energy contribution of each technology together, it is found that total energy delivered by the thermal system over one year is 10,945kWh. This total delivered energy is divided by the energy consumption of 2,147kWh from the compact unit over the same year to find the annual average COP value for the whole thermal system, which is a significant 5.15. Finally, the performance of MVHR and TSC contribute 42% of the space heating although without the TSC, the MVHR alone contributes 28% to the space heating.

In the third section, the full LCA of the Solcer House case study indicates that it is not only carbon negative on its energy use stage, but it is also low carbon in its construction and demolition stages. The total CO_2 emissions of the Solcer House over a lifetime of 50 years is $56tCO_2$, which represent an 88% reduction from a traditional house. The large majority of the impact (81%) is from the construction stage, with the use contributing 16% and the demolition stage the remaining 3%. This percentage distribution is unusual when compared against a house without renewable technologies.

In the fourth section, the build costs of the Solcer House are described and analysed. The analysis of the breakdown costs indicates that the building fabric represents 45% of the total cost and is the most expensive element of the Solcer House, followed by the energy systems which represent around 21%. When looking at the replicability of the EPH design and its economy of scale, results indicate that the build cost to replicate the Solcer House project would be between 1,050 £/m^2 and 927 £/m^2, which is almost the same than the build costs of a traditional house design. This indicates that an energy positive house model can be built for an affordable cost if low carbon technologies are integrated in the building design during the early stages of the design process.

Finally, in the fifth section, an online survey is done to the visitors of the Solcer House with the aim to consider the potential impact of the systems-based approach implemented in the Solcer House and to know what people like or dislike about it. In general, Solcer House's visitors were impressed with the design and the idea of a replicable and affordable energy positive house but raised some questions and concerns that could prevent the house being replicated in the short term. Regarding the novelty of the project and its technologies, the survey reveals that in general there is a very positive feedback from the public, who would widely accept the implementation of LED lights, building integrated PV panels, MVHR, batteries, TSCs and air source heat pumps. Results also revealed that the choice of discarding other low carbon technologies such as ground source heat pumps, biomass boiler, radiators or wind turbines was a good decision because these are much less popular.

The aim of the detailed and broad evaluation of the EPH design is to respond to visitors' questions and to provide reassurance that the house is a viable option when considering low carbon replicable and affordable housing. This would refine the information provided to these stakeholders which would reduce the risk for organizations interested in replicating the house in the future in different locations.

8 Conclusions and recommendations

Considering the challenging goal to decrease the UK's carbon emissions by at least 80% by 2050 (CCC, 2008), this thesis defends that a solution to current energy related problems – i.e. scarcity of fossil fuels, impact of climate change, growth of population numbers, rise of fuel poverty, lack of housing stock, insecurity of national grid and increase of peak demand – is feasible with a bottom-up correction of the built environment.

The thesis starts by describing the challenges presented by climate change and the chances to generate decarbonised energy by means of renewable energy sources, and then focuses on what the UK's new housing sector can do to support this achievement and to accelerate the transition towards a low carbon built environment. In response, a holistic performance-driven design method for housing is proposed. First, a modelling simulation EPH tool is developed with the potential to be used at early design stages to inform architects and designers about the integration of energy systems into the building design. Once this fundamental step is achieved, research goes forward with the optimised selection of technologies for the EPH system and the design of the EPH design. Finally, the construction of the real case study of the Solcer House allows to evaluate the performance-driven design method by validating the EPH tool against monitored energy data, comparing technologies' real performance against manufacturers' specifications and analysing public opinion and concerns. This last chapter reports the conclusions that resulted from this study, defends the importance of the EPH design for a future low carbon built environment, identifies the barriers of its implementation, proposes further improvements to the performance-driven design method and makes recommendations for further research.

8.1 Response to the research questions

This section briefly answers the specific research questions that were established at the start of this thesis in section 1.4. These are as follows.

8.1.1 HOW TO EMBED ENERGY PERFORMANCE DURING THE DESIGN PROCESS?

Architects face an increased pressure to design low carbon buildings that can meet the challenging goal to decrease the UK's carbon emissions by at least 80% by 2050 (CCC, 2008). Subsequently, there is a growing interest in providing support for low carbon design of buildings via the implementation of new design methods capable to use energy modelling simulation to integrate low carbon technologies into the building design.

This research identifies some of the challenges faced by architects to incorporate energy simulation during the traditional design process and analyses the status of current modelling tools as boundary calculation methods that intercept the communication and cooperation between the team members of a holistic design team, which in many cases are not fully experienced with low carbon buildings design.

Despite the advantages of using energy modelling simulation of buildings being widely accepted in literature, it is also clear that there are difficulties in incorporating modelling in traditional design methods. Two main reasons are identified:

- First, the architect's design thinking usually differs from the performance-driven thinking of energy modellers and engineers; hence an alternative holistic approach is needed towards the low carbon performance of buildings that does not dismiss architectural principles, use and aesthetics.
- Second, the energy modelling tools available on the market are too complicate to use with no-user friendly interfaces, require a high expertise on the field of energy simulation and modelling, ask for too much technical information of the building materials and its energy systems' specifications and produce results that often are too difficult to read and interpret by building designers.

Therefore, the author identifies the need of a simple and user-friendly energy modelling tool, that can be used by all the members of a design team at the early design stage, to run dynamic simulations that automatically generate detailed and easy to read results. The EPH tool aims to allow architects to be more engaged with the low carbon agenda and to design buildings that incorporate low carbon principles at the core of the project.

8.1.2 HOW TO INTEGRATE LOW CARBON TECHNOLOGIES DURING THE DESIGN PROCESS?

Architects should follow three considerations when integrating low carbon technologies to design green buildings with low energy consumption and CO_2 emissions. The three steps are as follows:

- Reduce energy demand by maximizing energy efficiency of new buildings using energy efficient appliances and lighting or making behavioural changes in the use of a building.
- Implement renewable energy technologies capable to generate thermal and electrical energy free of CO_2 emissions. The review of the latest technologies available in the market that are appropriate for the UK's climate identifies solar technologies as the best solution because they can be integrated in buildings, are reliable and are capable to generate both electrical energy and thermal energy.
- Integrate energy storage technologies to increase energy self-sufficiency at times of the day when energy from renewables is not available.

The most appropriate technologies for the EPH system are identified as photovoltaic panels connected to a Lithium-Ion battery, for electrical energy; and transpired solar collectors connected to a compact unit with exhaust air heat pump, MVHR and DHW tank, for thermal energy. The selected energy demand, supply and storage technologies are combined and synchronised to form a connected system which can be implemented and integrated into the EPH design at an early stage, considering the space needed for the battery storage and the heating unit and the full electrical and ductwork design.

8.1.3 HOW TO DESIGN A HOUSE FOR A LOW CARBON BUILT ENVIRONMENT?

During the past fifty years, green architecture has evolved significantly responding to similar needs and circumstances – i.e. conservation of energy and materials, response to climate, assurance of comfort, provision of shelter, reduction of CO_2 emissions and increase of self-sufficiency. Most of the housing projects reviewed from literature are pilot projects for housing exhibitions or technologies demonstration; but cost, technologies reliability and public acceptance have been the main barriers to let these projects hit the mass market.

Alternatively, the EPH design developed in this research aims to be a turning point and have a more replicable, affordable and sustainable approach. The main guidelines of the EPH design are as follows:

- Electrical energy demand is reduced using A+ appliances, LED lighting and highly efficient low carbon technologies for ventilation, space and water heating.

- Heating energy demand is reduced with a fabric-first approach using very high levels of insulation in walls, roofs, floors and windows; and minimising air leaks with good quality design and detailing to avoid unintended gaps and to achieve well sealed junctions.
- Passive solar gains are controlled, managed and optimised to exploit the sun's energy for heating purposes in the heating season and to minimize overheating during the cooling season.
- Energy generation from renewables is integrated and maximised using the building fabric, especially installing solar thermal collectors and PVs in south facing roofs and walls. The integrative approach to designing renewable energy systems as building elements helps to reduce costs and improves aesthetics.
- Energy storage for thermal and electrical energy is installed to increase energy self-sufficiency and reduce dependency from the grid.

The direct and active use of renewable energy, in particular solar radiation, frees the EPH design from the limitations of purely passive strategies. It considers that sometimes it is more economic to compensate for a slightly higher heating demand with the active generation of renewable energy on site. This can potentially avoid installing a disproportionate amount of extra insulation that result in excessively thick walls, installing overpriced triple glazed windows or having compulsory large openings facing south to increase solar gains in winter and therefore avoid the risk of undesirable summer overheating. However, this slightly reduced rigorousness in the thermal insulation standards of the building fabric must not lead to a loss of comfort.

The EPH's performance-driven design approach leaves room for creativity. The EPH design can be freely twisted and modified because is less oriented towards strict requirements. The critical factor is to show an optimised energy balance between generation and consumption, or supply and demand; thus, a building that in the end produces an excess of energy in terms of its energy balance. However, this cannot be applied universally, because it depends on the use, the density of development and the availability of renewable sources.

In conclusion, the proposed EPH design is a sustainable house able to generate around 4,135kWh of electrical energy with renewable energy technologies, an energy positive house able to export around 1,360 kWh of surplus energy to the grid, an energy autonomous house able to store energy to be used during peak or night times, and finally an affordable house that costs around 1,050£/m^2 to build and 7£/year to use it and could be built for the mass market with a long-term certainty.

8.2 Achievement of the research objectives

After the research questions have been answered, this section discusses how these responses have helped to achieve the research objectives that were established at the start of this thesis.

The research described in this thesis contributes to the development of 'Energy Positive Houses' (EPH) as a model that could potentially decarbonise the housing sector and help solving, with a bottom-up approach, the energy trilemma of security of supply, affordability and sustainability. To accomplish this aim, important objectives had to be outlined.

8.2.1 Identify the situation of current research and the barriers and limitations to develop the EPH design in relation to the context of low carbon built environment

The study and review of literature in Chapter 2 addressed this objective and was essential during the first stages of this thesis. Related to this effort, the main lessons learnt from the literature review helped identifying the EPH design's main principles. These are as follows:

- Reduce energy demand: This principle considers that energy inefficiency is a primary cause of fuel poverty (Boardman, 2010), thus any improvements in energy efficiency of the building's fabric and equipment could potentially reduce energy bills while increasing comfort (Middlemiss & Gillard, 2015).
- Remove the use of natural gas and replace it with electricity as a source for heat energy generation: This principle considers the requirement to remove all direct CO_2 emissions from space heating by 2050 (DECC, 2010), owning to the fact that nowadays the two main fuels supplied to a household in the UK are natural gas (62%) used mainly for space and water heating, and electricity (25%) used mainly for lighting and appliances. The aim is to design the EPH as an all-electric house model.
- Incorporate renewable energy generation and energy storage technologies: This principle considers that electricity can be a clean energy locally generated from renewable energy sources and can be stored to ensure the use of electricity and heat at times when the renewable energy sources are not available. The aim is to increase self-consumed renewables electricity while reducing the energy consumed from the grid, thus increase the EPH design's self-sufficiency and autonomy.
- Optimise and integrate low carbon technologies into the building fabric: This principle aims to achieve a replicable, affordable and sustainable EPH design by reducing building costs, materials, resources and embodied carbon.

Literature revealed that the EPH design was not achievable using traditional design methods for standard housing, which led to the need for an alternative architectural design method capable to take a holistic approach towards energy and thermal performance of buildings while ensuring that architectural principles, use and aesthetics are not dismissed. In response, this research develops a performance-driven design method that combines modelling simulation, low carbon technologies performance and architecture design, to achieve an EPH design that could potentially decarbonise the new housing sector. Literature review revealed the main gaps and limitations in current research that needed to be addressed in order to achieve the proposed performance-driven design method. For modelling simulation, the need for a simple and uncomplicated pre-design tool to run dynamic simulations with detailed data generated automatically in a visual environment; for technologies performance, the need for an integrated systems approach to reduced energy demand, building-integrated renewable supply and on-site energy storage; and for architecture design, the need for a replicable, affordable and sustainable design suitable for the UK's climate and able to hit the mass market.

8.2.2 Develop an EPH design method that uses energy modelling to integrate and optimise low carbon technologies into a house design

Initially, in Chapter 4 the EPH tool is developed as a versatile pre-design modelling tool to size renewable energy supply and storage integrated with the grid, to simulate the system's behaviour predicting demand, supply and storage profiles, and to evaluate the system's potential considering autonomy, supply/demand ratio and export/import ratio.

Afterwards, in Chapter 5 the outputs of the modelling are fed into the design of the EPH system, which combines photovoltaic panels (PV) and lithium-ion (LFP) batteries, for electrical energy; and transpired solar collectors (TSC) and a compact unit with exhaust air heat pump (EAHP), mechanical ventilation heat recovery (MVHR) and hot water tank, for thermal energy.

Finally, in Chapter 6 the energy system is integrated into the EPH design, which is built with innovative materials such as low carbon cement, structural insulated panels, insulated render and low-emissivity double-glazed composite windows. The main energy saving strategies for the EPH design are identified in the technologies review section 2.3.1 and the green housing case studies section 2.4. For example, a fabric first approach with high levels of insulation and airtightness (89% of the case studies reviewed in literature) and the use of MVHR (64%), energy efficient appliances (38%) and LED lighting (24%). The EPH design is based on the principles of minimising building's energy losses, its internal energy consumption and exploiting the direct passive use of solar radiation by the building itself. However, these principles are normally not enough in an average year in the UK to provide the building with comfortable living conditions and to supply heating, cooling, ventilation, lighting and electricity throughout the year. These measures are therefore supplemented by the active use of energy from renewable sources, for example from the conversion of solar radiation, ambient heat or wind flows into heat and electricity for the building. Therefore, the EPH design not only saves energy, but is also designed to generate energy from its building envelope and its immediate environment. The EPH design relies less on the usual major external energy supply systems such as power plants. Instead, it uses the high self-sufficiency potential of its immediate environment by optimising the design of its elements to perform efficiently while generating energy.

8.2.3 Evaluate the EPH method to reveal the accuracy of the modelling tool, the efficiency of the energy system and the success of the house design

The built EPH case study, Solcer House, is monitored over different seasons for three years. In Chapter 7, the extensive set of monitored data is used to validate and calibrate the EPH tool so modelling is accurate and reliable; to assess the performance of each component of the EPH system comparing real performance against manufacturers' claims; and to evaluate the holistic performance and the design assumptions of the EPH design to propose future feedback and improvements.

The validation of the EPH tool in section 7.1 shows that the modelled results predicted with the tool are reliable in terms of energy supply and storage, with an average annual accuracy of 92% and 93% respectively. For energy supply, the ±8% error is caused by the weather data source and by the monitoring sensors' uncertainty budget; while for energy storage, the ±7% error is caused by the variable and unpredictable batteries' depth of discharge. On the other hand, the EPH tool's modelled energy demand is significantly different from the Solcer House measured data due to the type of occupancy of the case study as office use, with an average annual accuracy of 84%. Therefore, further validation of energy demand with real housing case studies is recommended, although this is not considered a critical issue because the EPH tool's energy demand profiles refer to the highly reputable '*Household Energy Survey*' and *'24-Hour Profile Chooser Tool'* from DECC (CAR, 2013). Overall, the use of the EPH tool as an early-stage modelling guidance for EPH design is recommended with an accuracy above 90% for energy supply and storage, and above 80% for energy demand.

The assessment of the EPH systems in section 7.2 shows that the integration of all the energy technology components in a systems-based approach improves their individual efficiency and, as a result, the overall performance of the system. When studying electrical energy, results indicate that the all-electric EPH design is energy positive achieving 70% autonomy, 1/1.03 supply/demand ratio and 1:1.13 import/export ratio, even though PV panels efficiency is lower than expected and batteries only use 25% of their full capacity. When examining thermal energy, results show components efficiencies to be 8% for TSC, 78% for MVHR and 3.78 COP for HP. The total energy delivered by the whole thermal system over one year is 10,945kWh with an energy consumption of 2,147kWh, which reveals a significant 5.15 system's COP with a contribution of 42% from the TSC and MVHR.

The assessment of the EPH design in section 7.3 shows that over 80% of the visitors to the Solcer House are impressed with the EPH design and the idea of a replicable and affordable EPH design. However, some questions and concerns are raised in regard to the modern external design, the adaptation of the model to different locations or the influence of the occupants' behaviour, that could prevent the house being replicated in the short term. The work presented in this thesis aims to respond to these concerns to reassure that the EPH design is a viable option when considering low carbon replicable and affordable housing. Regarding the novelty of the project and its technologies, the survey reveals that in general there is a very positive feedback from the public, who would widely accept the implementation of LED lights, building integrated PV panels, MVHR, batteries, TSCs and air source heat pumps.

8.3 Research applications and implications

The work in this thesis develops a performance-driven design method to push the principles of building standards rationally into the future, taking the need for sustainability in buildings fully into account. In addition to an increase in efficiency and moderate behaviour to reduce energy demand, this involves switching to the use of building integrated technologies for the generation of energy and a rethink in the direction of storage of energy. The UK's energy trilemma goals of sustainability, affordability and security of supply are touchstones in the development of the EPH concept and are used as guidance for the EPH's sustainability strategies of low carbon, low cost and high autonomy.

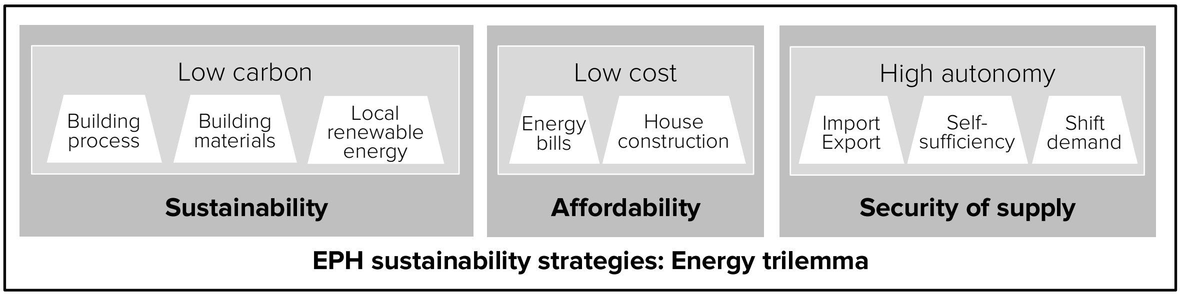


Figure 212 – Diagram showing how the EPH's strategies respond to the UK's energy trilemma.

Research findings confirm that the integration of energy modelling, technologies performance and architecture design has resulted in an accurate EPH tool, an effective EPH system and a successful and viable EPH design that could decarbonise the new housing sector and help solving, with a bottom-up approach, the UK's energy trilemma. The proposed EPH performance-driven design method has the advantage of allowing designers to optimise and integrate low carbon energy technologies into the building from an early-design stage, while leaving room for their creativity. The EPH method is not a quantitatively defined standard, but rather a design strategy that pays attention to both the principles of passive solar as well as the direct and active use of renewable energy, in particular solar radiation, therefore liberating the EPH design from the limitations of purely passive strategies such as the Passivhaus standard.

Usually when householders think about energy consumption they consider only the utilisation stage at the point of use, forgetting about all the other energy processes that happen before the energy ends being used. This means that final users completely ignore not only how the electricity supplied at their home has been previously generated and transmitted but also all the energy losses occurred on these processes. Instead, with the EPH design, the integration of energy technologies into the building allows the user to become involved in the three stages – i.e. generation, transmission and utilisation. With this integrated systems-approach, it is not a matter of knowing how much energy is spent on gas, electricity or petrol; but is a matter of knowing how much sun or wind energy are collected and stored to cover householder's demand. What must be highlighted is that while in the traditional approach the user spends, in the EPH approach the user generates. This is key not only because consumers are engaged on driving for energy efficiency, but also because the three stages occur locally at the building scale reducing the pressure on the generation plants and the stress on the electrical transmission network. Figure 213 shows how the UK's future energy scenario could be if the EPH housing became the mainstream housing model.

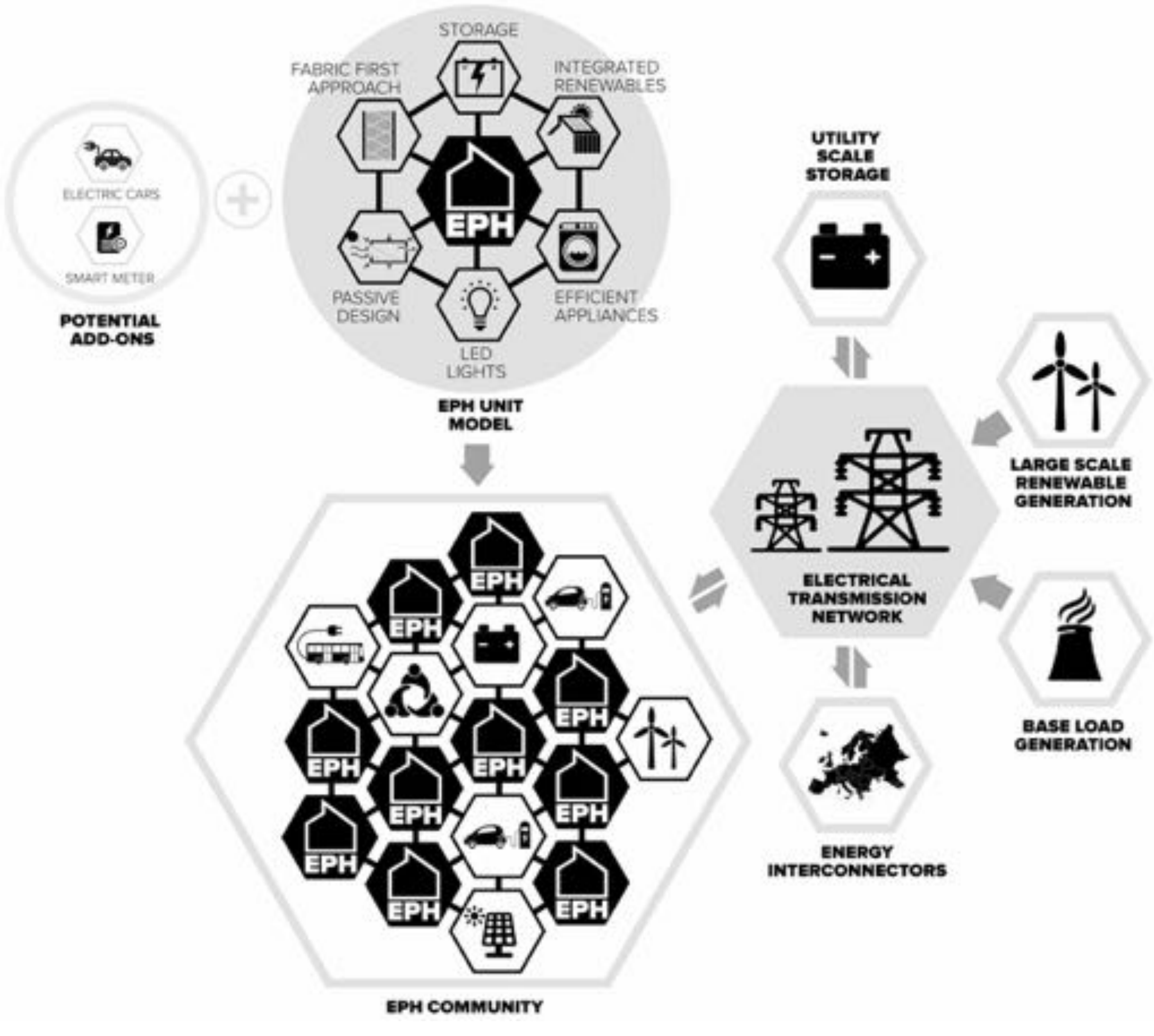


Figure 213 – Diagram showing a hypothetical future low carbon built environment scenario in the UK with the EPH housing model.

The hypothesis presented in Figure 213 shows how the EPH unit could be replicated and interconnected at a community scale linked with other types of low carbon strategies such as electrical charging points for cars and buses, local wind and solar farms, local S.T.O.R. or community energy schemes. The proposed EPH community, with its reduced energy demand and its excess of renewable energy generation being fed into the grid, could represent a real alternative to highly pollutant power stations, such as coal-fired or nuclear plants, which could then be responsible of just the base load generation, thus reduce their contribution to the grid. In an EPH community, space and water heating demand would dramatically drop by 83%, from around 12,000kWh/year per household – i.e. based on typical domestic consumption values for a medium customer (Ofgem, 2017) – to around 2,000kWh/year per EPH household. This reduction would come together with a change of energy source from gas to electricity; hence, electricity demand would also be affected. As a result of the all-electric EPH housing model, electricity demand would slightly rise by 20%, from around 3,100kWh/year per household – i.e. based on typical domestic consumption values for a medium customer (Ofgem, 2017) – to around 4,000kWh/year per household. However, with the EPH approach, this 4,000kWh/year would be mostly generated on-site with building integrated renewable energy technologies, which as a result will reduce the energy supply needed from the grid, with fossil fuels finally disappearing – i.e. oil, coal and natural gas – and an annual energy bill reduced dramatically.

It can be concluded that the proposed EPH housing model, particularly when replicated at a community scale, could help reducing dependence on fossil fuels, mitigating climate change, increasing low carbon energy sources, improving the built environment and reducing fuel poverty; which were the five-main energy related problems that led to the aim of decarbonising the new housing sector. This could not only eliminate current problems of insecurity of energy supply, scarcity of fossil fuels, fuel poverty among population and excess of CO_2 emissions; but could also potentially reduce current problems of housing stock caused by the population growth. Considering the UK Government's aim to build at least 200,000 new homes a year over the next five years to tackle the housing crisis (Federation of Master Builders, 2015); the effect on the UK's national carbon budget will depend on how these new houses are constructed.

Moreover, the benefits of an EPH community and its local energy presented in Figure 213 go far beyond to just solving the UK's energy trilemma of security of supply, sustainability and affordability. The implementation of local energy growth could promote economic growth, generate new income streams, create jobs, regenerate deprived areas, reduce fuel poverty, improve quality of life and health and provide innovative solutions to distributed generation. The EPH design can be regionally driven providing jobs, investment and benefits at a local scale. This bottom-up approach has a direct impact to people's day to day life, especially compared to the more abstract concept of reducing CO_2 emissions or mitigating climate change, which people may not fully understand or may not relate to their daily activities.

8.4 Contribution to knowledge

8.4.1 RESEARCH ORIGINALITY AND NOVELTY

This research develops a new design method that is performance-driven and that could be used by designers to create low carbon energy positive residential buildings and communities; considering the integration of energy modelling, technologies performance and architectural design.

The research provides with an early-design modelling tool to designers that integrates reduced energy demand, integrated renewable energy supply and localised energy storage technologies with a systems approach. This process has the advantage of allowing designers to explore the context of the building such as its orientation and location, the renewable energy sources available and the energy saving strategies to be used; therefore, ensuring that they consider low carbon options at early design stages. The outcomes of the modelling indicate the suitability criteria for different low carbon design strategies under different housing case scenarios. For example, it provides guidance on the choice of suitable technologies for different building scales, occupancy profiles and site locations; revealing favourable and optimised technologies in regard to the house's energy autonomy, energy self-sufficiency, energy savings or energy bills. These modelling outcomes can be incorporated into the conceptual design process, giving guidance to master planners and building designers, yet not interfering with the detailed design of the project.

Considering that there are more detailed and powerful modelling tools already in the market, it was essential that the proposed EPH tool had an easy to use interface that could be used by designers with no specific knowledge or expertise on low carbon design. The design process described in this thesis and the outputs of this investigation provide a guidance tool on the integration of low carbon energy technologies with a systems approach into any housing scheme revealing emerging possibilities in the future. However, a detailed analysis of each housing scheme detailed design would be recommended for each case.

Due to the research scope and timeline constrains not all possible scenarios for low carbon, renewable generation or energy storage technologies could be explored. However, this thesis has provided a basis for understanding how energy demand and supply could be balanced at a building scale and the opportunities available. On the other hand, the tool has only been developed for the UK context and for housing type buildings but ensuring that the methods used are transferable and applicable to other climates and locations as well as to other types of buildings. This work could further inform the development of a software tool, which could incorporate a wider range of low carbon technologies or different future energy scenarios in order to address the integration of low carbon technologies with a systems approach in the UK's future low carbon built environment. By selecting the preferred technology or the criteria regarding the storage system or the relationship between the building and the electrical transmission network, the integration aspects could be predicted, and the optimal technology solution could be revealed.

On another note, the original contribution of this study is also evidenced from the high impact that the built case study Solcer House has had not only in the UK but also abroad. Following the launch of the Solcer House in July 2015, the house was received with significant interest and has been awarded several prizes. The work has been presented on UK National and international TV and radio including the BBC, ITV and BBC World, and articles have been published in a number of British newspapers, EU wide documents and trade articles. It has been presented in national and international conferences to different types of audiences, from academic institutions to industry and government. It featured in a COST Action Smart Energy Regions publication considering Good Practice associated with Supply Chains (Patterson, et al., 2016), in journal papers and in the European Energy Innovation magazine (Europese Commissie, 2015).

8.4.2 RESEARCH LIMITATIONS

The following limitations are identified and recommendations are offered as possible ways to improve this study.

1. When using a real case study, in this case the Solcer House, ensure that it is possible to use it for the real purpose of the building. For example, the funding body conditioned the use of the building to the public use only; hence the Solcer House was occupied as a test facility with daily office-type user profiles. This could reduce the problems related with data validation and data comparison.
2. Although it is costly, it would be more beneficial to use more than one house case study to validate the EPH design. The Solcer House is a good reference to begin with, but a wider variety of occupancy patterns and housing designs, would increase the reliability of the EPH design.
3. Once issues with some of the technologies' performance have been identified, it would be beneficial to correct the problem or to replace the technology for a better version.

4. The EPH tool has been designed as one excel-based spreadsheet that includes all the formulas, calculations, databases and interface screens. At the moment the tool is not available for public use yet, therefore its use and application cannot be tested with designers. To allow this to happen, the excel spreadsheet needs to be converted into an app that could be easily downloaded and used in computers and tablets. However, this will mean to code and convert all the excel data into a web-based app, and this is an expertise that the author does not have.

8.5 Further work

8.5.1 RECOMMENDATIONS FOR RESEARCHERS

The following recommendations are offered for related research in the field of performance-driven architectural design:

1. In the field of energy modelling simulation, additional research is needed on the actual data of household's energy demand, not just monitoring, that allows to better understand different demand patterns and to model the variations due to changes of occupants and their behaviour.
2. In the field of low carbon technologies, additional research is needed on the seasonal variation of the COP of exhaust air heat pumps and on the actual performance of batteries to further prove their cost-effectiveness and to justify their need. Also, given the changing nature of technology, a series of longitudinal studies, based on the review model presented in Chapter 2, would document technology trends and thereby increase the potential that decisions regarding the selection of the technology would be relatively current and less exposed to market bias.
3. In the field of architectural design, additional research is needed to determine the impact of an EPH design approach to see if architectural practices are prepared, in terms of interdisciplinary knowledge and technical skills, to move towards a low carbon built environment with energy positive building designs.
4. While the proposed spheres of modelling/architecture/technologies interaction model consider the energy balance of demand/supply/storage from a housing design viewpoint, it may be advantageous to conduct research which considers other building typologies across this model in the context of different climate zones or future climate scenarios.

8.5.2 RECOMMENDATIONS FOR PRACTITIONERS

The following recommendations are offered for practitioners in the field of architectural design:

1. The EPH tool presented in Chapter 4 of this thesis provides a systematic approach for designing the EPH design with a performance-driven approach. It is recommended that architects and designers, whether interested or not in the sustainability field, use this tool as a basis for evaluating the sustainability potential of their housing designs and optimising their energy systems.

2. Based on the results of this research, it is recommended an energy analysis at early design stages to achieve good design results. Particular attention should be given at the integration of energy technologies into the building envelope to reduce materials and costs, and to optimise the performance of all the building elements.
3. Design characteristics such as quality, adaptability, novelty and functionality are essential to design a good house; but not enough to achieve a good EPH design model. On top of that, key energy characteristics are needed, such as reduced energy demand, optimised renewable energy supply or localised energy storage, as well as a perfect balance between energy demand, supply and storage.

8.5.3 RECOMMENDATIONS FOR POLICY MAKERS AND INDUSTRY

The following recommendations are offered for policy makers and the housing industry:

1. The findings from this study should propel policy makers and industry to develop some method of analysing the cost-benefit ratio between EPH community developments and the beneficial impact of these developments on the lower levels, such as on fuel poverty and housing availability, as well as on the upper levels, such as grid network and housing providers. For example, if EPH houses have an extremely beneficial impact on those living in them in terms of reduced energy bills or comfortable living spaces, but are believed to be too costly by those in charge of budgets; perhaps new avenues of funding for sustainable housing developments could be found or created. Such avenues could include persuading relevant businesses and industries to partner with communities in order to provide grant money to help defray some of the costs for developers and housing providers willing to move towards the EPH design approach.
2. As the UK moves towards the low carbon agenda, the decisions currently being undertaken and plans currently being made by policy makers and construction industry leaders will shape the direction and efficacy of the low carbon agenda for decades to come. This investigation may assist them in their visionary tasks – encouraging them to move towards a bottom-up approach to sustainable housing expeditiously but cautiously.
3. The electricity system is generally described at high level in terms of energy generation, transmission and utilisation. However, future EPH communities should be regarded as a distinct asset class within the electricity system because their localised energy would be interacting with the electrical transmission network in new ways.

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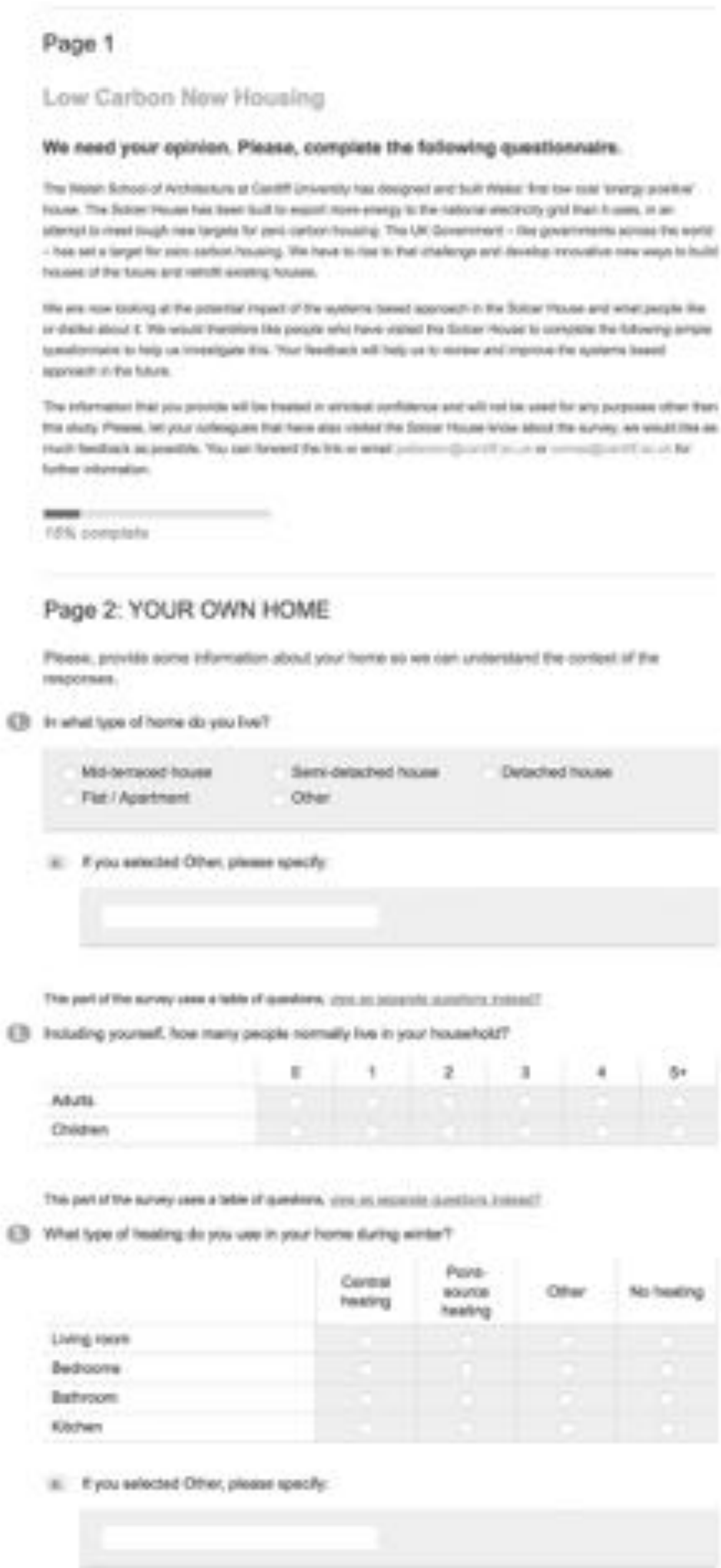
Annex 1: Public Survey

This section's overview is as follows:

1. Survey template.
2. Ethics approval.
3. Survey results.

A1.1 Survey template



Page 1

Low Carbon New Housing

We need your opinion. Please, complete the following questionnaire.

The Welsh School of Architecture at Cardiff University has designed and built Wales' first low cost 'energy positive' house. The Solcer House has been built to export more energy to the national electricity grid than it uses, in an attempt to meet tough new targets for zero carbon housing. The UK Government – like governments across the world – has set a target for zero carbon housing. We have to rise to that challenge and develop innovative new ways to build houses of the future and retrofit existing houses.

We are now looking at the potential impact of the systems based approach in the Solcer House and what people like or dislike about it. We would therefore like people who have visited the Solcer House to complete the following simple questionnaire to help us investigate this. Your feedback will help us to review and improve the systems based approach in the future.

The information that you provide will be treated in strictest confidence and will not be used for any purposes other than this study. Please, let your colleagues that have also visited the Solcer House know about the survey, we would like as much feedback as possible. You can forward the link or email [illegible] or [illegible] for further information.

15% complete

Page 2: YOUR OWN HOME

Please, provide some information about your home so we can understand the context of the responses.

In what type of home do you live?

- Mid-terraced house
- Semi-detached house
- Detached house
- Flat / Apartment
- Other

a. If you selected Other, please specify:

This part of the survey uses a table of questions, view as separate questions instead?

Including yourself, how many people normally live in your household?

	0	1	2	3	4	5+
Adults						
Children						

This part of the survey uses a table of questions, view as separate questions instead?

What type of heating do you use in your home during winter?

	Central heating	Point-source heating	Other	No heating
Living room				
Bedrooms				
Bathroom				
Kitchen				

a. If you selected Other, please specify:

What is the main fuel source you use for heating your home?

Gas	Electric	Biomass
Oil	Other	

a. If you selected Other, please specify:

Do you have renewable energy **supply** and/or energy **storage** at your home?

Solar photovoltaic panels	Solar thermal panels	Wind turbine
Biomass boiler	Air source heat pump	Ground source heat pump
Battery storage	None	Other

a. If you selected Other, please specify:

Do you have energy efficiency **demand** reduction technologies at your home?

LED lighting	Mechanical ventilation heat recovery (MVHR)	A+ appliances
Insulation on walls	Insulation on roof	Triple glazing
None	Other	

a. If you selected Other, please specify:

This part of the survey uses a table of questions. [illegible]

Do you have plans for any of the following in the next 12 months? Or in the next 5 years? *(pick all that apply)*

	No	Next 12 months	Next 5 years
Install energy-saving or low-carbon products or technologies (e.g. wall insulation, loft insulation, solar panels)			
Try to save energy through actions and habits of my household (e.g. turn off unwanted lights and appliances)			
Measure and monitor energy more actively (e.g. read meters regularly, get a display device)			
Get a home energy audit or energy performance certificate done			
Move home			

a. Please, provide further comments and suggestions.

Page 3: THE SOLCER HOUSE - Awareness

Have you visited the Solcer House?

- Yes
- No

a. How many times?

- 1
- 2
- 3 or more

b. What motivated you to visit the Solcer House?

- General interest in buildings
- General interest in sustainability
- Already doing a building or renovation project
- Plan or research a building or renovation project
- Find out how to save money on bills
- Meet others with similar interests
- Feel part of my local community
- Accompany someone else
- Work-related interest in visiting (paid or voluntary work)
- See what can be done to eco-renovate a home
- Have a property that is similar to this one
- Experience the home on the inside
- Find out about products and technologies used
- Find out about the energy-savings
- Recommendations of products, suppliers or installers for my own project
- Meet the occupiers
- Find out about the cost
- Specific questions to ask
- Other

i. If you selected Other, please specify:

This part of the survey uses a table of questions, view as separate questions instead?

c. How satisfied are you with your visit / tour around the Solcer House? (0) for low value and (5) for high value

More info

	0 (low)	1	2	3	4	5 (high)
Was it useful?						
Would you recommend it?						

How did you you hear about the Solcer House?

- Word of mouth
- Conference
- Flyer / poster
- Newspaper / magazine
- Web search
- Social media (e.g. Facebook/Twitter)
- Radio / TV
- Email / e-newsletter
- Other

a. If you selected Other, please specify:

Please, provide further comments and suggestions regarding your visit Optional

50% complete

Page 4: THE SOLCER HOUSE - Performance and Cost

Please, if you need more information or details about the Solcer House before answering this section, have a look at the Solcer House brochure.

This part of the survey uses a table of questions, view as separate questions instead?

How much do you value each of the following features of the Solcer House? (0) for low value and (5) for high value.

	0 (low)	1	2	3	4	5 (high)
Comfortable indoor environment						
Low cost of energy bills						
Low maintenance of home						
Low environmental impact						

This part of the survey uses a table of questions, view as separate questions instead?

Thinking about preference of technologies installed in the Solcer House, could you value the following if you were going to build a Solcer type house with a limited budget? (0) for low value and (5) for high value.

	0 (low)	1	2	3	4	5 (high)
Photovoltaic Panels						
Transpired solar air collectors						
Air source heat pump						
Batteries						
LED lighting						
Mechanical ventilation heat recovery (MVHR)						

This part of the survey uses a table of questions, view as separate questions instead?

Thinking about preference of technologies NOT installed in the Solcer House, could you prioritise the following if you were going to build a Solcer type with a limited budget? (0) for low value and (5) for high value.

	0 (low)	1	2	3	4	5 (high)
Solar thermal panels						
Wind turbine						
Ground source heat pump						
Biomass boiler						
Underfloor heating						
Radiators						
Other						

a. If you selected Other, please specify:

What sort of evidence would help to convince you to build a a Solcer type house in the future? *(0) for low value and (5) for high value.*

	0 (low)	1	2	3	4	5 (high)
Low energy bills						
Low impact on the environment						
Low maintenance costs						
User-friendly systems						
Long-term guarantee						
Long-life span						
Energy incentives						
Mortgage incentives						
Funding incentives						
Other						

a. If you selected Other, please specify:

[illegible]% complete

Page 5: THE SOLCER HOUSE - Aesthetics and Space features

This part of the survey uses a table of questions, view as separate questions instead?

Is the Solcer House design pleasing to you? *(0) for low value and (5) for high value.*

	0 (low)	1	2	3	4	5 (high)
Aesthetically						
Functionally						
Practically						
Spatially						
Externally						
Internally						

a. Please, provide further comments and suggestions for future designs. *Optional*

This part of the survey uses a table of questions, view as separate questions instead?

What issues do you think the Solcer House might pose if you wanted to build it? *(0) for low concern (5) for high concern.*

	0 (low)	1	2	3	4	5 (high)
It looks too modern						
It looks too different						
It could be difficult to maintain						
It could be difficult to operate						
It could be difficult to gain planning permission						
It could be difficult to sell						
It could be difficult to get mortgage						

Please, provide further concerns you may have. Optional

This part of the survey uses a table of questions, view as separate questions instead?

How much do you value each of the following features of the house?(0) for low value and (5) for high value.

	0 (low)	1	2	3	4	5 (high)
External render wall finish						
Integrated transpired solar air collector						
Integrated photovoltaic roof (South)						
Standing seam metal roof (North)						
Timber frame aluminium clad windows						
Size and location of windows (South)						
Size and location of windows (North)						
Openable windows in roof-attic space						
Extra area in roof-attic space						
Natural light in roof-attic space						
Access with built-in staircase to roof-attic space						
Access between kitchen-utility-living spaces						
Relatively higher ceiling height						
Extra cupboard storage space						
Greater flexibility of space due to no radiators						

Please, let us know if you have any comments. Optional

83% complete

Page 6: YOUR BACKGROUND

Finally, please provide some information about your background so we can understand the context of the responses. All information that you provide will be treated as STRICTLY CONFIDENTIAL.

What is the location of your home address?

- Wales
- England
- Scotland
- Northern Ireland
- Other country in Europe
- North-America
- South America
- Asia
- Africa
- Australia


What is your gender?

- Woman
- Man

Which of the following age brackets do you belong to?

- Under 18
- 18 – 25 years
- 26 – 35 years
- 36 – 45 years
- 46 – 55 years
- 56 – 65 years
- 66 years or above

What is the nature of your interest in the Solcer house, as a/an ...?

- Energy provider
- Policy maker
- Researcher
- Occupier
- Buyer
- Designer
- Self-builder
- House builder
- Developer
- Public sector housing
- Private sector housing
- Building components manufacturer
- Other

a. If you selected Other, please specify:

If you wish to be contacted to participate in follow up research about Solcer House or other similar projects, please leave us your email address.

‹ Previous

Finish ✓

100% complete

THIS IS THE END OF THE QUESTIONNAIRE THANK YOU VERY MUCH FOR YOUR HELP!

Please, contact us if you have any questions or would like to know about the project.

Jo Patterson -

Ester Coma -

The Solcar House project constructed by Cardiff University was funded by the Welsh European Funding Office (WEFO).

This survey prepared by Cardiff University has been funded by Engineering & Physical Sciences Research Council (EPSRC).

Powered by BOS | Copyright | Survey contact details

A1.2 Ethics approval

WELSH SCHOOL OF ARCHITECTURE
ETHICS APPROVAL FORM FOR STAFF AND PHD/MPHIL PROJECTS

Tick one box:	☑ STAFF ☐ PHD/MPHIL
Title of project:	EPSRC Impact Acceleration Account: Solcer House – from demonstrator to real world
Name of researcher(s):	Ester Coma Bassas
Name of principal investigator	Prof. Phil Jones and Dr. Jo Patterson
Contact e-mail address:	comae@cardiff.ac.uk
Date:	11th May 2016

Participants		YES	NO	N/A
Does the research involve participants from any of the following groups?	• Children (under 16 years of age)		✓	
	• People with learning difficulties		✓	
	• Patients (NHS approval is required)		✓	
	• People in custody		✓	
	• People engaged in illegal activities		✓	
	• Vulnerable elderly people		✓	
	• Any other vulnerable group not listed here		✓	
• When working with children: I have read the Interim Guidance for Researchers Working with Children and Young People (http://www.cardiff.ac.uk/archi/ethics_committee.php)				✓

Consent Procedure	YES	NO	N/A
• Will you describe the research process to participants in advance, so that they are informed about what to expect?	✓		
• Will you tell participants that their participation is voluntary?	✓		
• Will you tell participants that they may withdraw from the research at any time and for any reason?	✓		
• Will you obtain valid consent from participants? (specify how consent will be obtained in Box A)[1]	✓		
• Will you give participants the option of omitting questions they do not want to answer?	✓		
• If the research is observational, will you ask participants for their consent to being observed?			✓
• If the research involves photography or other audio-visual recording, will you ask participants for their consent to being photographed / recorded and for its use/publication?			✓

Possible Harm to Participants	YES	NO	N/A
• Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?		✓	
• Is there any realistic risk of any participants experience a detriment to their interests as a result of participation?		✓	

Data Protection		YES	NO	N/A
• Will any non-anonymous and/or personalised data be generated or stored?			✓	
• If the research involves non-anonymous and/or personalised data, will you:	• gain written consent from the participants			✓
	• allow the participants the option of anonymity for all or part of the information they provide			✓

Health and Safety	YES
Does the research meet the requirements of the University's Health & Safety policies? (http://www.cf.ac.uk/osheu/index.html)	✓

Research Governance	YES	NO	N/A
Does your study include the use of a drug? You need to contact Research Governance before submission (resgov@cf.ac.uk)		✓	
Does the study involve the collection or use of human tissue? You need to contact the Human Tissue Act team before submission (hta@cf.ac.uk)		✓	

[1] If any non-anonymous and/or personalised data be generated or stored, written consent is required.

If any of the shaded boxes have been ticked, you must explain in Box A how the ethical issues are addressed. If none of the boxes have been ticked, you must still provide the following information.
The list of ethical issues on this form is not exhaustive; if you are aware of any other ethical issues you need to make the SREC aware of them.

Box A The Project (provide all the information listed below in a separate attachment)

1. Title of Project

EPSRC Impact Acceleration Account: Solcer House – from demonstrator to real world

2. Purpose of the project and its academic rationale

This project would respond to market led questions already raised by stakeholders to encourage the uptake of the Solcer House in the real world.

3. Brief description of methods and measurements

The house has received over 500 visitors since July from a broad range of organisations Visitors have included The Chinese Vice Premier of the People's Republic of China, Liu Yangdong, Registered Social Landlords, architectural practices, manufacturing companies, construction institutions, a range of departments from Welsh Government, Natural Resources Wales and other academic institutions.
The visitors have expressed interest in replicating the building at other locations in Wales, the UK and further afield, using the house to lobby government to influence policy and using the House as a demonstrator to inform future practitioners on the incorporation of low carbon technologies into buildings. This has projected Cardiff University in a very positive light in moving forward low carbon policy in the building sector in Wales and stimulating the widescale roll out of replicable and affordable low energy housing.

4. Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria

During the visitors' attendance to the Solcer House visits, we asked them their contact details so we could approach them for feedback and they voluntarily gave their details to the project. We are now approaching them with an online survey in order to gather as much feedback as possible.

5. Consent and participation information arrangements - please attached consent forms if they are to be used

As stated above, all the participants to the survey gave their email addresses voluntarily during the various Open Days events that have been held in the Solcer House.

6. A clear and concise statement of the ethical considerations raised by the project and how is dealt with them.

Initial statement used as an introduction to the survey:

The Welsh School of Architecture at Cardiff University has designed and built Wales' first low cost "energy positive" house. The Solcer House has been built to export more energy to the national electricity grid than it uses, in an attempt to meet tough new targets for zero carbon housing. The UK Government – like governments across the world – has set a target for zero carbon housing. We have to rise to that challenge and develop innovative new ways to build houses of the future and retrofit existing houses.

We are now looking at the potential impact of the systems based approach in the Solcer House and what people like or dislike about it. We would therefore like people who have visited the Solcer House to complete the following simple questionnaire to help us investigate this. Your feedback will help us to review and improve the systems based approach in the future.

The information that you provide will be treated in strictest confidence and will not be used for any purposes other than this study. Please, let your colleagues that have also visited the Solcer House know about the survey, we would like as much feedback as possible. You can forward the link or email patterson@cardiff.ac.uk or comae@cardiff.ac.uk for further information.

7. Estimated start date and duration of project.

February to June 2016

All information must be submitted along with this form to the School Research Ethics Committee for consideration

Researcher's declaration (tick as appropriate)	
• I consider this project to have **negligible ethical implications** (*can only be used if none of the grey areas of the checklist have been ticked*)	✓
• I consider this project research to have **some ethical implications**.	
• I consider this project to have **significant ethical implications**	

Signature		**Name**	Ester Coma Bassas	**Date**	11/5/16
Researcher or MPhil/PhD student					
Signature		**Name**	Dr. Jo Patterson	**Date**	11/5/16
Lead investigator or supervisor					

Advice from the School Research Ethics Committee

STATEMENT OF ETHICAL APPROVAL					
This project had been considered using agreed Departmental procedures and is now approved					
Signature		**Name**	JULIET DAVIS	**Date**	24.05.16
Chair, School Research Ethics Committee					

A1.3 Survey results

Showing 88 of 88 responses
Showing **all** responses
Showing **all** questions
Response rate: 17%

Summary | Browse responses | Views | Advanced

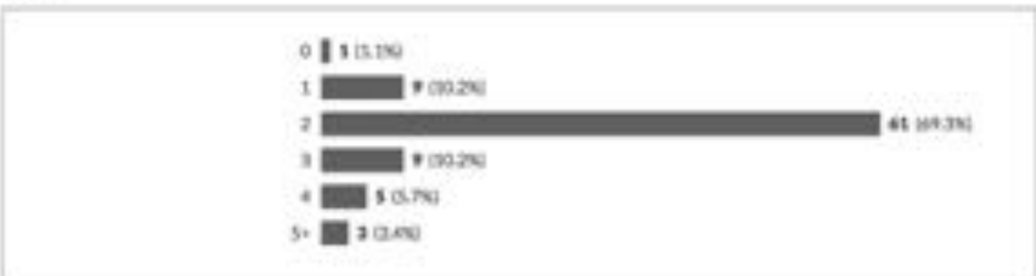
1 In what type of home do you live?

1.a If you selected Other, please specify:

Showing all 6 responses Show less	
End of terrace converted chapel	197987-197980-12990568
Detached Bungalow	197987-197980-14101763
dormer detached bungalow	197987-197980-14104993
End of terrace	197987-197980-14133100
End of terrace	197987-197980-14136968
not relevant	197987-197980-14194190

2 Including yourself, how many people normally live in your household?

2.1 Adults



2.2 Children

3 What type of heating do you use in your home during winter?

3.1 Living room

3.2 Bedrooms

3.3 Bathroom

3.4 Kitchen

3.a If you selected Other, please specify:

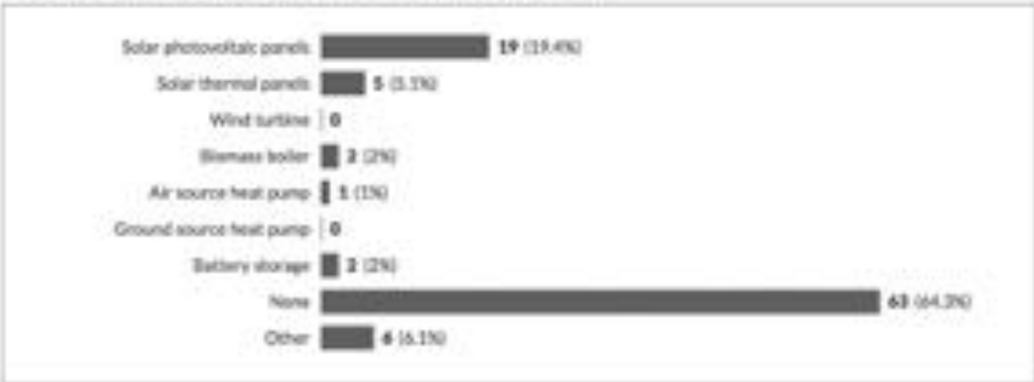
Showing all 11 responses Show less	
Wood burning fire in living room	197987-197980-13985034
underfloor heating	197987-197980-14104842
not relevant	197987-197980-14194190
multi fuel burner	197987-197980-14198207
13 solar panels	197987-197980-14207183
wood burning stove	197987-197980-14208689
Gas fire and wood burner	197987-197980-14214608
2 x wood burners in house - living rooms	197987-197980-14218278
wood burner	197987-197980-14220883
Water based underfloor	197987-197980-14227390
Electric underfloor heat	197987-197980-14279307

4 What is the main fuel source you use for heating your home?

4.a If you selected Other, please specify:

Showing all 3 responses	
Solid Fuel	197987-197980-14107694
ditto	197987-197980-14194190
LPG	197987-197980-14306238

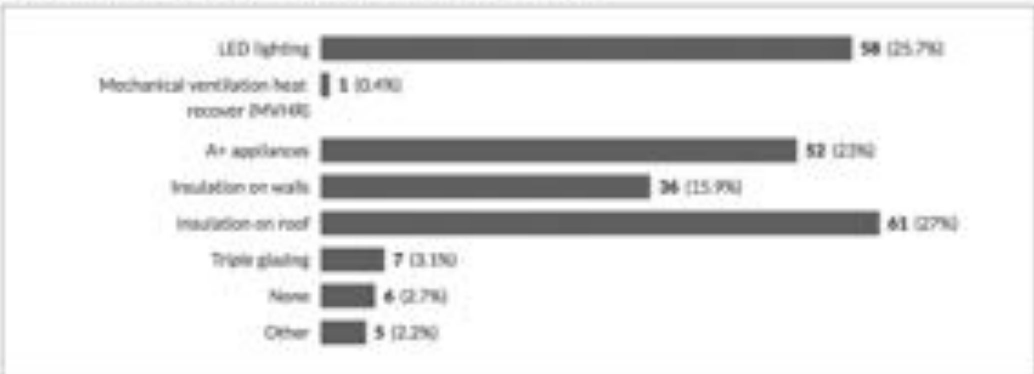
5 Do you have renewable energy supply and/or energy storage at your home?



5.a If you selected Other, please specify:

Showing all 6 responses Show less	
fuel cell	197987-197980-13983511
biomass heater	197987-197980-13984270
Biomass (Wood)	197987-197980-14101538
ditto	197987-197980-14194190
Immersun for hot water	197987-197980-14206089
Renewable energy supply from Good Energy	197987-197980-14220885

6 Do you have energy efficiency demand reduction technologies at your home?

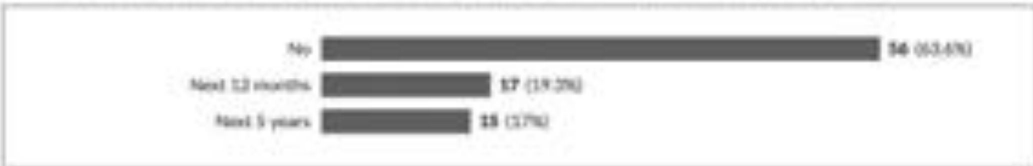


6.x If you selected Other, please specify:

Showing all 5 responses	
volt op	197987-197980-14083468
cavity wall, loft insulation,double glazing	197987-197980-14104993
ditto	197987-197980-14194190
Underfloor insulation	197987-197980-14214608
Energy monitor, electric car	197987-197980-14220881

7 Do you have plans for any of the following in the next 12 months? Or in the next 5 years? (tick all that apply)

7.1 Install energy-saving or low-carbon products or technologies (e.g. wall insulation, loft insulation, solar panels)



7.2 Try to save energy through actions and habits of my household (e.g. turn off unwanted lights and appliances)

7.3 Measure and monitor energy more actively (e.g. read meters regularly, get a display device)

7.4 Get a home energy audit or energy performance certificate done

7.5 Move home

7.a Please, provide further comments and suggestions.

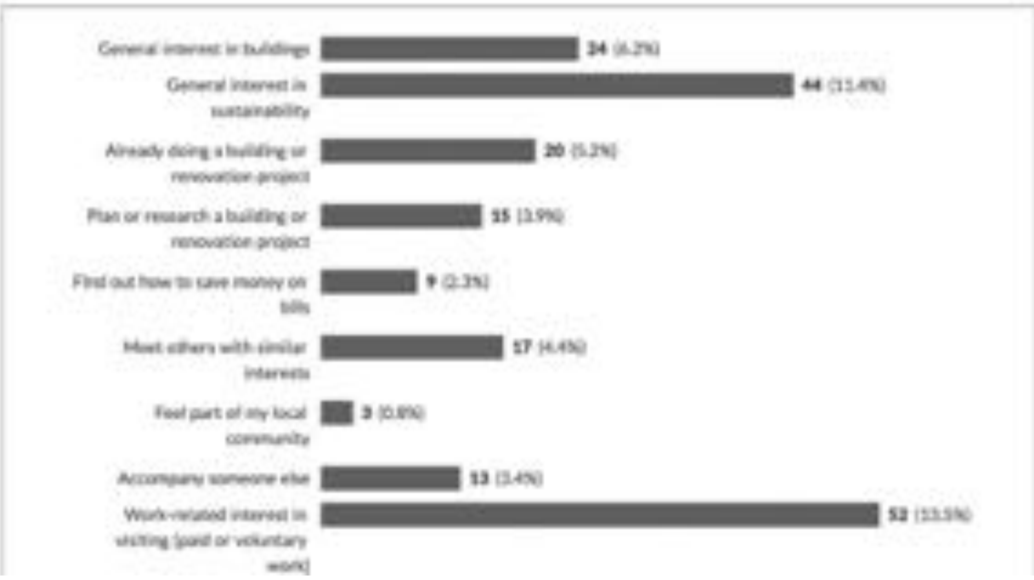
Showing all 21 responses Show less	
I have selected no as I have already done them	197987-197980-13983465
I will be building a new dwelling next year	197987-197980-13983876

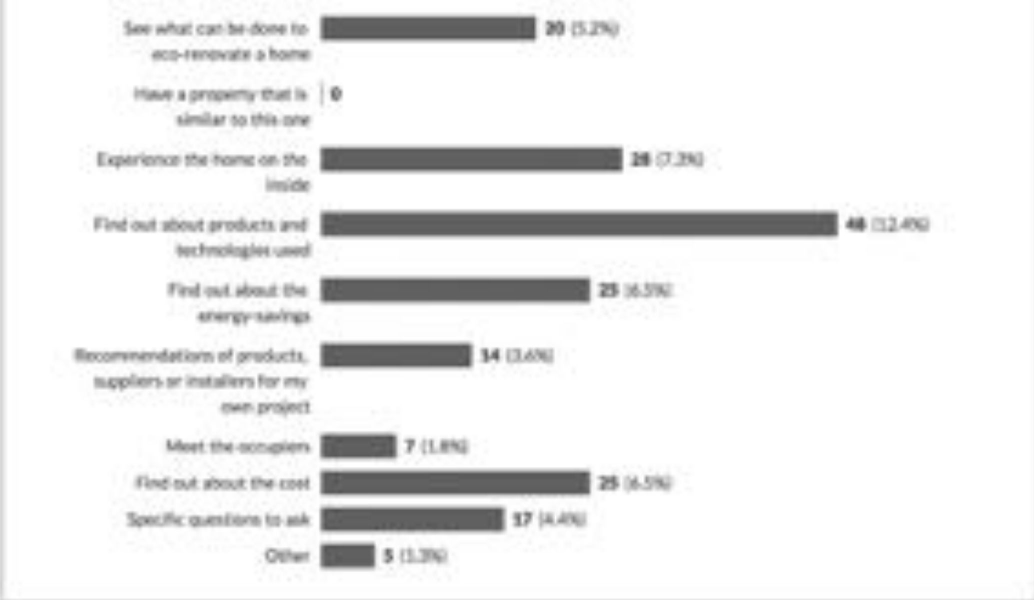
House not suitable for solar Pv	[illegible]
already done most of these	[illegible]
improve airtight rating of structure; already know energy audit	[illegible]
already do items 2 and 3 in everyday actions and have EPC	[illegible]
in a conservation area the alterations possible are limited	[illegible]
In a conservation area - external mods difficult	[illegible]
Air source heat pump, ground source heat pump	[illegible]
The house we live in is five years old, so is relativley well insulated and efficient	[illegible]
Considering under floor heating	[illegible]
ditto	[illegible]
I live in an area where I cannot modify the outside of my house which is a challenge!	[illegible]
move to smaller property more suited to single person living	[illegible]
Solcer House inspirational. It will feature in a forthcoming clog from 'Sustainable Wales'	[illegible]
We already monitor energy weekly	[illegible]
New Windows possibly triple glazed and possibly battery storage as the pv is battery ready	[illegible]
Just moved home here to care for aged parent in her home, so not possible to make changes	[illegible]
acclimatising to lower internal winter temperatures.	[illegible]
I rent so can't make improvements to fabric of house. Planning to move off grid	[illegible]
we hope to build a passiv haus in our locality, land already purchased , collecting data now	[illegible]

6 Have you visited the Solcer House?

6.a How many times?

6.b What motivated you to visit the Solcer House?





8.b.1 If you selected Other, please specify:

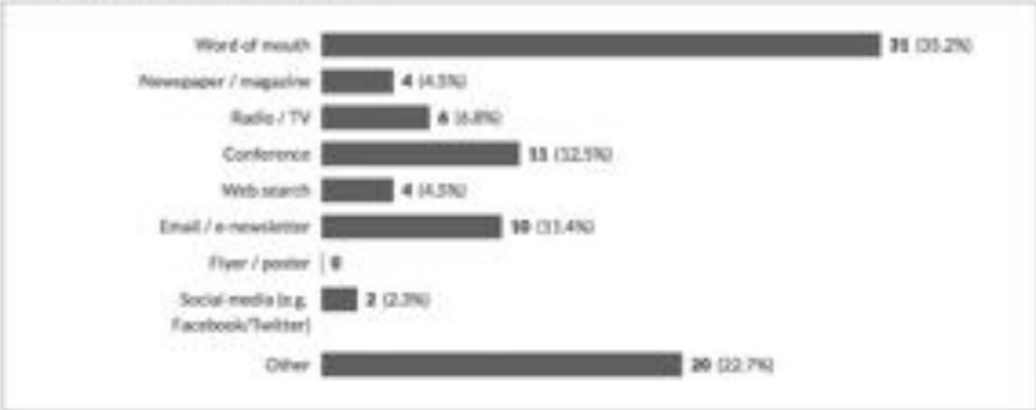
Showing all 5 responses	
Insulation supplier/project partner	197987-197980-14008034
Our EWI system (Knauf) was used at 1, Galltcwm Terrace in Bryn. I visited site to monitor the installation and also to meet other parties who were involved	197987-197980-14049362
I was the sips contractor	197987-197980-14111283
Solcer Partner	197987-197980-14198225
Part of the team	197987-197980-14207101

8.c How satisfied are you with your visit / tour around the Solcer House? (0) for low value and (5) for high value.

8.c.1 Was it useful?

8.c.2 Would you recommend it?

9 How did you you hear about the Solcer House?



9.a If you selected Other, please specify:

Showing all 20 responses Show less	
Involved with the construction process	197987-197980-13983430
SPECIFIC	197987-197980-13983465
I was the lead on-site electrician for the build	197987-197980-13983744
Work with Cardiff university on several projects	197987-197980-13983578
Introduced / awareness by Cenin	197987-197980-13986033
Involved in project	197987-197980-14008036
Through Warm Wales	197987-197980-14049362
Planning Application	197987-197980-14100801
Work	197987-197980-14102935
We carried out some work on the property	197987-197980-14102979
Invited to tender	197987-197980-14106239
Worked on the construction	197987-197980-14111283
through my work	197987-197980-14122699
Through my work, I am involved with the project	197987-197980-14133322
work	197987-197980-14198133
Partner	197987-197980-14198225
Planning Application	197987-197980-14198207
Invite	197987-197980-14215892
Supplier of the ventilation/heating system	197987-197980-14220484
Worked on it	197987-197980-14279715

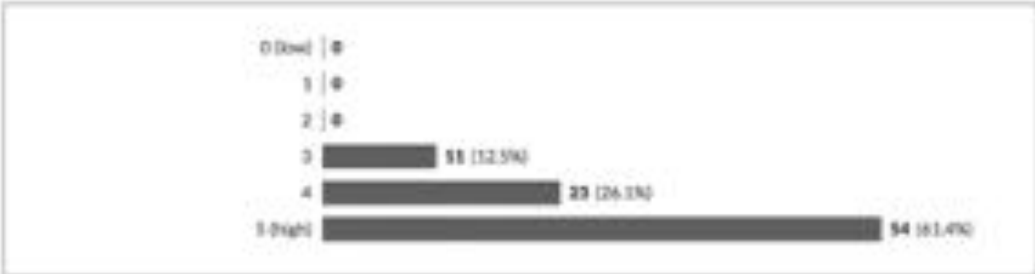
10 Please, provide further comments and suggestions regarding your visit

Showing all 18 responses Show less	
A list of detailed costs of products use	197987-197980-13983876
hard to believe <£1000/sqm, sorry to say	197987-197980-13984658
The two guides were lovely	197987-197980-13985034
Visit was very informative and inspiring	197987-197980-13986381
I seek feedback on reliability and systems management	197987-197980-13986547
Innovation colleague advised	197987-197980-13991024
I would like to see data on performance across different seasons	197987-197980-13990968

I would like to see data on performance across different seasons	197987-197980-13990968
It was a great opportunity to see how the sustainable technologies can be integrated into a house to reduce energy consumption	197987-197980-14017299
aplicability to social housing removing people from fuel poverty	197987-197980-14104993
Little about SMARTtechnology or integration with EV vehicles. No understanding of how	197987-197980-14118887
The house is very impressive; the only minor issue is finding it so some additional labelling etc and checking the fit to all sat navs would be good	197987-197980-14198225
The house is a new build, it was built with sustainability in mind and it was designed around the latest technologies. Most of the technologies used are not transferrable or replicable in existing homes. If you want people to be inspired to effect those changes in their own homes, you need to a) make that link for them and b) show them how. Providing a take away nudge list prompting them to consider their own insulation, solar panels, windows, heating systems etc. may help them consider taking action.	197987-197980-14201493
We need more such houses	197987-197980-14207183
Presenter excellent. Time too short.	197987-197980-14216076
I would like a technical specification pack for all elements.	197987-197980-14219882
Didn't realise on an industrial estate - would be good to also have options to visit the AD and low carbon cement works. Was disappointed that the materials used in the house were not more low embodied energy/natural based	197987-197980-14220885
we were inspired and encouraged at what can be achieved on a relatively low budget.	197987-197980-14251930
Should be advertised more widely	197987-197980-14306258

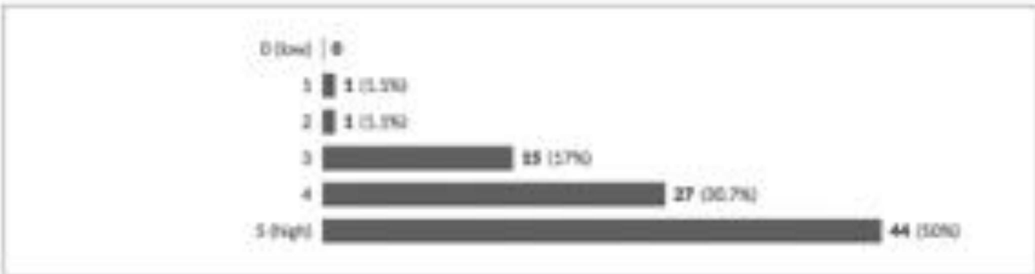
11 How much do you value each of the following features of the Solcer House? (0) for low value and (5) for high value.

11.1 Comfortable indoor environment



11.2 Low cost of energy bills

11.3 Low maintenance of home



11.4 Low environmental impact

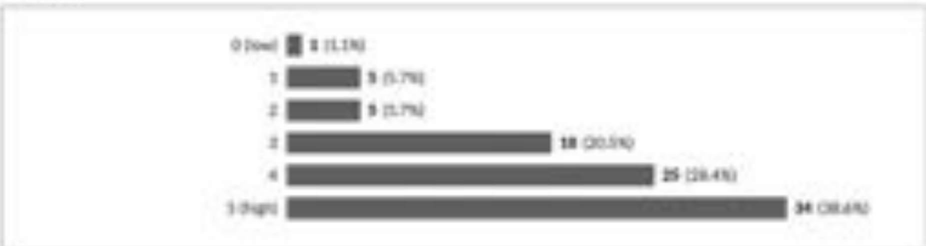
12 Thinking about preference of technologies installed in the Solcer House, could you value the following if you were going to build a Solcer type house with a limited budget? (0) for low value and (5) for high value.

12.1 Photovoltaic Panels

12.2 Transpired solar air collectors

12.3 Air source heat pump

12.4 Batteries



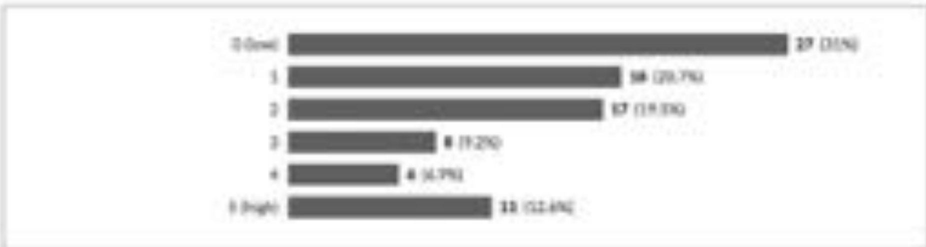
LED lighting

Mechanical ventilation heat recovery (MVHR)

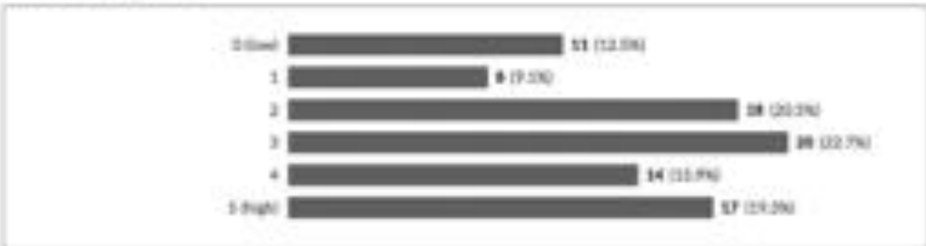
13 Thinking about preference of technologies NOT installed in the Solcer House, could you prioritise the following if you were going to build a Solcer type with a limited budget? (0) for low value and (5) for high value.

13.1 Solar thermal panels

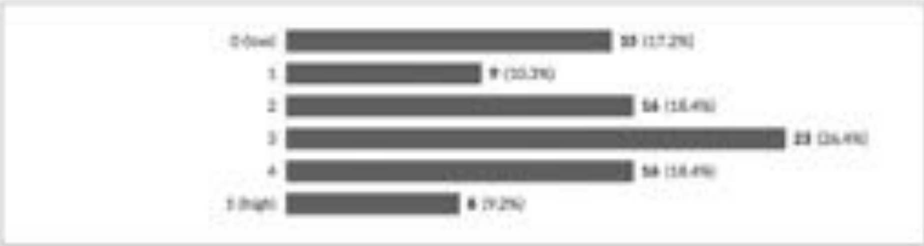
13.2 Wind turbine



13.3 Ground source heat pump

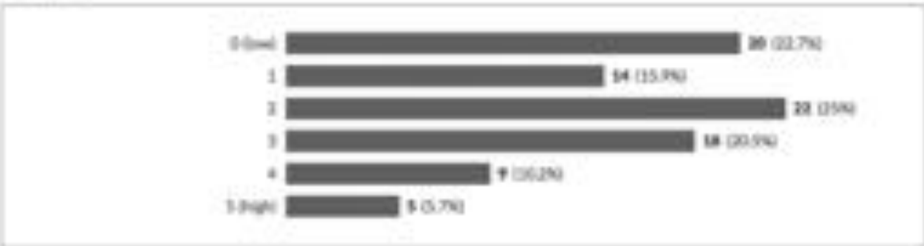


13.4 Biomass boiler



13.5 Underfloor heating

13.6 Radiators



13.7 Other

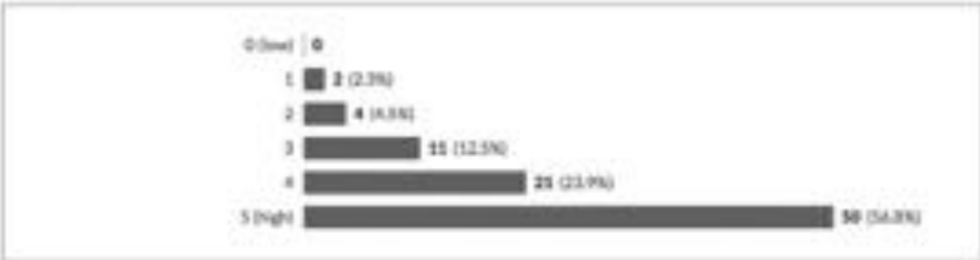
13.8 If you selected Other, please specify:

Showing all 11 responses Show less	
Gel state or infra red heating / Aquion battery technology / optimised BIPV solar array	[illegible]
Heat recovery from waste water	[illegible]
Timber frame construction	[illegible]
Aspect and using heat storage technology	[illegible]
Hydro technology	[illegible]
would be nice if we could explore a waste to energy system	[illegible]
Hybrid Boiler	[illegible]
For both question 12 and 13 I would have to carry out research into the suggested technologies to compare the outlay to the efficacy and long term savings.	[illegible]
Extra underfloor heating ,non fossil fuel where possible	[illegible]
Use of nearby hydro electric (on a small scale) from nearby river	[illegible]
Was sad to see not many low environmental impact products used in the house eg most materials were high carbon/petrochemical based and not eco friendly natural products like sheep wool insulation from Wales	[illegible]

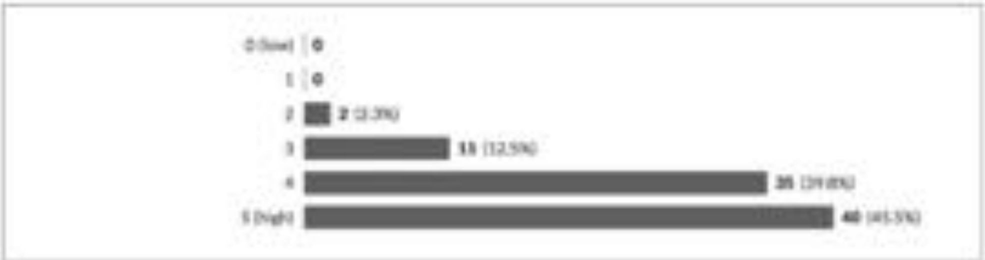
14 What sort of evidence would help to convince you to build a a Solcer type house in the future? (0) for low value and (5) for high value.

14.1 Low energy bills

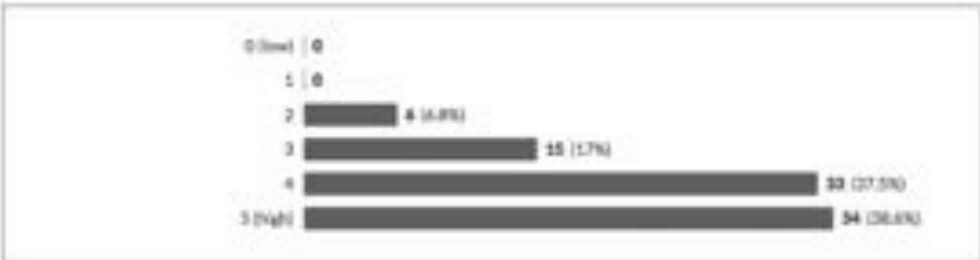
14.2 Low impact on the environment



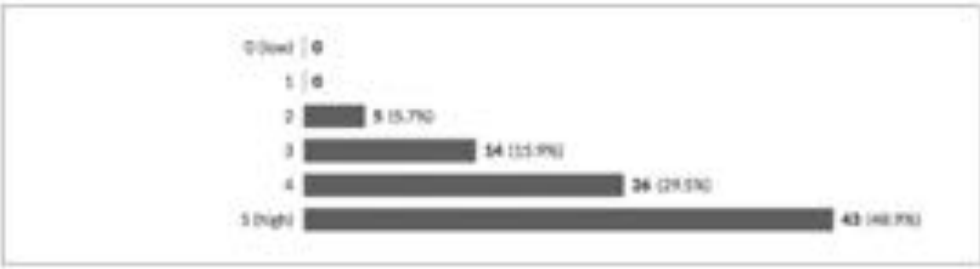
14.3 Low maintenance costs



14.4 User-friendly systems

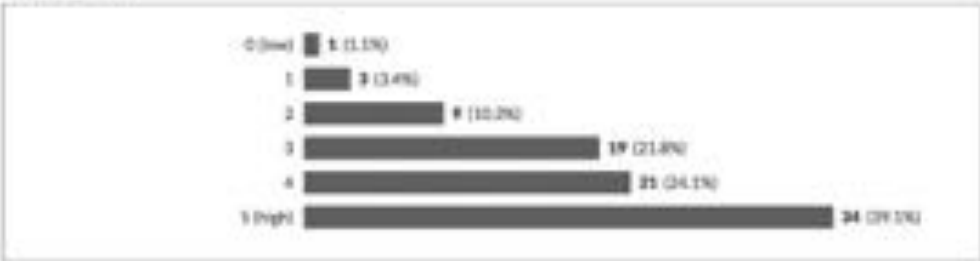


14.5 Long-term guarantee

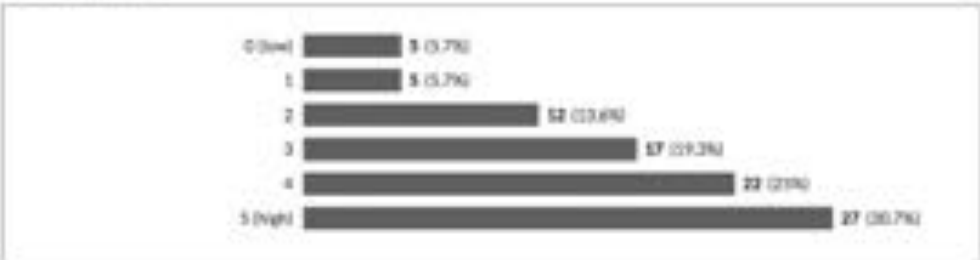


14.6 Long life span

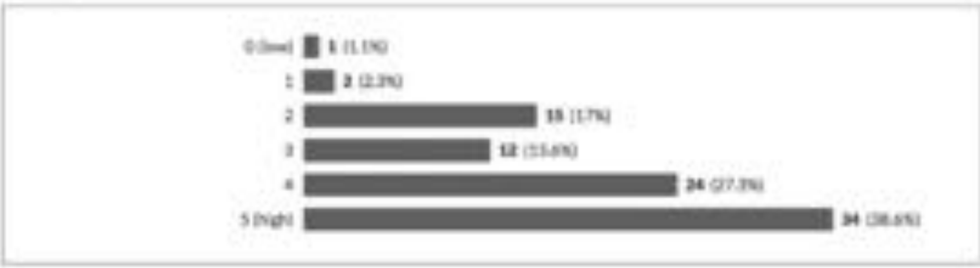
14.7 Energy incentives



14.8 Mortgage incentives



14.9 Funding incentives



14.10 Other

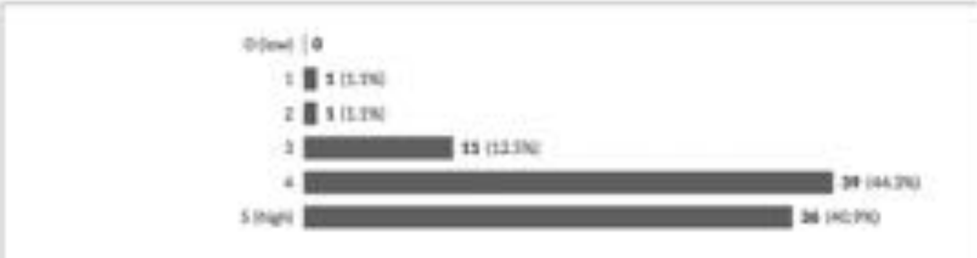
14.a If you selected Other, please specify:

Showing all 6 responses Show less	
comfortable, controllable, stable, efficient, living quarters	[illegible]
Aesthetic value	[illegible]
Again it would help if you supplied people with a list of approved suppliers/contractors as it is complicated.	[illegible]
Long term affordable but controls need to be minimised as tenants often find them tricky.	[illegible]
Seen in positive light by planning authorities.	[illegible]
Low cost to build.	[illegible]

15 Is the Solcer House design pleasing to you? (0) for low value and (5) for high value.

15.1 Aesthetically

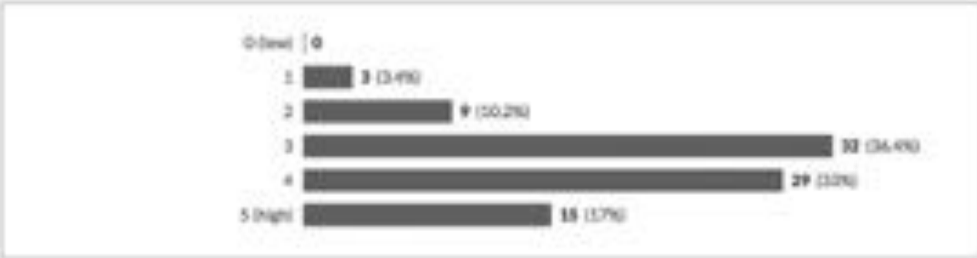
15.2 Functionally



15.3 Practically

15.4 Spatially

13.5 Externally



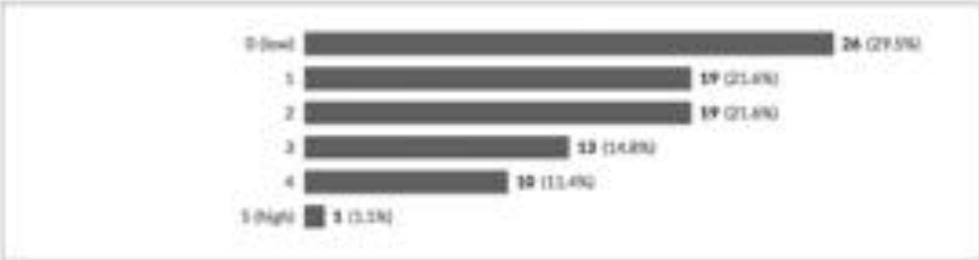
13.6 Internally

13.a Please, provide further comments and suggestions for future designs.

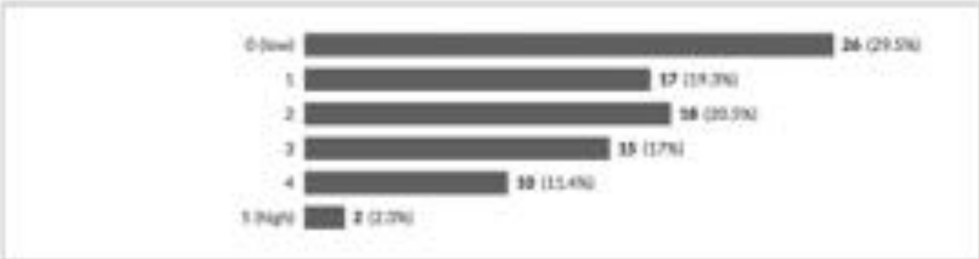
Showing all 15 responses Show less	
Variations for different clients, e.g. flats all the way to executive homes	197987-197980-12983465
volume housing gets 0 or 1 out of 5 in my book, so 3 is an average between that and genuinely interesting new design.	197987-197980-12984658
I realise aesthetics are very subjective. Although I understand the reasons for the black panels on the facade, I find them unattractive.	197987-197980-12985176
reference to traditional design features (without it being merely decorative) would appeal to wider audience	197987-197980-12986547
Some further work needed on the aesthetics of the outside to help normalise. Trick is that it looks like a normal house	197987-197980-12991024
More use of natural light	197987-197980-12990966
Outside needs to be more conventional in looks to hit the mass market	197987-197980-12999100
The interior layout I would prefer to utilise a common living area for kitchen and dining/sitting room. The external aesthetics could be improved further.	197987-197980-14102935
Would be less appealing as a terrace, particularly as it would be several metres higher. "wall effect" in community	197987-197980-14118887
As a single person living alone it is too big.	197987-197980-14200284
It concerns me that houses are being designed to meet sustainability and efficiency targets at the expense of creativity and individuality. They would all ultimately need to be exactly the same in order to get the benefit of the broad side to the south. I glimpsed a vision of row upon regimented row of cookie cutter houses in block after block. There needs to be room for personal taste and an organic shape in sustainable house design. It felt far too utilitarian - like some of the 70's council estates. It felt as though it had been designed by a computer to meet efficiency targets - not by someone who has lived in a variety of houses and who understands how houses work when a family lives in them. The house was not aesthetically pleasing. Functionally there was too much wasted space (specifically the hallway from lounge to kitchen). The window sizes weren't proportionate. And there were no windows in the bathrooms.	197987-197980-14201495
External appearance a bit bland.	197987-197980-14208689
Better use of attic	197987-197980-14214608
Loved to transparent roof tiles and light into the attic	197987-197980-14216074
More eco-friendly products and colours. Layout Ok but maybe more storage and use of the roof space and garden for growing food? Living walls to grow plants on outside of building?	197987-197980-14220881

16 What issues do you think the Solcer House might pose if you wanted to build it? (0) for low concern (5) for high concern.

16.1 It looks too modern



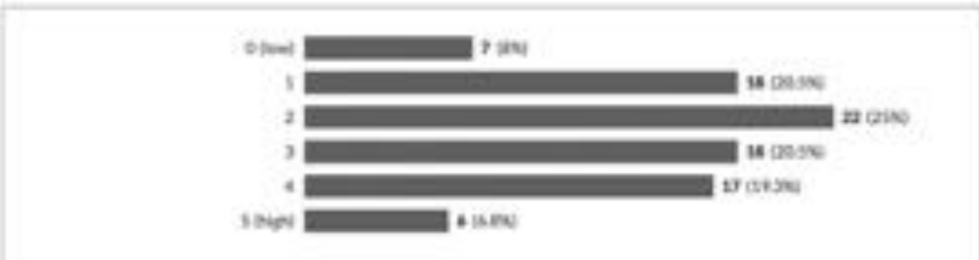
16.2 It looks too different



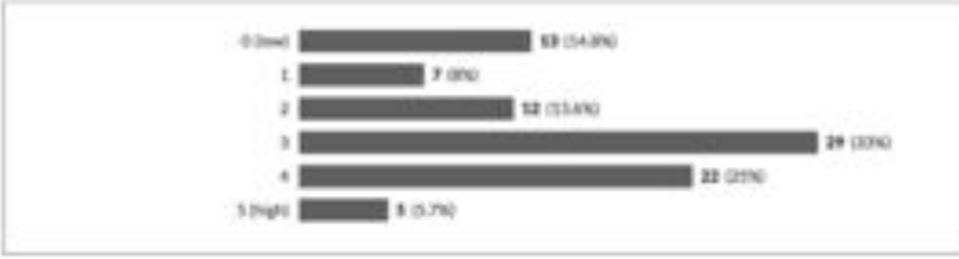
16.3 It could be difficult to maintain

16.4 It could be difficult to operate

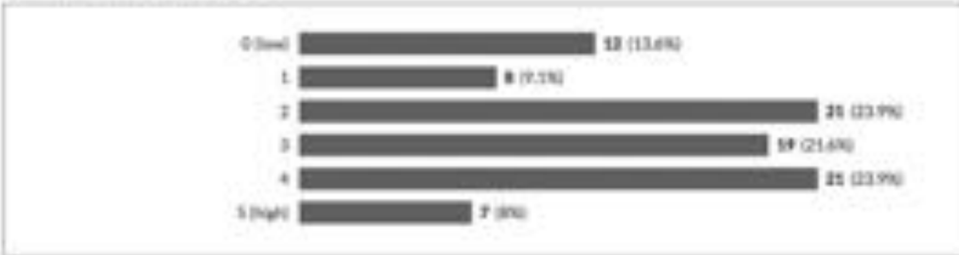
16.5 It could be difficult to gain planning permission



16.6 It could be difficult to sell



16.7 It could be difficult to get mortgage

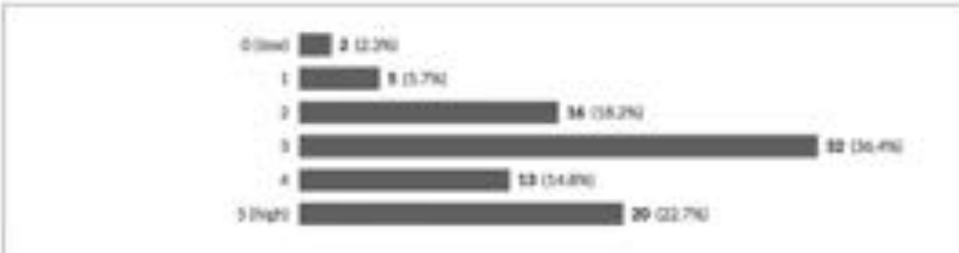


16.8 Please, provide further concerns you may have.

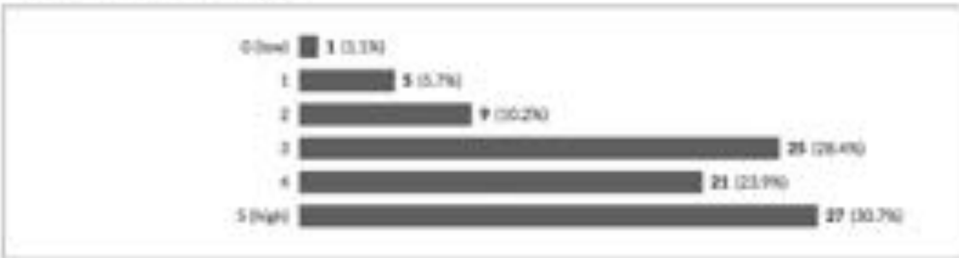
Showing all 6 responses Show less	
Other issues could be a shaded site, awkward shaped site, sloping site, etc	197987-197980-[illegible]
still can't believe it cost <£1000/sqm...	197987-197980-[illegible]
Although I don't expect any of the components to be unreliable, it may not be easy to find competent tradespeople to deal with any issues which may arise with such novel systems. Also, I'm aware of heat pump systems which occupants have found intimidating, so open windows to release heat rather than adjust the system resulting in wasted energy. The operability by general population feeds into my concerns about the "sellability" of the house	197987-197980-[illegible]
A support package for the various systems should be offered at a reasonable price, with guaranteed performance.	197987-197980-[illegible]
Fossil fuel based materials and tenants difficulty with controls.	197987-197980-[illegible]
I might find it hard to match the design to the necessary energy saving rates with the precision shown at SOLCER. How do I get the same energy saving efficiency on my site.	197987-197980-[illegible]

17 How much do you value each of the following features of the house?(0) for low value and (5) for high value.

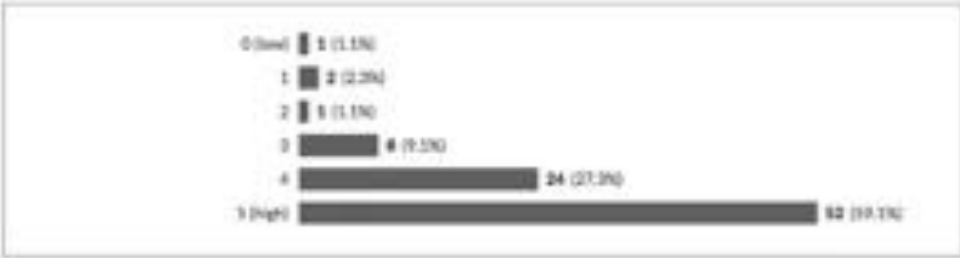
17.1 External render wall finish



17.2 Integrated transpired solar air collector



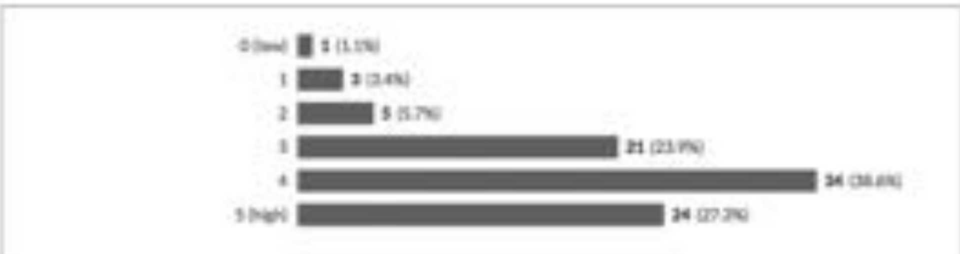
17.3 Integrated photovoltaic roof (South)



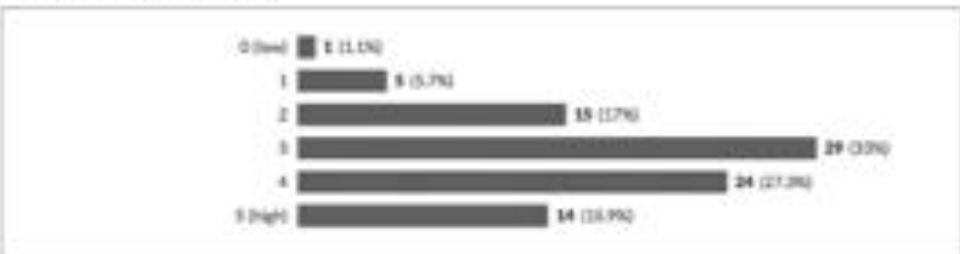
17.4 Standing seam metal roof (North)

17.5 Timber frame aluminium clad windows

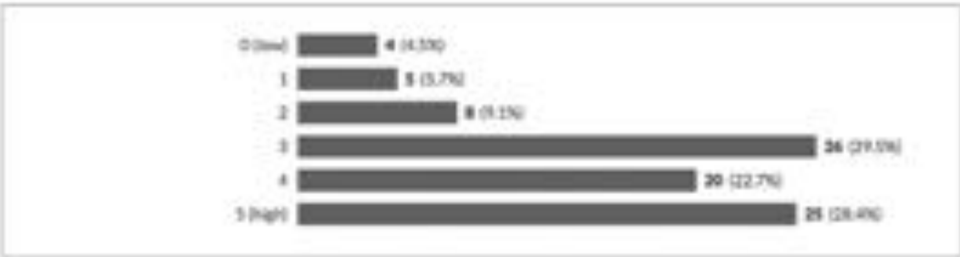
17.6 Size and location of windows (South)



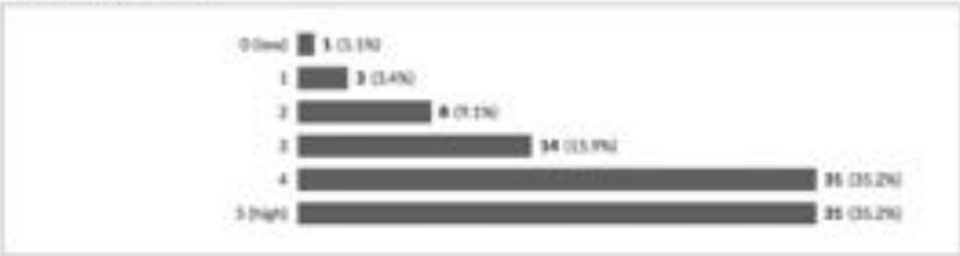
17.7 Size and location of windows (North)



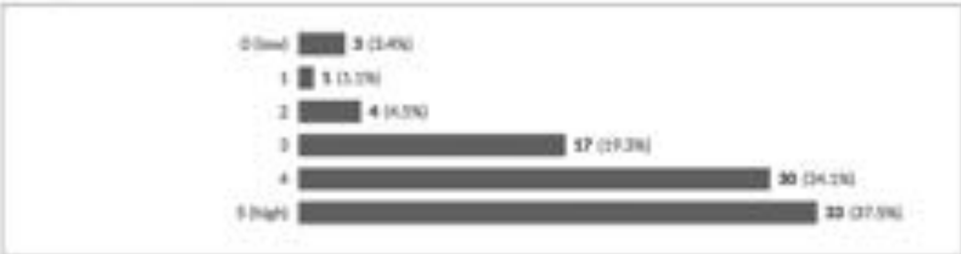
17.8 Openable windows in roof-attic space



17.9 Extra area in roof-attic space

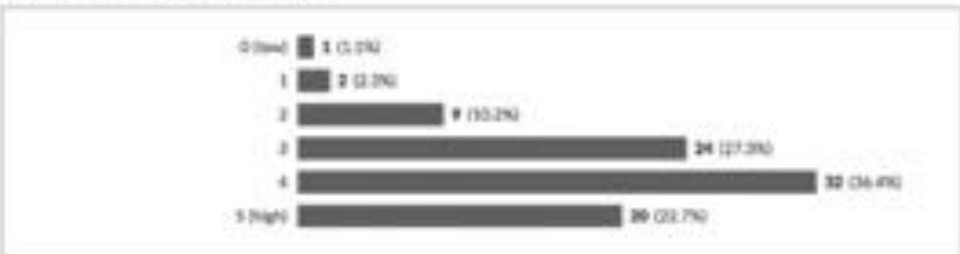


17.10 Natural light in roof-attic space

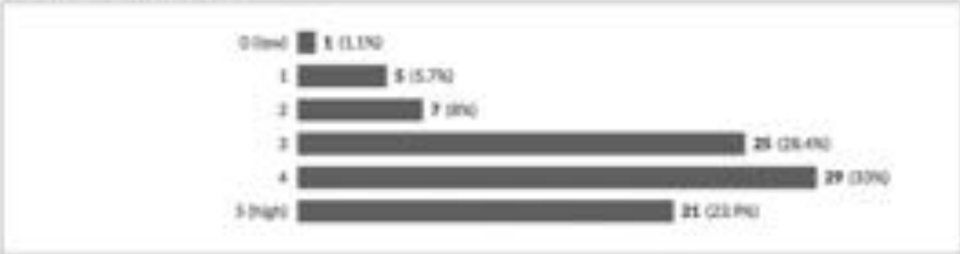


17.11 Access with built-in staircase to roof-attic space

17.12 Access between kitchen-utility-living spaces



17.13 Relatively higher ceiling height



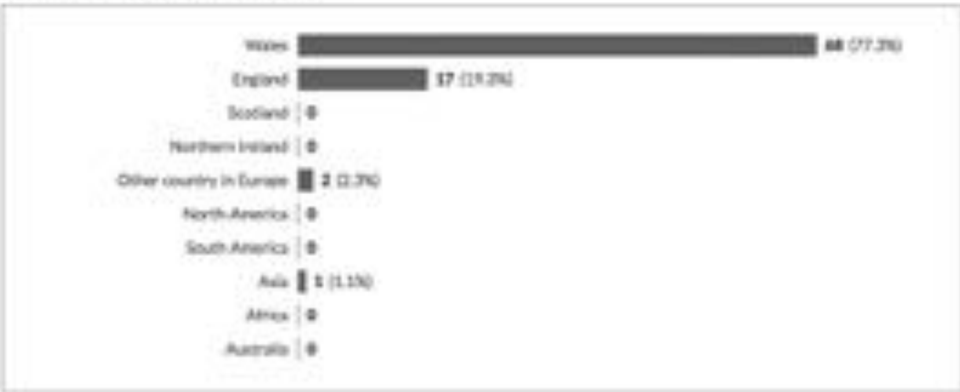
17.14 Extra cupboard storage space

17.15 Greater flexibility of space due to no radiators

17.a Please, let us know if you have any comments.

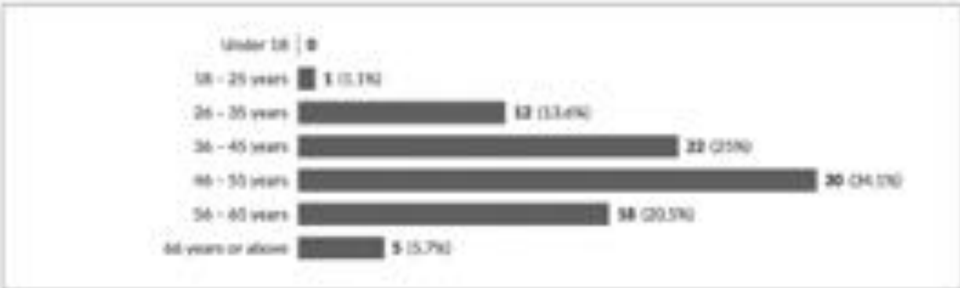
Showing all 10 responses Show less	
transparent pv panels were great in a show home but hard to believe the space wouldn't get too hot to be in or even store stuff in	[illegible]
I enquired re. warranty on voltaic panels, which was not long enough. I am recommending Chinese.	[illegible]
the technology makes the house less affordable in areas of low value housing	[illegible]
The use of the roof space is particularly attractive, i would like to see this developed further	[illegible]
Height in ground and 1st floor could be reduced to make proper use of the roof space- weights for loft hatch would need to be redesigned as they are not an efficient use of space.	[illegible]
Attic space would be better if it was usable (i.e. triple glazed and insulated)	[illegible]
I thought the ideas for the roof space were inspired!	[illegible]
Very exciting project but we worried that it was not possible to assess it with occupants in place.	[illegible]
Internal design was very pleasing. Lots of storage space.	[illegible]
Needed more eco friendly materials. And actual family living in to feed back experience living there - office use is not living in experience. More space to grow food plants in and outside the house.	[illegible]

18 What is the location of your home address?

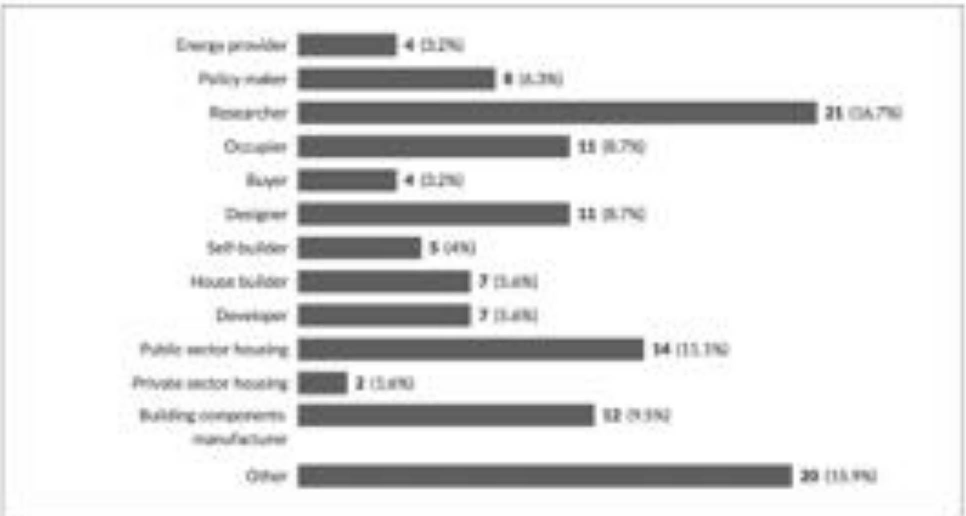


19 What is your gender?

20 Which of the following age brackets do you belong to?



21 What is the nature of your interest in the Solcer house, as a/an ...?



Annex 2: Temperature Analysis

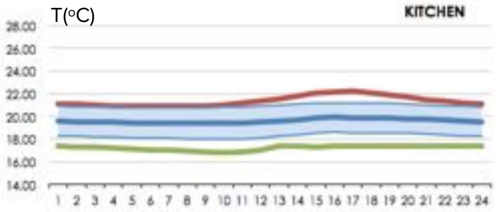
This section's overview is as follows:

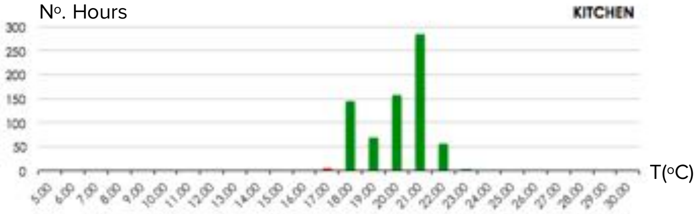
1. The aim of this temperature analysis is to determine whether the heating system of the Solcer House is using more energy than predicted because of an incorrect sizing or selection of the system or because of the type of occupancy and use of the building.
2. The temperature analysis consists in collecting, ordering and analysing the monitored data from the Solcer House using Microsoft Excel. The internal temperature of each room is measurements with a temperature sensor located at approximately 1.5m from the floor. Data is analysed from November 2015 until March 2016.
3. This assessment looks at two main aspects:
   - Minimum, average (showing also standard deviation) and maximum hourly temperature in each room.
   - Temperature distribution in number of hours in each room.

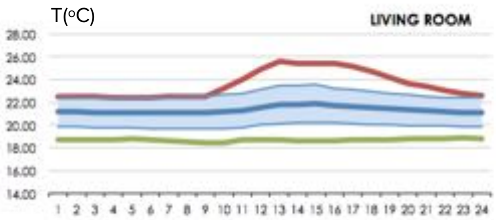
A2.1 Results

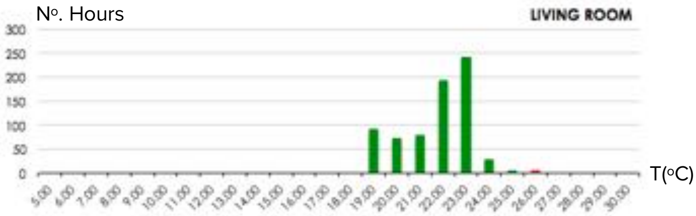
Hourly temperature analysis

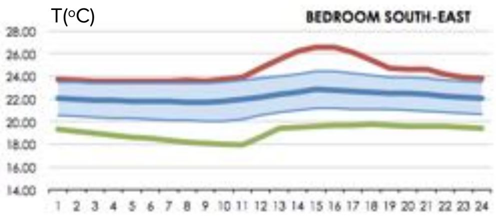
Temperature distribution

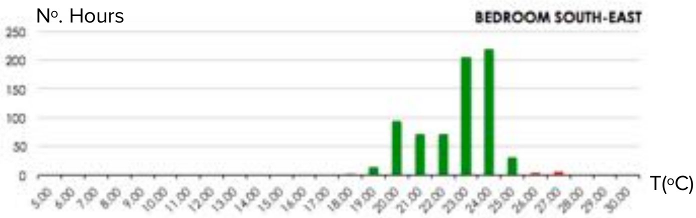


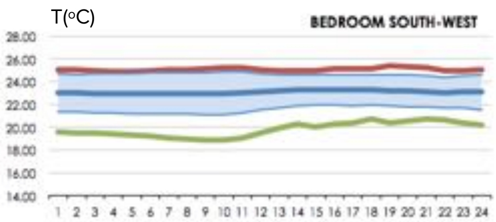


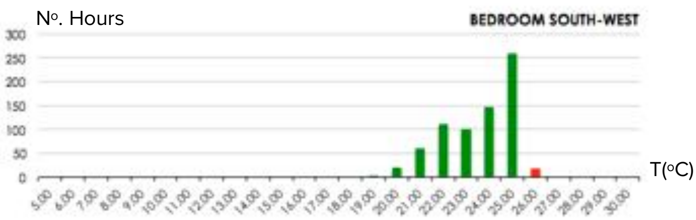


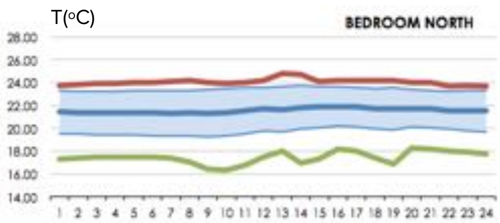


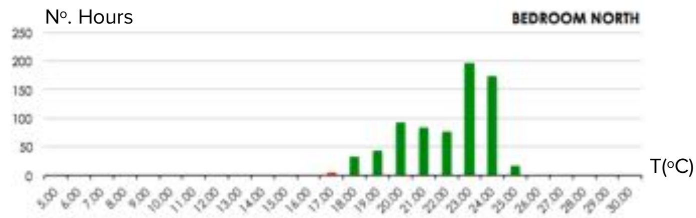


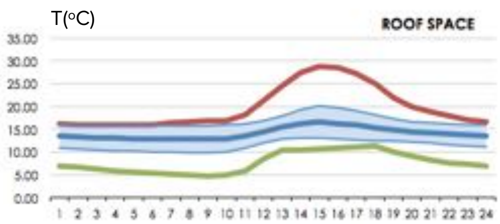


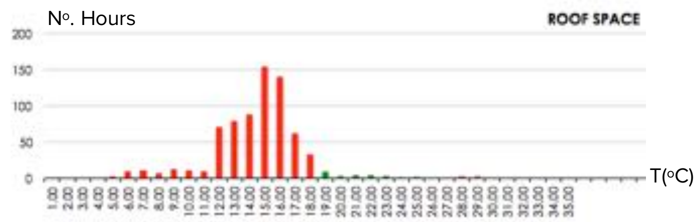












Maximum temperature

Average temperature (+/- STD)

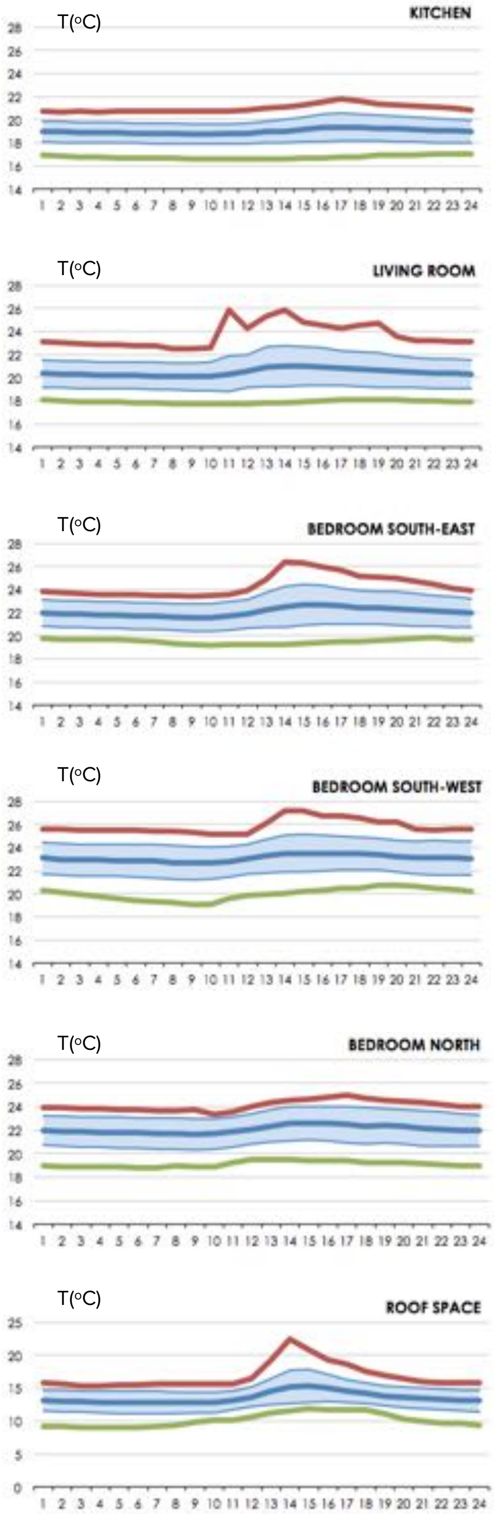
Minimum temperature

Comfort temperature

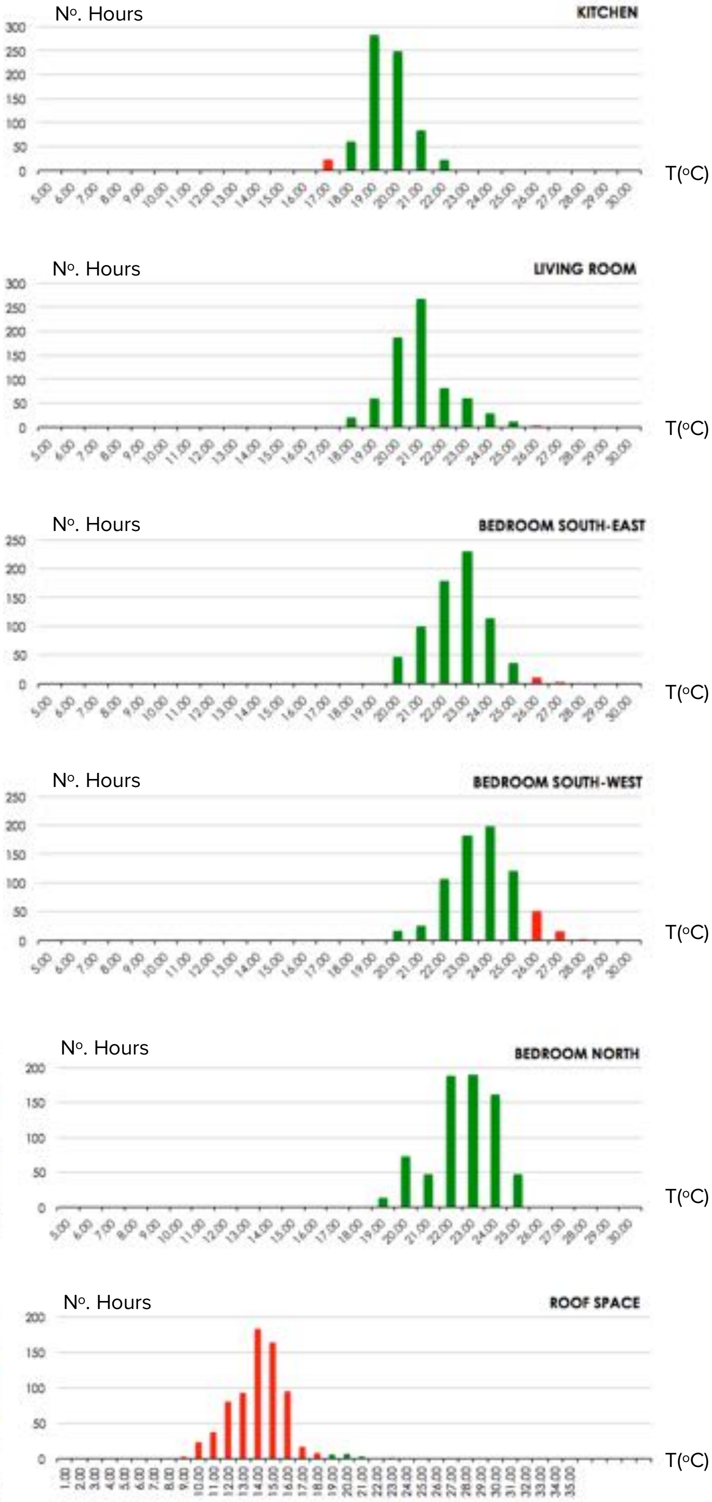
Not comfort temperature

NOVEMBER

Hourly temperature analysis



Temperature distribution



Maximum temperature

Average temperature (+/- STD)

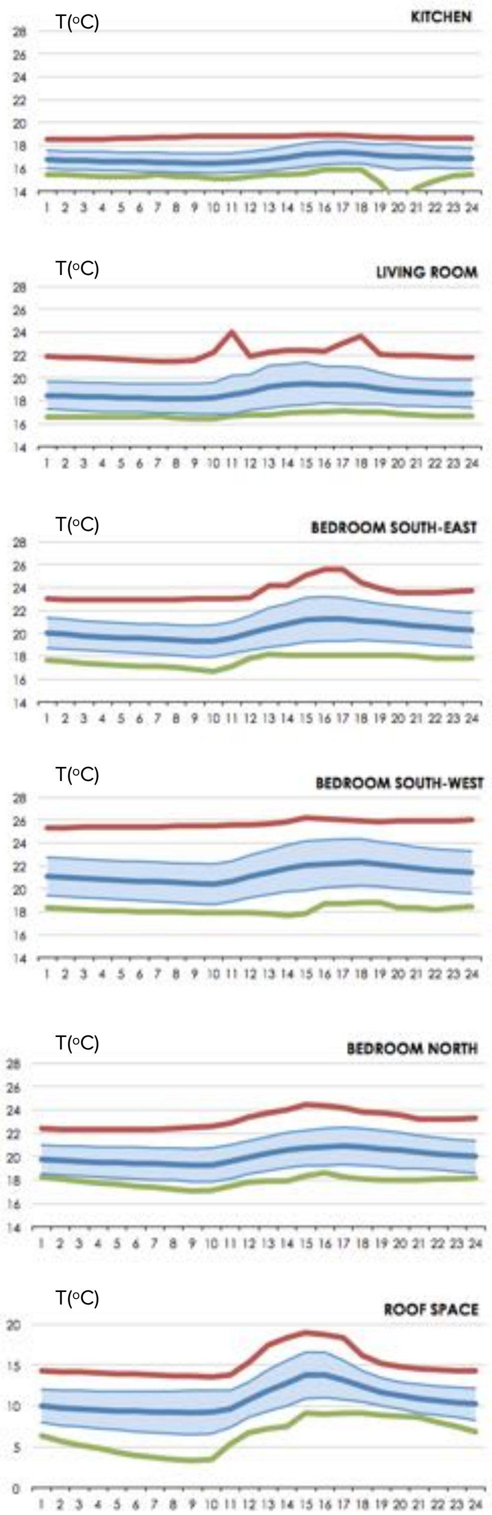
Minimum temperature

Comfort temperature

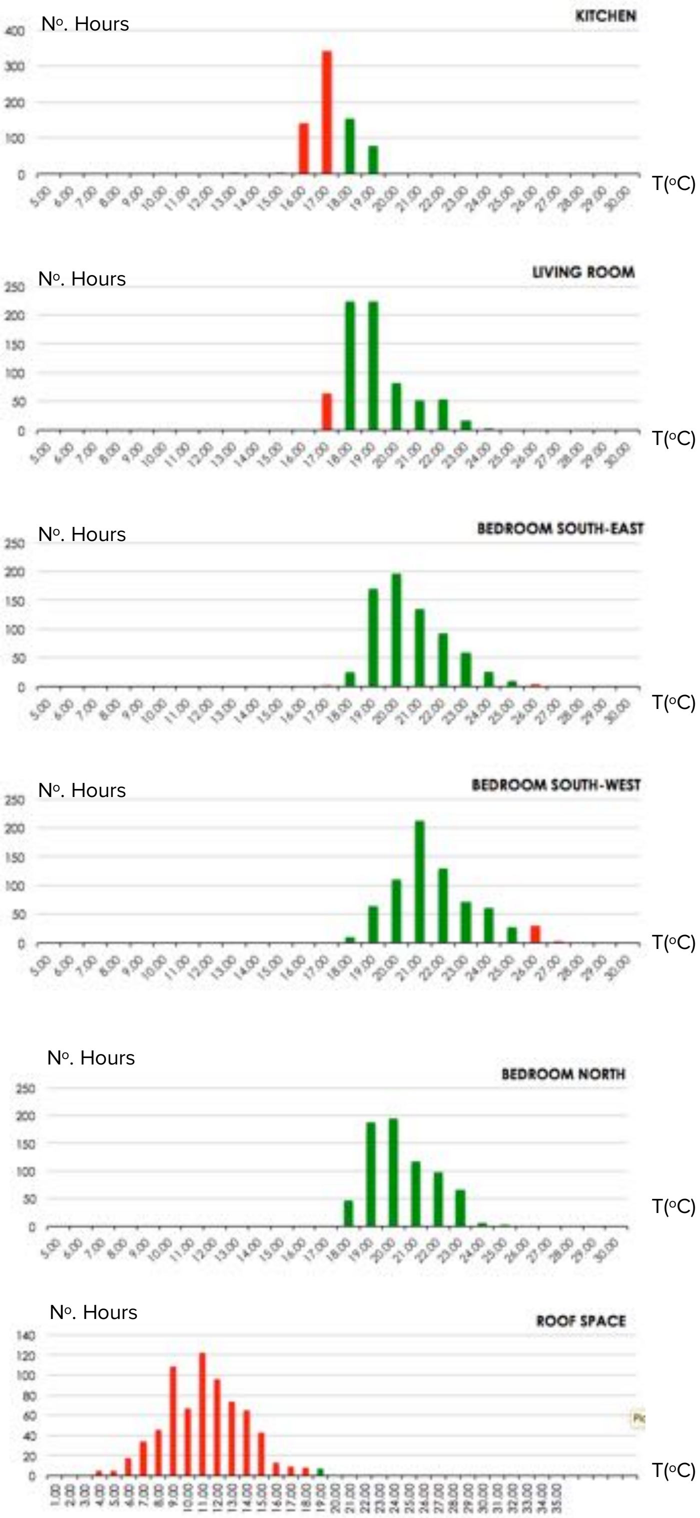
Not comfort temperature

DECEMBER

Hourly temperature analysis



Temperature distribution



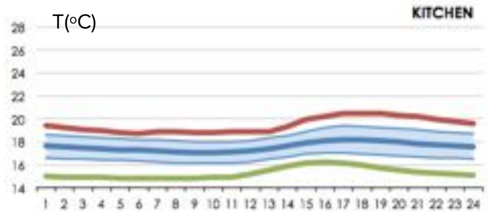
Maximum temperature
Average temperature (+/- STD)
Minimum temperature

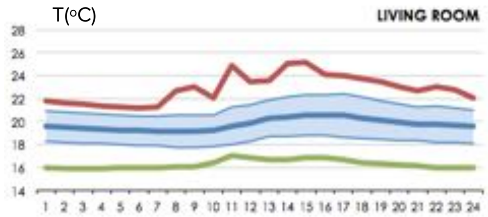
Comfort temperature
Not comfort temperature

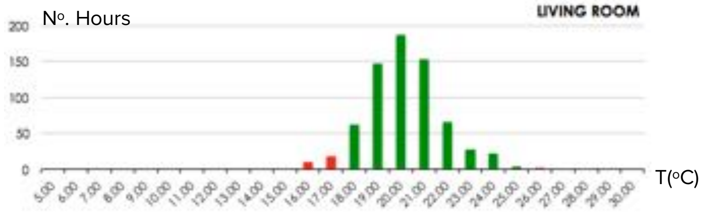
JANUARY

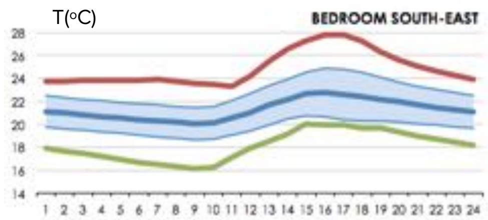
Hourly temperature analysis

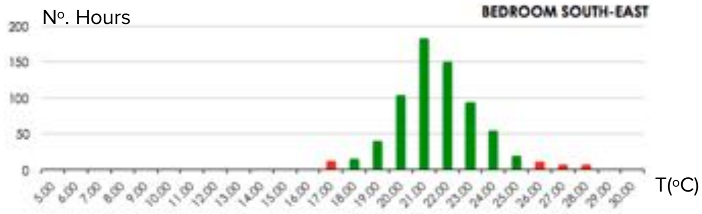
Temperature distribution

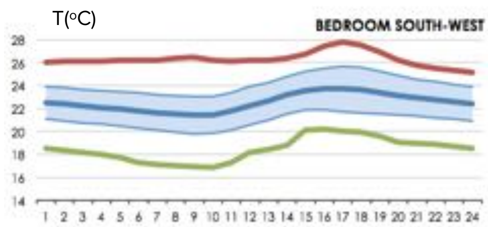


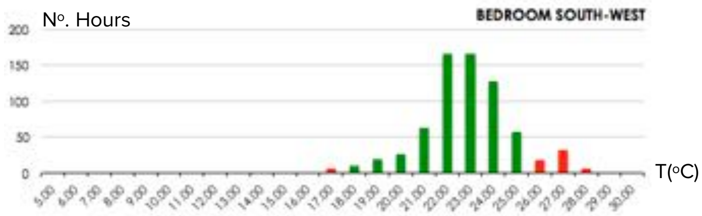


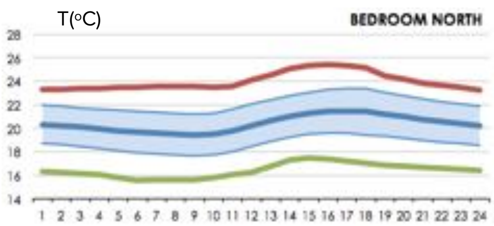


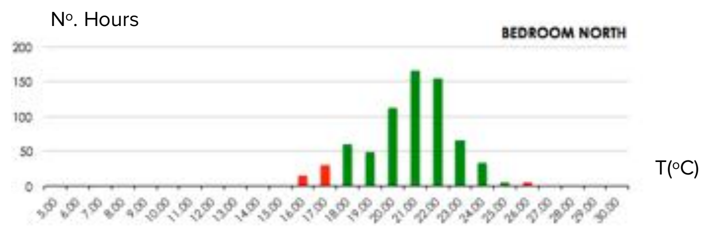


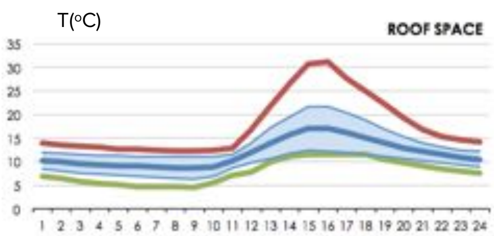


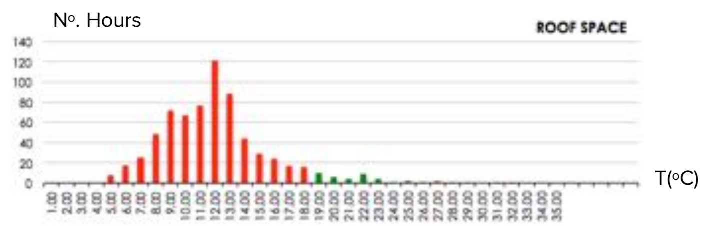










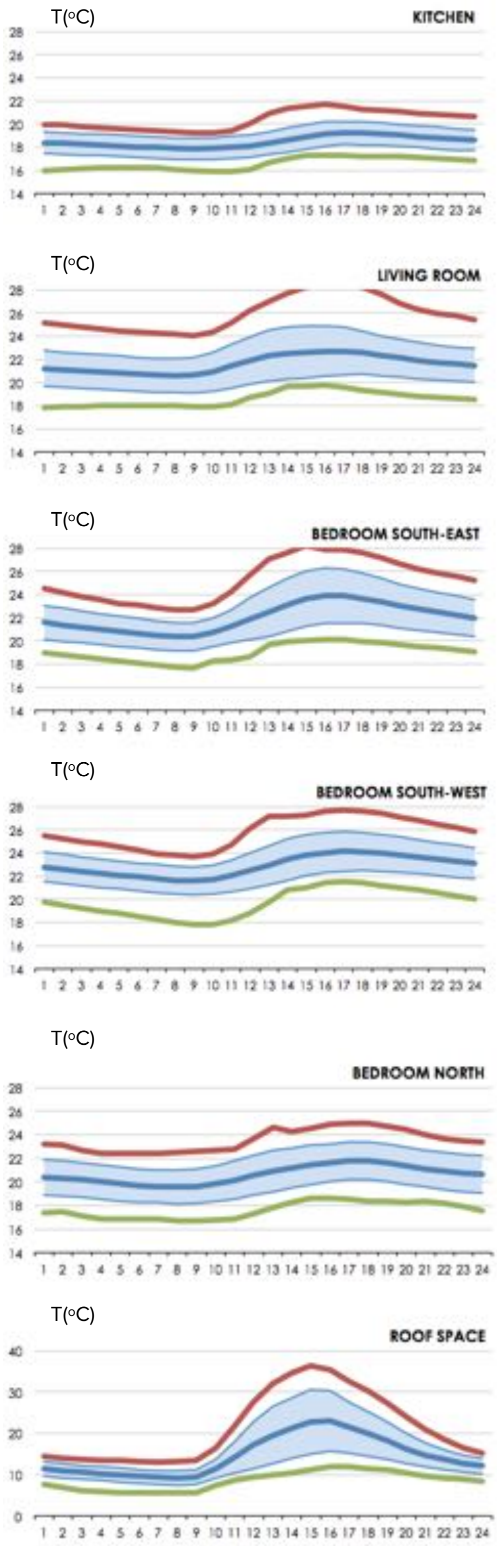


Maximum temperature
Average temperature (+/- STD)
Minimum temperature

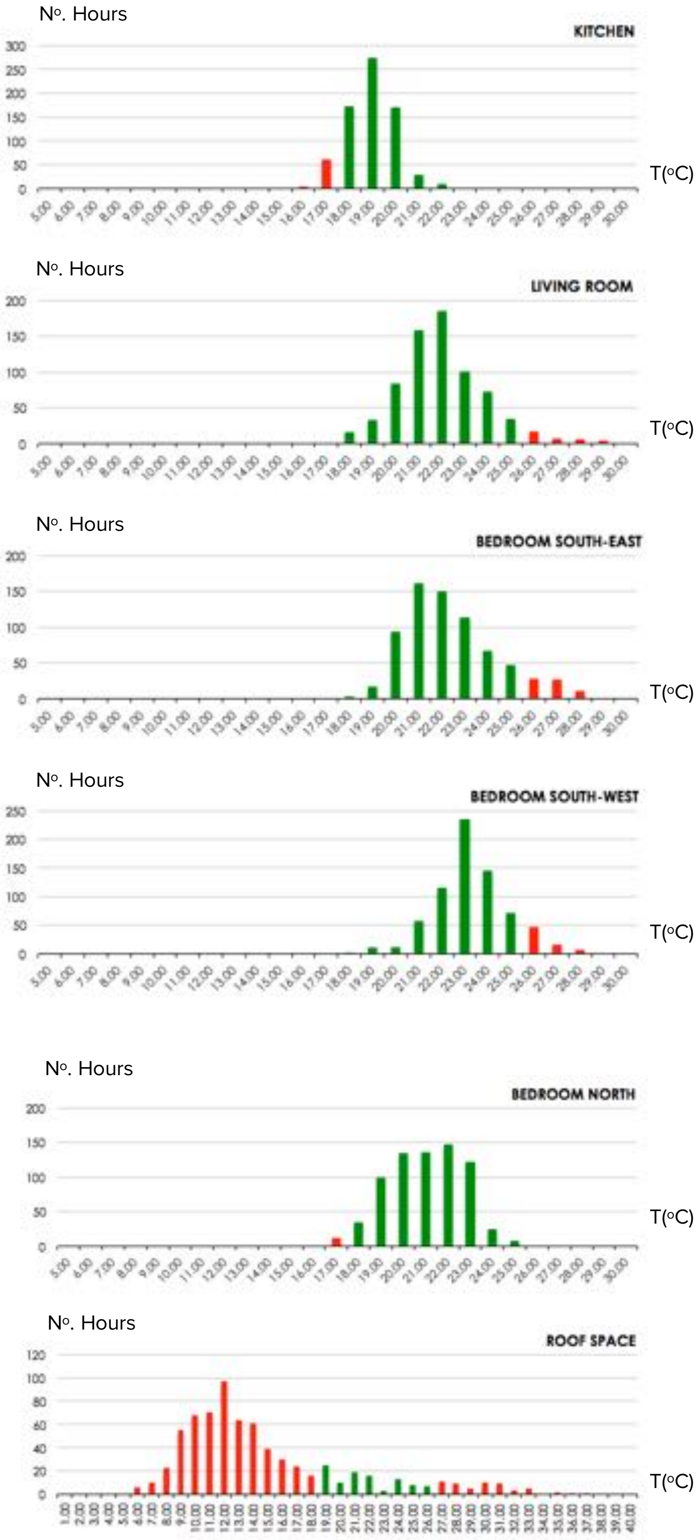
Comfort temperature
Not comfort temperature

FEBRUARY

Hourly temperature analysis



Temperature distribution



Maximum temperature
Average temperature (+/- STD)
Minimum temperature

Comfort temperature
Not comfort temperature

MARCH

Annex 3: SAP modelling

This section's overview is as follows:

1. SAP Input data.
2. SAP Worksheet.
3. SAP Checklist.

A3.1 SAP Input

SAP Input

Property Details: 4P2B House

Address:	Cenin Ltd, Unit 1 Parc Stormy, Stormy Down, Pyle, BRIDGEND, CF33 4RS
Located in:	Wales
Region:	Wales
UPRN:	3759068578
Date of assessment:	31 May 2018
Date of certificate:	13 June 2018
Assessment type:	New dwelling as built
Transaction type:	New dwelling
Tenure type:	Rented (social)
Related party disclosure:	No related party
Thermal Mass Parameter:	Indicative Value Medium
Water use <= 125 litres/person/day:	True
PCDF Version:	424

Property description:

Dwelling type:	House	
Detachment:	Detached	
Year Completed:	2015	
Floor Location:	**Floor area:**	**Storey height:**
Floor 0	50 m²	2.35 m
Floor 1	50 m²	2.35 m
Living area:	19.45 m² (fraction 0.188)	
Front of dwelling faces:	South	

Opening types:

Name:	Source:	Type:	Glazing:	Argon:	Frame:
Main Entrance	Manufacturer	Solid			Wood
Living Room	SAP 2012	Windows	double-glazed	Yes	Wood
Bedroom W1	SAP 2012	Windows	double-glazed	Yes	Wood
Bedroom W2	SAP 2012	Windows	double-glazed	Yes	Wood
Living room door	SAP 2012	Windows	double-glazed	Yes	Wood
Kitchen door	SAP 2012	Windows	double-glazed	Yes	Wood
Kitchen	SAP 2012	Windows	double-glazed	Yes	Wood
Bedroom W1	SAP 2012	Windows	double-glazed	Yes	Wood
Bedroom W2	SAP 2012	Windows	double-glazed	Yes	Wood

Name:	Gap:	Frame Factor:	g-value:	U-value:	Area:	No. of Openings:
Main Entrance	mm	0.7	0	1.6	1.6	1
Living Room	12mm	0.7	0.76	1.2	2.88	1
Bedroom W1	12mm	0.7	0.76	1.2	2.88	1
Bedroom W2	12mm	0.7	0.76	1.2	1.44	1
Living room door	12mm	0.7	0.76	1.2	2.4	1
Kitchen door	12mm	0.7	0.76	1.2	0.6	1
Kitchen	12mm	0.7	0.76	1.2	1.44	1
Bedroom W1	12mm	0.7	0.76	1.2	1.44	1
Bedroom W2	12mm	0.7	0.76	1.2	0.72	1

Name:	Type-Name:	Location:	Orient:	Width:	Height:
Main Entrance		South	South	0.8	2
Living Room		South	South	2.4	1.2
Bedroom W1		South	South	2.4	1.2
Bedroom W2		South	South	1.2	1.2
Living room door		South	South	1.2	2
Kitchen door		North	North	0.3	2
Kitchen		North	North	2.4	0.6

Figure 214 – SAP Input, Page 1/3. Data source: Stroma FSAP 2012 software.

SAP Input

Bedroom W1	North	North	2.4	0.6
Bedroom W2	North	North	1.2	0.6

Overshading: Very Little

Opaque Elements:

Type:	Gross area:	Openings:	Net area:	U-value:	Ru value:	Curtain wall:	Kappa:
External Elements							
South	32.4	11.2	21.2	0.12	0	False	N/A
North	32.4	4.2	28.2	0.12	0	False	N/A
East	55	0	55	0.12	0	False	N/A
West	55	0	55	0.12	0	False	N/A
Roof	50	0	50	0.15	0		N/A
Floor	50			0.15			N/A
Internal Elements							
Party Elements							
Ceiling	50						N/A

Thermal bridges:

Thermal bridges: No information on thermal bridging (y=0.15) (y =0.15)

Ventilation:

Pressure test: No (Assumed)

Ventilation: Balanced with heat recovery
Number of wet rooms: Kitchen + 2
Ductwork: Insulation, rigid
Approved Installation Scheme: False

Number of chimneys: 0
Number of open flues: 0
Number of fans: 0
Number of passive stacks: 0
Number of sides sheltered: 1
Pressure test: 15

Main heating system:

Main heating system: Heat pumps with warm air distribution
Electric heat pumps
Fuel: Electricity
Info Source: SAP Tables
SAP Table: 524
Air source heat pump
Fan coil units
Design flow temperature: Design flow temperature >45°C
Unknown

Main heating Control:

Main heating Control: Time and temperature zone control
Control code: 2506

Secondary heating system:

Secondary heating system: None

Water heating:

Water heating: From main heating system
Water code: 901
Fuel :Electricity
Hot water cylinder
Cylinder volume: 185 litres

Figure 215 – SAP Input, Page 2/3. Data source: Stroma FSAP 2012 software.

SAP Input

	Cylinder insulation: Factory 100 mm Primary pipework insulation: True Cylinderstat: True Cylinder in heated space: True Solar panel: False
Others:	
Electricity tariff:	Standard Tariff
In Smoke Control Area:	Yes
Conservatory:	No conservatory
Low energy lights:	100%
Terrain type:	Rural
EPC language:	English
Wind turbine:	No
Photovoltaics:	Photovoltaic 1 Installed Peak power: 4.3 Tilt of collector: 30° Overshading: None or very little Collector Orientation: South
Assess Zero Carbon Home:	No

Figure 216 – SAP Input, Page 3/3. Data source: Stroma FSAP 2012 software.

A3.2 SAP Worksheet

SAP WorkSheet: New dwelling as built

User Details:

Assessor Name: **Stroma Number:**

Software Name: Stroma FSAP 2012 **Software Version:** Version: 1.0.4.14

Property Address: 4P2B House

Address : Cenin Ltd, Unit 1 Parc Stormy, Stormy Down, Pyle, BRIDGEND, CF33 4RS

1. Overall dwelling dimensions:

	Area(m²)		Av. Height(m)		Volume(m³)	
Ground floor	50	(1a) x	2.35	(2a) =	117.5	(3a)
First floor	50	(1b) x	2.35	(2b) =	117.5	(3b)
Total floor area TFA = (1a)+(1b)+(1c)+(1d)+(1e)+.....(1n)	100	(4)				
Dwelling volume		(3a)+(3b)+(3c)+(3d)+(3e)+.....(3n) =			235	(5)

2. Ventilation rate:

	main heating		secondary heating		other		total		m³ per hour	
Number of chimneys	0	+	0	+	0	=	0	x 40 =	0	(6a)
Number of open flues	0	+	0	+	0	=	0	x 20 =	0	(6b)
Number of intermittent fans							0	x 10 =	0	(7a)
Number of passive vents							0	x 10 =	0	(7b)
Number of flueless gas fires							0	x 40 =	0	(7c)

			Air changes per hour	
Infiltration due to chimneys, flues and fans = (6a)+(6b)+(7a)+(7b)+(7c) =	0	÷ (5) =	0	(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (ns)		0	(9)
Additional infiltration	[(9)-1]x0.1 =	0	(10)
Structural infiltration: 0.25 for steel or timber frame or 0.35 for masonry construction		0	(11)
if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal user 0.35			
If suspended wooden floor, enter 0.2 (unsealed) or 0.1 (sealed), else enter 0		0	(12)
If no draught lobby, enter 0.05, else enter 0		0	(13)
Percentage of windows and doors draught stripped		0	(14)
Window infiltration	0.25 - [0.2 x (14) ÷ 100] =	0	(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =	0	(16)
Air permeability value, q50, expressed in cubic metres per hour per square metre of envelope area		15	(17)
If based on air permeability value, then	(18) = [(17) ÷ 20]+(8), otherwise (18) = (16)	0.75	(18)
Air permeability value applies if a pressurisation test has been done or a degree air permeability is being used			
Number of sides sheltered		1	(19)
Shelter factor	(20) = 1 - [0.075 x (19)] =	0.92	(20)
Infiltration rate incorporating shelter factor	(21) = (18) x (20) =	0.69	(21)

Infiltration rate modified for monthly wind speed

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(22)m=	5.1	5	4.9	4.4	4.3	3.8	3.8	3.7	4	4.3	4.5	4.7

Figure 217 – SAP Worksheet, Page 1/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

Wind Factor (22a)m = (22)m ÷ 4

(22a)m=	1.27	1.25	1.23	1.1	1.08	0.95	0.95	0.92	1	1.08	1.12	1.18

Adjusted infiltration rate (allowing for shelter and wind speed) = (21a) x (22a)m

0.88	0.87	0.85	0.76	0.75	0.66	0.66	0.64	0.69	0.75	0.78	0.82

Calculate effective air change rate for the applicable case

If mechanical ventilation: 0.5 (23a)

If exhaust air heat pump using Appendix N, (23b) = (23a) × Fmv (equation (N5)) , otherwise (23b) = (23a) 0.5 (23b)

If balanced with heat recovery: efficiency in % allowing for in-use factor (from Table 4h) = 68 (23c)

a) If balanced mechanical ventilation with heat recovery (MVHR) (24a)m = (22b)m + (23b) × [1 – (23c) ÷ 100]

(24a)m=	1.04	1.03	1.01	0.92	0.91	0.82	0.82	0.8	0.85	0.91	0.94	0.98	(24a)

b) If balanced mechanical ventilation without heat recovery (MV) (24b)m = (22b)m + (23b)

(24b)m=	0	0	0	0	0	0	0	0	0	0	0	0	(24b)

c) If whole house extract ventilation or positive input ventilation from outside

if (22b)m < 0.5 × (23b), then (24c) = (23b); otherwise (24c) = (22b) m + 0.5 × (23b)

(24c)m=	0	0	0	0	0	0	0	0	0	0	0	0	(24c)

d) If natural ventilation or whole house positive input ventilation from loft

if (22b)m = 1, then (24d)m = (22b)m otherwise (24d)m = 0.5 + [(22b)m² x 0.5]

(24d)m=	0	0	0	0	0	0	0	0	0	0	0	0	(24d)

Effective air change rate - enter (24a) or (24b) or (24c) or (24d) in box (25)

(25)m=	1.04	1.03	1.01	0.92	0.91	0.82	0.82	0.8	0.85	0.91	0.94	0.98	(25)

3. Heat losses and heat loss parameter:

ELEMENT	Gross area (m²)	Openings m²	Net Area A ,m²		U-value W/m2K		A X U (W/K)	k-value kJ/m²·K	A X k kJ/K	
Doors			1.6	x	1.6	=	2.56			(26)
Windows Type 1			2.88		x1/[1/(1.2)+ 0.04]	=	3.3			(27)
Windows Type 2			2.88		x1/[1/(1.2)+ 0.04]	=	3.3			(27)
Windows Type 3			1.44		x1/[1/(1.2)+ 0.04]	=	1.65			(27)
Windows Type 4			2.4		x1/[1/(1.2)+ 0.04]	=	2.75			(27)
Windows Type 5			0.6		x1/[1/(1.2)+ 0.04]	=	0.69			(27)
Windows Type 6			1.44		x1/[1/(1.2)+ 0.04]	=	1.65			(27)
Windows Type 7			1.44		x1/[1/(1.2)+ 0.04]	=	1.65			(27)
Windows Type 8			0.72		x1/[1/(1.2)+ 0.04]	=	0.82			(27)
Floor			50	x	0.15	=	7.5			(28)
Walls Type1	32.4	11.2	21.2	x	0.12	=	2.54			(29)
Walls Type2	32.4	4.2	28.2	x	0.12	=	3.38			(29)
Walls Type3	55	0	55	x	0.12	=	6.6			(29)
Walls Type4	55	0	55	x	0.12	=	6.6			(29)
Roof	50	0	50	x	0.15	=	7.5			(30)
Total area of elements, m²			274.8							(31)
Party ceiling			50							(32b)

Figure 218 – SAP Worksheet, Page 2/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

** for windows and roof windows, use effective window U-value calculated using formula 1/[(1/U-value)+0.04] as given in paragraph 3.2*
*** include the areas on both sides of internal walls and partitions*

Fabric heat loss, W/K = S (A x U)	(26)…(30) + (32) =	52.49	(33)
Heat capacity Cm = S(A x k)	((28)…(30) + (32) + (32a)…(32e) =	8384.6	(34)
Thermal mass parameter (TMP = Cm ÷ TFA) in kJ/m²K	Indicative Value: Medium	250	(35)

For design assessments where the details of the construction are not known precisely the indicative values of TMP in Table 1f can be used instead of a detailed calculation.

Thermal bridges : S (L x Y) calculated using Appendix K		41.22	(36)

if details of thermal bridging are not known (36) = 0.15 x (31)

Total fabric heat loss	(33) + (36) =	93.71	(37)

Ventilation heat loss calculated monthly (38)m = 0.33 × (25)m x (5)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
(38)m=	81	79.66	78.31	71.59	70.24	63.52	63.52	62.17	66.21	70.24	72.93	75.62	(38)

Heat transfer coefficient, W/K (39)m = (37) + (38)m

(39)m=	174.71	173.37	172.02	165.3	163.95	157.23	157.23	155.88	159.92	163.95	166.64	169.33	

Average = Sum(39)1…12 /12= 164.96 (39)

Heat loss parameter (HLP), W/m²K (40)m = (39)m ÷ (4)

(40)m=	1.75	1.73	1.72	1.65	1.64	1.57	1.57	1.56	1.6	1.64	1.67	1.69	

Average = Sum(40)1…12 /12= 1.65 (40)

Number of days in month (Table 1a)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
(41)m=	31	28	31	30	31	30	31	31	30	31	30	31	(41)

4. Water heating energy requirement: kWh/year:

Assumed occupancy, N 2.74 (42)
if TFA > 13.9, N = 1 + 1.76 x [1 - exp(-0.000349 x (TFA -13.9)2)] + 0.0013 x (TFA -13.9)
if TFA £ 13.9, N = 1

Annual average hot water usage in litres per day Vd,average = (25 x N) + 36 99.26 (43)
Reduce the annual average hot water usage by 5% if the dwelling is designed to achieve a water use target of not more that 125 litres per person per day (all water use, hot and cold)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Hot water usage in litres per day for each month Vd,m = factor from Table 1c x (43)

(44)m=	109.19	105.22	101.25	97.28	93.31	89.34	89.34	93.31	97.28	101.25	105.22	109.19

Total = Sum(44)1…12 = 1191.16 (44)

Energy content of hot water used - calculated monthly = 4.190 x Vd,m x nm x DTm / 3600 kWh/month (see Tables 1b, 1c, 1d)

(45)m=	161.93	141.62	146.14	127.41	122.25	105.49	97.76	112.18	113.52	132.29	144.41	156.82

Total = Sum(45)1…12 = 1561.81 (45)

If instantaneous water heating at point of use (no hot water storage), enter 0 in boxes (46) to (61)

(46)m=	24.29	21.24	21.92	19.11	18.34	15.82	14.66	16.83	17.03	19.84	21.66	23.52	(46)

Water storage loss:

Storage volume (litres) including any solar or WWHRS storage within same vessel	185	(47)

If community heating and no tank in dwelling, enter 110 litres in (47)
Otherwise if no stored hot water (this includes instantaneous combi boilers) enter ‘0’ in (47)
Water storage loss:

a) If manufacturer’s declared loss factor is known (kWh/day):	0	(48)
Temperature factor from Table 2b	0	(49)

Figure 219 – SAP Worksheet, Page 3/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

Energy lost from water storage, kWh/year	(48) x (49) =	185	(50)
b) If manufacturer's declared cylinder loss factor is not known:			
Hot water storage loss factor from Table 2 (kWh/litre/day)		0.01	(51)
If community heating see section 4.3			
Volume factor from Table 2a		0.87	(52)
Temperature factor from Table 2b		0.54	(53)
Energy lost from water storage, kWh/year	(47) x (51) x (52) x (53) =	0.89	(54)
Enter (50) or (54) in (55)		0.89	(55)

Water storage loss calculated for each month ((56)m = (55) × (41)m

(56)m=	27.58	24.91	27.58	26.69	27.58	26.69	27.58	27.58	26.69	27.58	26.69	27.58	(56)

If cylinder contains dedicated solar storage, (57)m = (56)m x [(50) – (H11)] ÷ (50), else (57)m = (56)m where (H11) is from Appendix H

(57)m=	27.58	24.91	27.58	26.69	27.58	26.69	27.58	27.58	26.69	27.58	26.69	27.58	(57)

Primary circuit loss (annual) from Table 3 — 0 — (58)

Primary circuit loss calculated for each month (59)m = (58) ÷ 365 × (41)m

(modified by factor from Table H5 if there is solar water heating and a cylinder thermostat)

(59)m=	23.26	21.01	23.26	22.51	23.26	22.51	23.26	23.26	22.51	23.26	22.51	23.26	(59)

Combi loss calculated for each month (61)m = (60) ÷ 365 × (41)m

(61)m=	0	0	0	0	0	0	0	0	0	0	0	0	(61)

Total heat required for water heating calculated for each month (62)m = 0.85 × (45)m + (46)m + (57)m + (59)m + (61)m

(62)m=	212.77	187.54	196.98	176.61	173.1	154.7	148.6	163.02	162.72	183.14	193.61	207.66	(62)

Solar DHW input calculated using Appendix G or Appendix H (negative quantity) (enter '0' if no solar contribution to water heating)

(add additional lines if FGHRS and/or WWHRS applies, see Appendix G)

(63)m=	0	0	0	0	0	0	0	0	0	0	0	0	(63)

Output from water heater

(64)m=	212.77	187.54	196.98	176.61	173.1	154.7	148.6	163.02	162.72	183.14	193.61	207.66	

Output from water heater (annual)$_{1...12}$ — 2160.45 — (64)

Heat gains from water heating, kWh/month 0.25 ´ [0.85 × (45)m + (61)m] + 0.8 x [(46)m + (57)m + (59)m]

(65)m=	94.52	83.83	89.27	81.73	81.32	74.44	73.18	77.97	77.11	84.66	87.38	92.82	(65)

include (57)m in calculation of (65)m only if cylinder is in the dwelling or hot water is from community heating

5. Internal gains (see Table 5 and 5a):

Metabolic gains (Table 5), Watts

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
(66)m=	164.37	164.37	164.37	164.37	164.37	164.37	164.37	164.37	164.37	164.37	164.37	164.37	(66)

Lighting gains (calculated in Appendix L, equation L9 or L9a), also see Table 5

(67)m=	59.16	52.55	42.73	32.35	24.18	20.42	22.06	28.68	38.49	48.87	57.04	60.81	(67)

Appliances gains (calculated in Appendix L, equation L13 or L13a), also see Table 5

(68)m=	382.58	386.55	376.54	355.25	328.36	303.09	286.21	282.24	292.25	313.55	340.43	365.7	(68)

Cooking gains (calculated in Appendix L, equation L15 or L15a), also see Table 5

(69)m=	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	54.18	(69)

Pumps and fans gains (Table 5a)

(70)m=	0	0	0	0	0	0	0	0	0	0	0	0	(70)

Losses e.g. evaporation (negative values) (Table 5)

(71)m=	-109.58	-109.58	-109.58	-109.58	-109.58	-109.58	-109.58	-109.58	-109.58	-109.58	-109.58	-109.58	(71)

Figure 220 – SAP Worksheet, Page 4/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

Water heating gains (Table 5)

(72)m=	127.04	124.74	119.98	113.51	109.31	103.39	98.36	104.8	107.09	113.79	121.36	124.75	(72)

Total internal gains = (66)m + (67)m + (68)m + (69)m + (70)m + (71)m + (72)m

(73)m=	677.75	672.81	648.23	610.08	570.82	535.87	515.6	524.69	546.8	585.18	627.8	660.23	(73)

6. Solar gains:

Solar gains are calculated using solar flux from Table 6a and associated equations to convert to the applicable orientation.

Orientation:		Access Factor Table 6d		Area m²		Flux Table 6a		g_ Table 6b		FF Table 6c		Gains (W)	
North	0.9x	1	x	0.6	x	10.63	x	0.76	x	0.7	=	3.05	(74)
North	0.9x	1	x	1.44	x	10.63	x	0.76	x	0.7	=	7.33	(74)
North	0.9x	1	x	1.44	x	10.63	x	0.76	x	0.7	=	7.33	(74)
North	0.9x	1	x	0.72	x	10.63	x	0.76	x	0.7	=	3.67	(74)
North	0.9x	1	x	0.6	x	20.32	x	0.76	x	0.7	=	5.84	(74)
North	0.9x	1	x	1.44	x	20.32	x	0.76	x	0.7	=	14.01	(74)
North	0.9x	1	x	1.44	x	20.32	x	0.76	x	0.7	=	14.01	(74)
North	0.9x	1	x	0.72	x	20.32	x	0.76	x	0.7	=	7.01	(74)
North	0.9x	1	x	0.6	x	34.53	x	0.76	x	0.7	=	9.92	(74)
North	0.9x	1	x	1.44	x	34.53	x	0.76	x	0.7	=	23.81	(74)
North	0.9x	1	x	1.44	x	34.53	x	0.76	x	0.7	=	23.81	(74)
North	0.9x	1	x	0.72	x	34.53	x	0.76	x	0.7	=	11.9	(74)
North	0.9x	1	x	0.6	x	55.46	x	0.76	x	0.7	=	15.93	(74)
North	0.9x	1	x	1.44	x	55.46	x	0.76	x	0.7	=	38.24	(74)
North	0.9x	1	x	1.44	x	55.46	x	0.76	x	0.7	=	38.24	(74)
North	0.9x	1	x	0.72	x	55.46	x	0.76	x	0.7	=	19.12	(74)
North	0.9x	1	x	0.6	x	74.72	x	0.76	x	0.7	=	21.46	(74)
North	0.9x	1	x	1.44	x	74.72	x	0.76	x	0.7	=	51.51	(74)
North	0.9x	1	x	1.44	x	74.72	x	0.76	x	0.7	=	51.51	(74)
North	0.9x	1	x	0.72	x	74.72	x	0.76	x	0.7	=	25.76	(74)
North	0.9x	1	x	0.6	x	79.99	x	0.76	x	0.7	=	22.98	(74)
North	0.9x	1	x	1.44	x	79.99	x	0.76	x	0.7	=	55.15	(74)
North	0.9x	1	x	1.44	x	79.99	x	0.76	x	0.7	=	55.15	(74)
North	0.9x	1	x	0.72	x	79.99	x	0.76	x	0.7	=	27.57	(74)
North	0.9x	1	x	0.6	x	74.68	x	0.76	x	0.7	=	21.45	(74)
North	0.9x	1	x	1.44	x	74.68	x	0.76	x	0.7	=	51.49	(74)
North	0.9x	1	x	1.44	x	74.68	x	0.76	x	0.7	=	51.49	(74)
North	0.9x	1	x	0.72	x	74.68	x	0.76	x	0.7	=	25.74	(74)
North	0.9x	1	x	0.6	x	59.25	x	0.76	x	0.7	=	17.02	(74)
North	0.9x	1	x	1.44	x	59.25	x	0.76	x	0.7	=	40.85	(74)
North	0.9x	1	x	1.44	x	59.25	x	0.76	x	0.7	=	40.85	(74)
North	0.9x	1	x	0.72	x	59.25	x	0.76	x	0.7	=	20.42	(74)

Figure 221 – SAP Worksheet, Page 5/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

North	0.9x	1	x	0.6	x	41.52	x	0.76	x	0.7	=	11.93	(74)
North	0.9x	1	x	1.44	x	41.52	x	0.76	x	0.7	=	28.62	(74)
North	0.9x	1	x	1.44	x	41.52	x	0.76	x	0.7	=	28.62	(74)
North	0.9x	1	x	0.72	x	41.52	x	0.76	x	0.7	=	14.31	(74)
North	0.9x	1	x	0.6	x	24.19	x	0.76	x	0.7	=	6.95	(74)
North	0.9x	1	x	1.44	x	24.19	x	0.76	x	0.7	=	16.68	(74)
North	0.9x	1	x	1.44	x	24.19	x	0.76	x	0.7	=	16.68	(74)
North	0.9x	1	x	0.72	x	24.19	x	0.76	x	0.7	=	8.34	(74)
North	0.9x	1	x	0.6	x	13.12	x	0.76	x	0.7	=	3.77	(74)
North	0.9x	1	x	1.44	x	13.12	x	0.76	x	0.7	=	9.04	(74)
North	0.9x	1	x	1.44	x	13.12	x	0.76	x	0.7	=	9.04	(74)
North	0.9x	1	x	0.72	x	13.12	x	0.76	x	0.7	=	4.52	(74)
North	0.9x	1	x	0.6	x	8.86	x	0.76	x	0.7	=	2.55	(74)
North	0.9x	1	x	1.44	x	8.86	x	0.76	x	0.7	=	6.11	(74)
North	0.9x	1	x	1.44	x	8.86	x	0.76	x	0.7	=	6.11	(74)
North	0.9x	1	x	0.72	x	8.86	x	0.76	x	0.7	=	3.06	(74)
South	0.9x	1	x	2.88	x	46.75	x	0.76	x	0.7	=	64.47	(78)
South	0.9x	1	x	2.88	x	46.75	x	0.76	x	0.7	=	64.47	(78)
South	0.9x	1	x	1.44	x	46.75	x	0.76	x	0.7	=	32.23	(78)
South	0.9x	1	x	2.4	x	46.75	x	0.76	x	0.7	=	53.72	(78)
South	0.9x	1	x	2.88	x	76.57	x	0.76	x	0.7	=	105.58	(78)
South	0.9x	1	x	2.88	x	76.57	x	0.76	x	0.7	=	105.58	(78)
South	0.9x	1	x	1.44	x	76.57	x	0.76	x	0.7	=	52.79	(78)
South	0.9x	1	x	2.4	x	76.57	x	0.76	x	0.7	=	87.99	(78)
South	0.9x	1	x	2.88	x	97.53	x	0.76	x	0.7	=	134.49	(78)
South	0.9x	1	x	2.88	x	97.53	x	0.76	x	0.7	=	134.49	(78)
South	0.9x	1	x	1.44	x	97.53	x	0.76	x	0.7	=	67.25	(78)
South	0.9x	1	x	2.4	x	97.53	x	0.76	x	0.7	=	112.08	(78)
South	0.9x	1	x	2.88	x	110.23	x	0.76	x	0.7	=	152.01	(78)
South	0.9x	1	x	2.88	x	110.23	x	0.76	x	0.7	=	152.01	(78)
South	0.9x	1	x	1.44	x	110.23	x	0.76	x	0.7	=	76	(78)
South	0.9x	1	x	2.4	x	110.23	x	0.76	x	0.7	=	126.67	(78)
South	0.9x	1	x	2.88	x	114.87	x	0.76	x	0.7	=	158.4	(78)
South	0.9x	1	x	2.88	x	114.87	x	0.76	x	0.7	=	158.4	(78)
South	0.9x	1	x	1.44	x	114.87	x	0.76	x	0.7	=	79.2	(78)
South	0.9x	1	x	2.4	x	114.87	x	0.76	x	0.7	=	132	(78)
South	0.9x	1	x	2.88	x	110.55	x	0.76	x	0.7	=	152.44	(78)
South	0.9x	1	x	2.88	x	110.55	x	0.76	x	0.7	=	152.44	(78)
South	0.9x	1	x	1.44	x	110.55	x	0.76	x	0.7	=	76.22	(78)
South	0.9x	1	x	2.4	x	110.55	x	0.76	x	0.7	=	127.03	(78)
South	0.9x	1	x	2.88	x	108.01	x	0.76	x	0.7	=	148.94	(78)

Figure 222 – SAP Worksheet, Page 6/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

South	0.9x	1	x	2.88	x	108.01	x	0.76	x	0.7	=	148.94	(78)
South	0.9x	1	x	1.44	x	108.01	x	0.76	x	0.7	=	74.47	(78)
South	0.9x	1	x	2.4	x	108.01	x	0.76	x	0.7	=	124.12	(78)
South	0.9x	1	x	2.88	x	104.89	x	0.76	x	0.7	=	144.64	(78)
South	0.9x	1	x	2.88	x	104.89	x	0.76	x	0.7	=	144.64	(78)
South	0.9x	1	x	1.44	x	104.89	x	0.76	x	0.7	=	72.32	(78)
South	0.9x	1	x	2.4	x	104.89	x	0.76	x	0.7	=	120.54	(78)
South	0.9x	1	x	2.88	x	101.89	x	0.76	x	0.7	=	140.49	(78)
South	0.9x	1	x	2.88	x	101.89	x	0.76	x	0.7	=	140.49	(78)
South	0.9x	1	x	1.44	x	101.89	x	0.76	x	0.7	=	70.25	(78)
South	0.9x	1	x	2.4	x	101.89	x	0.76	x	0.7	=	117.08	(78)
South	0.9x	1	x	2.88	x	82.59	x	0.76	x	0.7	=	113.88	(78)
South	0.9x	1	x	2.88	x	82.59	x	0.76	x	0.7	=	113.88	(78)
South	0.9x	1	x	1.44	x	82.59	x	0.76	x	0.7	=	56.94	(78)
South	0.9x	1	x	2.4	x	82.59	x	0.76	x	0.7	=	94.9	(78)
South	0.9x	1	x	2.88	x	55.42	x	0.76	x	0.7	=	76.42	(78)
South	0.9x	1	x	2.88	x	55.42	x	0.76	x	0.7	=	76.42	(78)
South	0.9x	1	x	1.44	x	55.42	x	0.76	x	0.7	=	38.21	(78)
South	0.9x	1	x	2.4	x	55.42	x	0.76	x	0.7	=	63.68	(78)
South	0.9x	1	x	2.88	x	40.4	x	0.76	x	0.7	=	55.71	(78)
South	0.9x	1	x	2.88	x	40.4	x	0.76	x	0.7	=	55.71	(78)
South	0.9x	1	x	1.44	x	40.4	x	0.76	x	0.7	=	27.85	(78)
South	0.9x	1	x	2.4	x	40.4	x	0.76	x	0.7	=	46.42	(78)

Solar gains in watts, calculated for each month (83)m = Sum(74)m …(82)m

(83)m=	236.28	392.81	517.75	618.23	678.25	668.98	646.65	601.29	551.8	428.25	281.1	203.52	(83)

Total gains – internal and solar (84)m = (73)m + (83)m , watts

(84)m=	914.02	1065.61	1165.98	1228.3	1249.07	1204.85	1162.25	1125.98	1098.6	1013.42	908.9	863.74	(84)

7. Mean internal temperature (heating season)

Temperature during heating periods in the living area from Table 9, Th1 (°C) 21 (85)

Utilisation factor for gains for living area, h1,m (see Table 9a)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
(86)m=	0.99	0.98	0.97	0.93	0.86	0.72	0.56	0.59	0.8	0.94	0.98	0.99	(86)

Mean internal temperature in living area T1 (follow steps 3 to 7 in Table 9c)

(87)m=	19.3	19.52	19.84	20.27	20.62	20.88	20.97	20.96	20.8	20.35	19.78	19.3	(87)

Temperature during heating periods in rest of dwelling from Table 9, Th2 (°C)

(88)m=	19.51	19.52	19.53	19.57	19.58	19.63	19.63	19.64	19.61	19.58	19.56	19.55	(88)

Utilisation factor for gains for rest of dwelling, h2,m (see Table 9a)

(89)m=	0.99	0.98	0.95	0.91	0.81	0.61	0.4	0.44	0.7	0.91	0.97	0.99	(89)

Mean internal temperature in the rest of dwelling T2 (follow steps 3 to 7 in Table 9c)

(90)m=	17.33	17.66	18.12	18.76	19.22	19.56	19.62	19.63	19.47	18.89	18.07	17.36	(90)

fLA = Living area ÷ (4) = 0.19 (91)

Figure 223 – SAP Worksheet, Page 7/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

Mean internal temperature (for the whole dwelling) = fLA × T1 + (1 – fLA) × T2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
(92)m=	17.71	18.02	18.46	19.05	19.49	19.82	19.88	19.89	19.73	19.17	18.4	17.74	(92)

Apply adjustment to the mean internal temperature from Table 4e, where appropriate

(93)m=	17.71	18.02	18.46	19.05	19.49	19.82	19.88	19.89	19.73	19.17	18.4	17.74	(93)

8. Space heating requirement

Set Ti to the mean internal temperature obtained at step 11 of Table 9b, so that Ti,m=(76)m and re-calculate the utilisation factor for gains using Table 9a

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Utilisation factor for gains, hm:													
(94)m=	0.98	0.97	0.94	0.89	0.8	0.62	0.43	0.47	0.71	0.9	0.97	0.98	(94)
Useful gains, hmGm , W = (94)m x (84)m													
(95)m=	895.85	1029.54	1099.16	1098.68	1001.3	752.5	504.44	527.53	780.14	911.45	877.95	849.54	(95)
Monthly average external temperature from Table 8													
(96)m=	4.3	4.9	6.5	8.9	11.7	14.6	16.6	16.4	14.1	10.6	7.1	4.2	(96)
Heat loss rate for mean internal temperature, Lm , W =[(39)m x [(93)m– (96)m]													
(97)m=	2343.25	2274.63	2056.55	1677.57	1277.88	819.97	516.35	543.57	900.38	1405.7	1883.06	2292.67	(97)
Space heating requirement for each month, kWh/month = 0.024 x [(97)m – (95)m] x (41)m													
(98)m=	1076.87	836.7	712.3	416.8	205.78	0	0	0	0	367.72	723.68	1073.69	

Total per year (kWh/year) = Sum(98)1...5,9...12 = 5413.54 (98)

Space heating requirement in kWh/m²/year 54.14 (99)

9a. Energy requirements – Individual heating systems including micro-CHP)

Space heating:

Fraction of space heat from secondary/supplementary system		0	(201)
Fraction of space heat from main system(s)	(202) = 1 – (201) =	1	(202)
Fraction of total heating from main system 1	(204) = (202) × [1 – (203)] =	1	(204)
Efficiency of main space heating system 1		170	(206)
Efficiency of secondary/supplementary heating system, %		0	(208)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	kWh/year
Space heating requirement (calculated above)													
	1076.87	836.7	712.3	416.8	205.78	0	0	0	0	367.72	723.68	1073.69	
(211)m = {[(98)m x (204)] } x 100 ÷ (206)													(211)
	633.45	492.18	419	245.18	121.05	0	0	0	0	216.31	425.69	631.58	

Total (kWh/year) =Sum(211)1...5,10...12= 3184.44 (211)

Space heating fuel (secondary), kWh/month
= {[(98)m x (201)] } x 100 ÷ (208)

(215)m=	0	0	0	0	0	0	0	0	0	0	0	0

Total (kWh/year) =Sum(215)1...5,10...12= 0 (215)

Water heating

Output from water heater (calculated above)

	212.77	187.54	196.98	176.61	173.1	154.7	148.6	163.02	162.72	183.14	193.61	207.66	
Efficiency of water heater												170	(216)
(217)m=	170	170	170	170	170	170	170	170	170	170	170	170	(217)
Fuel for water heating, kWh/month (219)m = (64)m x 100 ÷ (217)m													
(219)m=	125.16	110.32	115.87	103.89	101.82	91	87.41	95.89	95.72	107.73	113.89	122.15	

Total = Sum(219a)1...12 = [illegible] (219)

Figure 224 – SAP Worksheet, Page 8/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

Annual totals		kWh/year	kWh/year	
Space heating fuel used, main system 1			3184.44	
Water heating fuel used			1270.85	
Electricity for pumps, fans and electric keep-hot				
mechanical ventilation - balanced, extract or positive input from outside		369.27		(230a)
Total electricity for the above, kWh/year	sum of (230a)…(230g) =		369.27	(231)
Electricity for lighting			417.93	(232)
Electricity generated by PVs			-3713.57	(233)

10a. Fuel costs - individual heating systems:

	Fuel kWh/year	Fuel Price (Table 12)		Fuel Cost £/year	
Space heating - main system 1	(211) x	13.19	x 0.01 =	420.03	(240)
Space heating - main system 2	(213) x	0	x 0.01 =	0	(241)
Space heating - secondary	(215) x	13.19	x 0.01 =	0	(242)
Water heating cost (other fuel)	(219)	13.19	x 0.01 =	167.63	(247)
Pumps, fans and electric keep-hot	(231)	13.19	x 0.01 =	48.71	(249)
(if off-peak tariff, list each of (230a) to (230g) separately as applicable and apply fuel price according to Table 12a					
Energy for lighting	(232)	13.19	x 0.01 =	55.13	(250)
Additional standing charges (Table 12)				0	(251)
	one of (233) to (235) x)	13.19	x 0.01 =	-489.82	(252)
Appendix Q items: repeat lines (253) and (254) as needed					
Total energy cost	(245)...(247) + (250)...(254) =			201.67	(255)

11a. SAP rating - individual heating systems

Energy cost deflator (Table 12)		0.42	(256)
Energy cost factor (ECF)	[(255) x (256)] ÷ [(4) + 45.0] =	0.58	(257)
SAP rating (Section 12)		91.85	(258)

12a. CO2 emissions – Individual heating systems including micro-CHP

	Energy kWh/year	Emission factor kg CO2/kWh		Emissions kg CO2/year	
Space heating (main system 1)	(211) x	0.519	=	1652.72	(261)
Space heating (secondary)	(215) x	0.519	=	0	(263)
Water heating	(219) x	0.519	=	659.57	(264)
Space and water heating	(261) + (262) + (263) + (264) =			2312.29	(265)
Electricity for pumps, fans and electric keep-hot	(231) x	0.519	=	191.65	(267)
Electricity for lighting	(232) x	0.519	=	216.91	(268)
Energy saving/generation technologies					

Figure 225 – SAP Worksheet, Page 9/10. Data source: Stroma FSAP 2012 software.

SAP WorkSheet: New dwelling as built

Item 1		0.519	=	-1927.34	(269)
Total CO2, kg/year	sum of (265)…(271) =			793.51	(272)
CO2 emissions per m²	(272) ÷ (4) =			7.94	(273)
EI rating (section 14)				93	(274)

13a. Primary Energy

	Energy kWh/year		**Primary** factor		**P. Energy** kWh/year	
Space heating (main system 1)	(211)	x	3.07	=	9776.22	(261)
Space heating (secondary)	(215)	x	3.07	=	0	(263)
Energy for water heating	(219)	x	3.07	=	3901.52	(264)
Space and water heating	(261) + (262) + (263) + (264) =				13677.73	(265)
Electricity for pumps, fans and electric keep-hot	(231)	x	3.07	=	1133.66	(267)
Electricity for lighting	(232)	x	0	=	1283.06	(268)
Energy saving/generation technologies						
Item 1			3.07	=	-11400.65	(269)
'Total Primary Energy	sum of (265)…(271) =				4693.8	(272)
Primary energy kWh/m²/year	(272) ÷ (4) =				46.94	(273)

Figure 226 – SAP Worksheet, Page 10/10. Data source: Stroma FSAP 2012 software.

A3.3 SAP Checklist

Regulations Compliance Report

Approved Document L1A 2014 Edition, Wales assessed by Stroma FSAP 2012 program, 1.0.4.14
Printed on 13 June 2018 at 11:37:35

Project Information:

Assessed By: () **Building Type:** Detached House

Dwelling Details:

NEW DWELLING AS BUILT Total Floor Area: 100m²

Site Reference : Test House **Plot Reference:** 4P2B House

Address : Cenin Ltd, Unit 1 Parc Stormy, Stormy Down, Pyle, BRIDGEND, CF33 4RS

Client Details:

Name:

Address :

This report covers items included within the SAP calculations.
It is not a complete report of regulations compliance.

1 TER and DER

Fuel for main heating system: Electricity
Fuel factor: 1.55 (electricity)

Target Carbon Dioxide Emission Rate (TER)	26.38 kg/m²	
Dwelling Carbon Dioxide Emission Rate (DER)	11.34 kg/m²	OK

2 Fabric U-values

Element	Average	Highest	
External wall	0.12 (max. 0.21)	0.12 (max. 0.70)	OK
Floor	0.15 (max. 0.18)	0.15 (max. 0.70)	OK
Roof	0.15 (max. 0.15)	0.15 (max. 0.35)	OK
Openings	1.24 (max. 1.60)	1.60 (max. 3.30)	OK

2a Thermal bridging

Thermal bridging calculated using user-specified y-value of 0.15

3 Air permeability

Air permeability at 50 pascals	15.00 (As in this dwelling)	OK

4 Heating efficiency

Main Heating system:	Heat pumps with warm air distribution - electric Air source heat pump Efficiency 170 % Minimum 170 %	
Secondary heating system:	None	

5 Cylinder insulation

Hot water Storage:	Measured cylinder loss: 1.65 kWh/day	
	Permitted by DBSCG: 2.13 kWh/day	OK
Primary pipework insulated:	Yes	OK

6 Controls

Space heating controls	Time and temperature zone control	OK
Hot water controls:	Cylinderstat	OK
	Independent timer for DHW	OK

Figure 227 – SAP Checklist, Page 1/2. Data source: Stroma FSAP 2012 software.

Regulations Compliance Report

7 Low energy lights		
Percentage of fixed lights with low-energy fittings	100.0%	
Minimum	75.0%	**OK**
8 Mechanical ventilation		
Continuous supply and extract system		
Specific fan power:	0.92	
Maximum	1.5	**OK**
MVHR efficiency:	80%	
Minimum	70%	**OK**
9 Summertime temperature		
Overheating risk (Wales):	Slight	**OK**
Based on:		
Overshading:	Very Little	
Windows facing: South	2.88m²	
Windows facing: South	2.88m²	
Windows facing: South	1.44m²	
Windows facing: South	2.4m²	
Windows facing: North	0.6m²	
Windows facing: North	1.44m²	
Windows facing: North	1.44m²	
Windows facing: North	0.72m²	
Ventilation rate:	1.00	
Blinds/curtains:	Light-coloured curtain or roller blind Closed 100% of daylight hours	
10 Key features		
Windows U-value	1.2 W/m²K	
External Walls U-value	0.12 W/m²K	
Photovoltaic array		

Figure 228 – SAP Checklist, Page 2/2. Data source: Stroma FSAP 2012 software.