Thermal energy storage technologies for zero carbon housing in the UK

Jamal Khaled Alghamdi

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Welsh School of Architecture
Cardiff University
Cardiff, Wales, UK

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Summary of thesis

Carbon dioxide emissions reduction in the domestic sector in the UK has been increasingly in focus in recent years. Reducing carbon emissions for both operational and embedded building energy will contribute to lowering the overall emission levels.

This study aims to investigate the potential contribution of thermal energy storage systems in the UK's domestic buildings. It also aims to investigate multiple thermal energy storage technologies and their integration into zero-carbon buildings. The research process is conducted in two phases: building energy simulation, and thermal energy storage modelling.

Building energy simulation phase investigates energy performance of a single family zero-carbon house located in the UK. This simulation is performed to generate hourly thermal energy performance and calculate potential energy generated from on-site renewable sources. The energy simulation is conducted using HTB2, a computer based tool. The results show a total of 4158 kWh thermal demand while energy generation from renewables reached 6200 kWh. Although the generation exceeds demand, the simulated model requires an extra 1724 kWh of energy supply from the grid. The extra energy supply from the grid is a clear indication of an existing mismatch between energy demand and on-site energy generation.

The second phase of this research is conducted by creating a calculation model for the thermal energy storage system. This model is used to determine the performance of different thermal energy storage systems under the operational loads of the zero-carbon house. This step determines the thermal energy storage system contribution in energy demand reduction by shifting load peaks. Furthermore, this step compares the performance between different storage technologies in terms of thermal energy capacity, volumetric storage, storage medium, and annual performance. The final modelling in this study shows performance difference between different TES technologies. While thermochemical energy storage systems achieved higher energy storage capacities with lower volumes than sensible heat storage and PCM systems, all systems were able to reduce demand from grid energy. The annual energy performance of artificial thermochemical sorption materials like zeolite 13X have the ability to achieve zero-grid demand with low requirement of storage volume compared to other material types tested in this study.

Acknowledgment

Firstly, I would like to express my sincere gratitude to my main supervisor, professor Phil Jones for his academic guidance and continues support throughout the thesis research and writing. It was a privilege for me to have him as a PhD supervisor for his unparalleled knowledge, patience, dedication, and motivation. His mentoring and supervision have set an ideal example for me to follow in my research and academic career.

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Last but not least, my great and deep gratefulness to the love of my life, my wife Najwa. With her love, dedication, support, and understanding I was able to overcome every difficulty and enjoy every achievement in this phase of my life. With her by my side, I feel blessed and I would not fear to take on any challenge in life.

Jamal Alghamdi, March 2017

Table of content

Nomenclature

Abbreviation

ACH	Air change rate per hour
ASCII	American Standard Code for Information Interchange
ASHP	Air source heat pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BES	Building energy simulation
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of performance
CSH	Code for sustainable homes
CSPM	Composite salt porous matrix
DHW	Domestic hot water
EPBD	Energy Performance of Buildings Directive
GSHP	Ground source heat pump
GUI	Graphical user interface
HTB2	Heat Transfer in Buildings (Version2)
HVAC	Heating, ventilating, and air conditioning
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCRI	Low Carbon Research Institute
MVHR	Mechanical ventilation heat recovery
PCM	Phase changing material
PV	Photovoltaic
RIBA	Royal Institute of British Architects
SAP	Standards Assessment Procedure
SIPs	Structural insulated panels
TES	Thermal Energy Storage

Table of figures

1 Introduction

1.1 Background information

The emission of man-made greenhouse gases, such as sulphur oxides, nitrous oxide, and carbon dioxide, has been a significant contributor to climate change and global warming. The production of these gases is directly related to the current lifestyle of modern human beings. While most of the carbon emissions for which human beings are responsible come from various sources, the built environment is a major source of these emissions globally. In the UK, it has been estimated that the housing sector alone is responsible for a quarter of the total carbon emissions in the country (Palmer and Cooper 2012). Although these emission values show that there is scope for reducing CO_2 emissions, the move towards zero-carbon status for all new homes in the UK has resulted in a significant decrease in carbon emissions caused by the residential sector. Furthermore, the reduction in carbon emissions that results from adopting zero-carbon house technology is mainly due to the reduction in operational energy in general, and a decrease in thermal energy demand , specifically (see Figure 1-1, Figure 1-2, and Figure 1-3).

The fact that zero-carbon buildings depend on on-site energy generation means that limitations and irregularities of energy generation will affect the overall energy performance of the building. Therefore, on-site energy generation has a direct effect on the operational energy levels and zero-carbon status of the building. Furthermore, on-site energy generation in the UK generally falls into one of four main categories: solar, wind, ground source heat pump, and air source heat pump. Most of these share some operational properties, such as renewable sources, abundance, and feasibility. Overall, solar energy is considered to be the most abundant source of on-site energy (Sukhatme and Nayak 2008; Duffie and Beckman 2013). Diurnal and seasonal cycles mean that the performance of solar energy is both intermittent and variable.

In addition, the basic diurnal cycle greatly limits the benefit of solar energy, and seasonal changes in solar irradiance also significantly affect energy output (Weiss 2003). Furthermore, the energy potential of this source is also affected by the harvesting method used. For example, thermal panels can harvest up to 80% of direct solar radiation, whereas solar photovoltaic (PV) panels can be limited to 20-25% of both direct and indirect solar radiation (Lynn 2010). Other types of solar harvesting technologies have different energy outputs and operational efficiencies, but can only be used under specific conditions. For example, vacuum tubes and concentrated solar energy systems are more suitable for extremely cold conditions and locations that have short solar exposure time. In the UK, solar thermal panels and photovoltaic (PV) systems are the most desirable and efficient method for use in domestic settings (Williams 2012). The expected outcome of these solar energy systems is directly linked to several factors, such as the manufacturing method used, installation location, orientation, surface area, and degree of inclination (Lynn 2010).

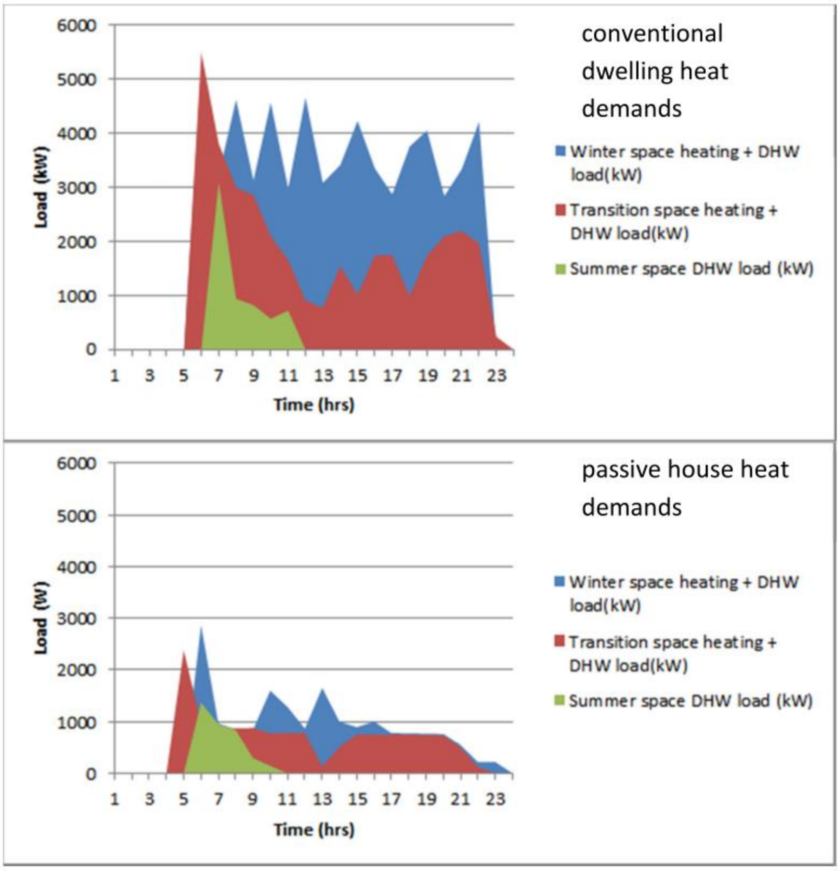


Figure 1-1: diurnal thermal energy demand comparisons between conventional dwelling and energy efficient (passive house) (Kelly et al. 2012)

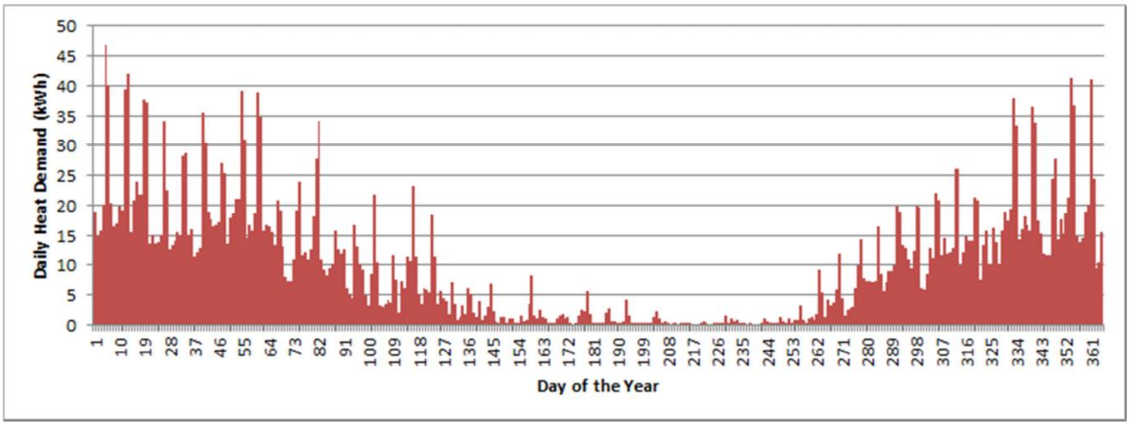


Figure 1-2: annual space heating energy demand (Kelly et al. 2012)

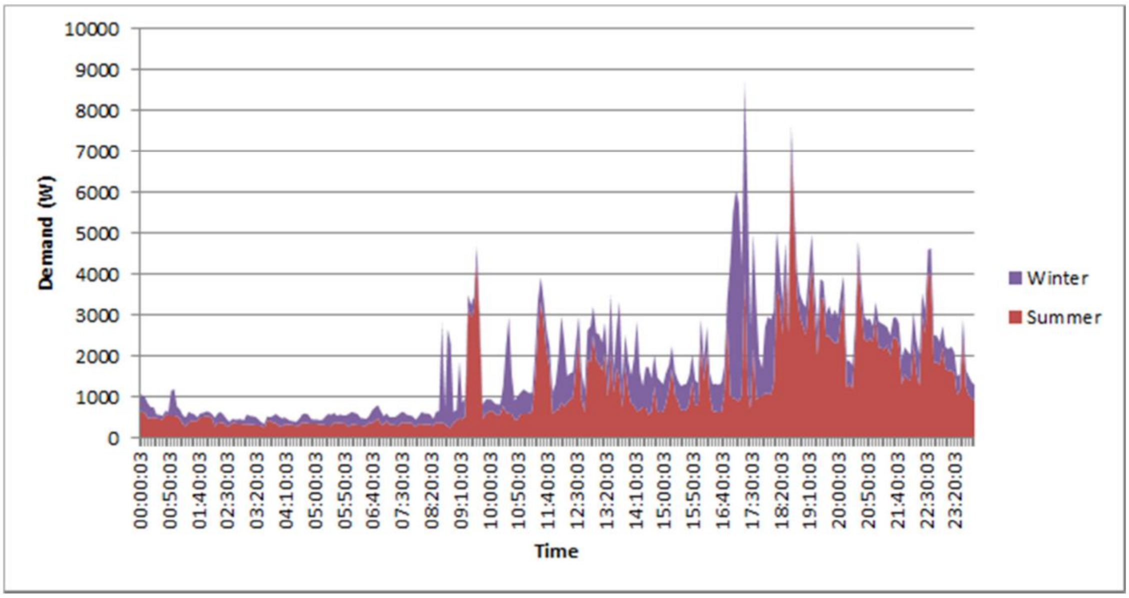


Figure 1-3: annual electrical energy demand (Kelly et al. 2012)

Finally, since it is possible to calculate both the energy consumption figures for a building and the amount of energy that can be generated on site, the problem facing energy systems designers is how to match the supply peaks to the demand peaks. Buildings that have a high-energy performance rating use energy storage methods and technologies in order to shift energy load peaks and reduce grid demand, while also integrating on-site energy generation or renewable energy sources. The principal methods used for this purpose are thermal energy storage (TES) systems; the operational theory behind these systems is the storage of excess energy for use when demand rises beyond generational capabilities or above a pre-set threshold (N'Tsoukpoe et al. 2009).

1.2 Research justifications

In energy-efficient buildings, it is necessary to reduce the thermal energy demand, or limit it with the aid of on-site energy generation, in order to achieve zero-carbon emission status, there will often be a large discrepancy between peaks in demand and the availability of energy from these sources (Heier et al. 2015). In order to reduce this mismatch between supply and demand, a thermal energy storage system is required.

There is an abundance of prior research into thermal energy storage systems in buildings. However, published studies and reviews usually focus on thermal energy storage, either by placing emphasis on specific storage methods, such as latent heat, or by narrowing their focus to storage techniques, such as building envelopes or fabric integrated storage (Heier et al. 2015). Figure 1-4 presents the current state of development for thermal energy storage systems, based on the storage technology from sensible heat to heat of reaction. The Figure also shows the theoretical energy density of these thermal energy storage technologies, which is in contrast to the state of development reported in the literature. Moreover, there is a lack of general studies on domestic thermal energy storage performance, particularly with regard to efficient energy-performing buildings. Furthermore, at the time of this study, there has been limited prior research into operational performance of thermal storage, or comparisons between different storage technologies under domestic thermal supply and demand.

The combining of efficient energy-performing domestic buildings with thermal energy storage systems has been established in the published literature. However, the available case studies do not make reference to the methods used to select thermal energy storage (TES) systems, in terms of technology and/or energy capacity. Furthermore, these case studies do not contain any operational performance measurements of the relevant thermal storage systems.

Thermal storage system	Energy density	State of development
Sensible heat	Low	High
Phase change		
Heat of sorption		
Heat of reaction	High	Low

Figure 1-4: current state of development for different TES systems (N'Tsoukpoe et al. 2009)

Therefore, one of the main motivations for conducting this research is to provide an effective way of reducing the thermal energy demand of zero-carbon domestic buildings. The outcomes of this study will make it possible for architects and system designers to select and size suitable thermal energy systems for zero-carbon buildings. Furthermore, this research will provide us with a better understanding of the different thermal energy storage media and technologies operating under zero-carbon building conditions.

1.3 Research aim and objectives

The study will seek to answer the following questions:

1- What is the thermal energy performance of zero-carbon houses in the UK, in terms of demand and potential generation from on-site sources?
2- To what extent can thermal energy storage systems shift load peaks in a zero-carbon house?
3- What is the capacity of the thermal energy storage system that can effectively reduce energy demand from grid?

Therefore, the aim of this research is:

> To investigate the potential of thermal energy storage in domestic zero-carbon houses in the UK and to investigate how thermal storage systems can shift load peaks on a diurnal and inter-seasonal basis.

In order to achieve the above-mentioned aim, this study will pursue the following three objectives:

1- Identify energy storage systems that can meet the energy demands of zero-carbon level domestic buildings.
2- Create a building energy simulation model that can calculate and predict energy supply and demand in zero-carbon domestic buildings with an energy storage system.
3- Assess the performance of diurnal and inter-seasonal thermal energy storage systems in domestic buildings in the UK.

To achieve the objectives set out above, the following three focus areas have been identified:

1- Domestic thermal energy demand patterns and consumption rates, with a special focus on zero-carbon houses. The study will also place a specific focus on the demand figures of each type of thermal energy demand in zero-carbon houses.
2- On-site energy generation in the UK in general, in terms of availability, possible energy input, and harvesting technologies. There will be a special focus on solar energy as a potential source.
3- Thermal storage systems, in terms of type, efficiency, capacity, and usage.

4- Energy simulation methods and tools for domestic buildings.
5- This research focuses on the UK as a location of interest.

1.4 Research methods and work flow

Three research methods have been used to answer the research questions and to achieve the research aim and objectives:

1. ***Literature review***

   This method was used to review existing knowledge regarding the three areas of this study. The first of these is domestic energy demand patterns and profiles in the UK. This area is also concerned with the current development of high energy performance buildings, including zero-carbon buildings. Secondly, the literature review was used to review the computational energy simulation tools that are currently available for simulating energy performance in domestic buildings, and to compare their properties and abilities. The third area is concerned with thermal energy storage technologies that have been developed for domestic applications, including storage methods, storage media, thermal and physical properties, energy storage capacities, and operational performance.
2. ***Computational energy simulation***

   This method was used to predict the energy performance of the zero-carbon building that was used as a case study in this research. This is a hypothetical case study that has been created by setting the physical and operational attributes of the building, including design, layout, orientation, geographical location, weather information, occupancy, and the fabric of the building.
3. ***Numerical modelling of thermal energy storage systems***

   This method is used to calculate the amount of energy charge/discharge over time for the selected thermal energy storage systems in this research, and is based on the findings of the simulation model. It combines the output data from the energy performance simulations with input from different thermal energy storage systems, and calculates the performance of each of the selected systems on an hourly basis.

These methods were carried out in four phases, and have been sequenced in an order that serves the purpose of this research. These phases are shown in Figure 1-5, and are ordered as follows: literature review, building the energy simulation, thermal energy storage calculation, and, finally, an analysis and discussion of the results.

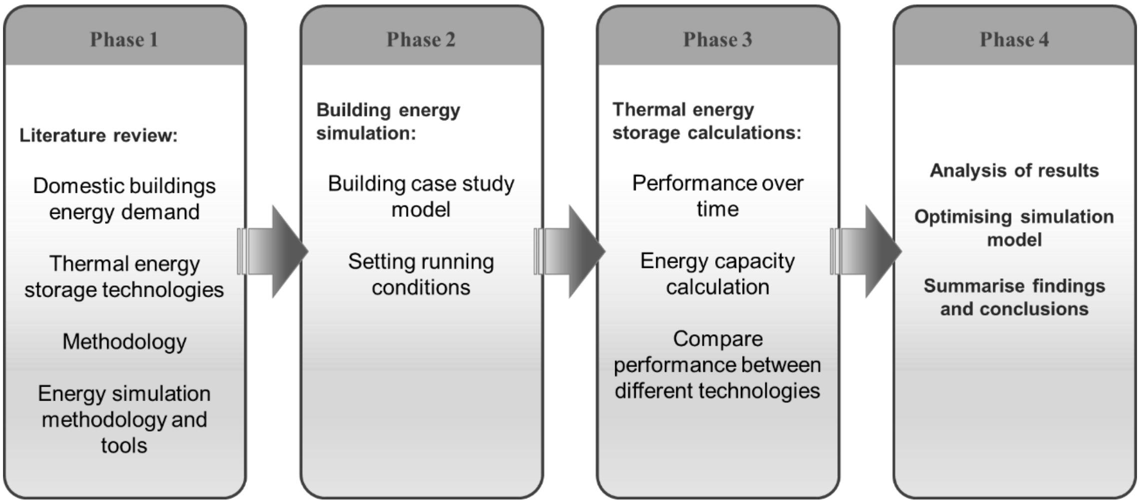


Figure 1-5: research workflow

1.5 Research contribution

This research has the potential to make the following contributions:

1. **Energy performance simulation:** thermal energy simulation of zero-carbon buildings will provide us with a better understanding of high energy performance buildings in the UK. Moreover, the results of the simulation will also provide an insight into the potential issues that may arise when implementing this type of building in the future.
2. **Thermal energy storage:** modelling the different TES technologies that are currently available for domestic applications will give system designers and architects a reference point. The results will identify load shifting ability on a diurnal and seasonal cycles, thus testing the extent to which each system reduces demand for energy from the grid. In addition, the results will also enable future studies to develop more efficient storage methods and will also make it possible to combine systems in order to achieve better performance and output.

1.6 Thesis outline

The chapters of this thesis will be organized as follows (see Figure 1-6):

Chapter 2: This chapter comprises a review of the literature on energy performance in buildings. In addition, this chapter examines the current profiles of thermal energy demand in UK houses, the possibilities for generating energy from on-site sources, and the current status of zero-carbon buildings in the UK, in terms of limitations and performance. Furthermore, this chapter also presents several case studies in the UK and EU that exemplify high energy performance with on-site energy sources.

Chapter 3: This chapter provides background knowledge on thermal energy storage systems. It gives an explanation of the thermal energy storage principle, energy storage types and media, system designs, heat loss factors, operational performance, storage improvements, and the integration of thermal energy storage systems with solar energy. This chapter also uses case studies to make brief comparisons between the various thermal storage designs.

Chapter 4: This chapter describes the methodology used in this research. It reviews the literature on energy performance calculation methods and identifies the most suitable method for this study. In addition, this chapter investigates different energy simulation tools, before going on to present the research methodology, the limitations of the selected methodology, and, finally, the research framework.

Chapter 5: This chapter describes the process of building the case study for this research. It includes a description of the concept of zero-carbon buildings and compares this concept to the Passivhaus standards, with regard to qualifications, standards, and performance. Moreover, this chapter provides a detailed account of the different aspects of case study design, simulation input, processing method, and any issues or uncertainties that arose during the course of the research.

Chapter 6: This chapter presents the results of the simulation and modelling. The results are shown in two phases: the first phase includes the results of the energy simulation of a zero-carbon house, and the second phase presents the results of incorporating the thermal energy storage system into the house. Furthermore, this chapter compares the performance of different thermal energy storage systems, in terms of energy storage capacity, volume required, storage medium, and applicability into domestic buildings.

Chapter 7: This chapter summarises the final conclusions that can be drawn from this research, highlighting the key findings and making recommendations for future research.

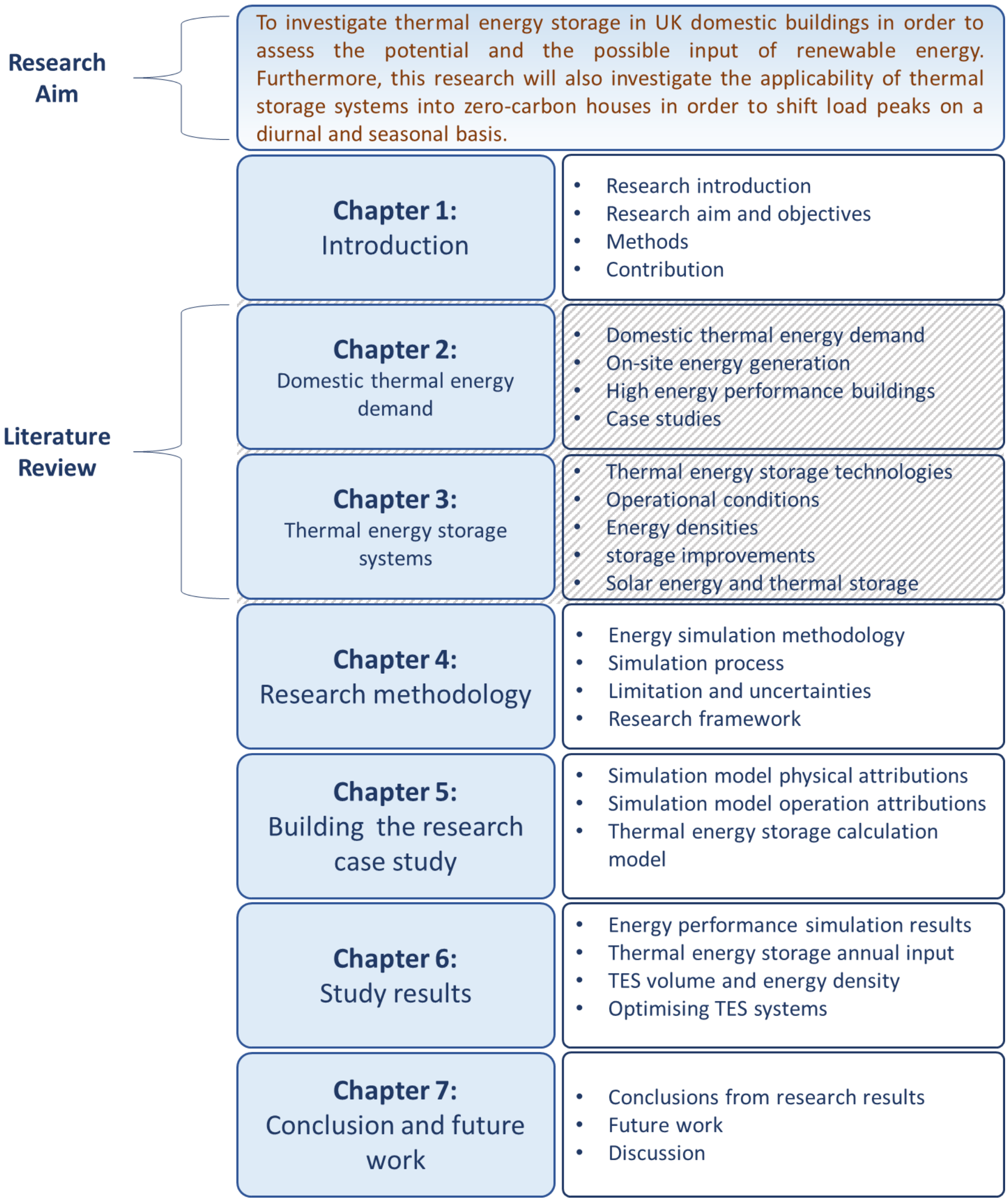


Figure 1-6: Structure of the chapters of the thesis

2 Domestic Thermal Energy Demand and potential on-site energy sources

This chapter explores the theoretical background of domestic energy consumption in the UK, focusing in particular on net zero-carbon houses. It also examines a number of related subjects, including: renewable energy sources; the concept of zero-carbon buildings; and the performance of domestic low energy buildings in the UK. This literature review thus provides an effective starting point for answering the research questions regarding the thermal energy performance of zero-carbon buildings, and developing a suitable methodology for predicting the energy performance of newly constructed zero-carbon houses. In addition, it also presents a separate case study concerning efficient energy of buildings in the UK and the EU zone relating to the general subject of this current research.

2.1 Domestic thermal energy demand in the UK

The UK Housing Energy Fact File (Palmer and Cooper 2012) states that the UK housing sector is responsible for generating one quarter of total national carbon emissions in the UK. Thus, domestic housing in the UK consumes more energy than the transportation and industrial sectors combined. Palmer and Cooper (2012) also estimated that the energy consumption of the housing sector in 2011 was approximately 452 TWh of the UK total of 1,710 TWh, i.e. almost one third of the total energy consumed in the UK. Furthermore, this share of energy has increased, from one quarter in 1970, to one third in 2011. Palmer and Cooper (2012) outlined the contributing factors in overall figures and graphs undertaken over the previous four decades of energy consumption in the domestic sector of the UK. Their report demonstrated that the level of energy usage and consumption patterns have increased in the UK's homes, regardless of the increased building thermal performance and the development of on-site energy microgeneration.

The following section discusses the published reports focussing on the thermal energy demand of the domestic sector in the UK, with particular attention given to the factors shaping the thermal energy demand profiles within UK homes.

2.1.1 Thermal energy demand in the UK's domestic sector

Thermal energy demand in the UK's domestic sector can be classified into two categories: (1) space heating and (2) domestic hot water. Both interchange according to the seasons, based on external environmental factors. An examination of government reports, and surveys carried by official agencies, indicated a similar trend in relation to annual thermal demand. The following section investigates each thermal demand category, as well as the factors contributing to the demand profiles.

2.1.1.1 Space heating

The section entitled 'How much energy is used in homes?' in the *UK Housing Energy Fact File* stated that space heating consumes the majority of the total energy used by UK households. The authors further argued that the records of the previous four decades reveal an increase in the energy demand of space heating by approximately one tenth since 1970 (see Figure 2-1). Although this increase in demand is limited by the higher insulation regulations for new houses, it still leads to a higher demand, as a result of the increase in the total number of homes in the UK (i.e. an increase of approximately 44% since 1970), alongside an increasing demand for warmer homes. The authors also noted that the share of space heating in the total energy consumed within UK's households has increased from 58% to 61.3% (see Figure 2-1). This increase in thermal demand results from a recent increase in the number of central heating systems, which has also increased the volume of heated spaces and extensions to UK homes (Palmer and Cooper 2013).

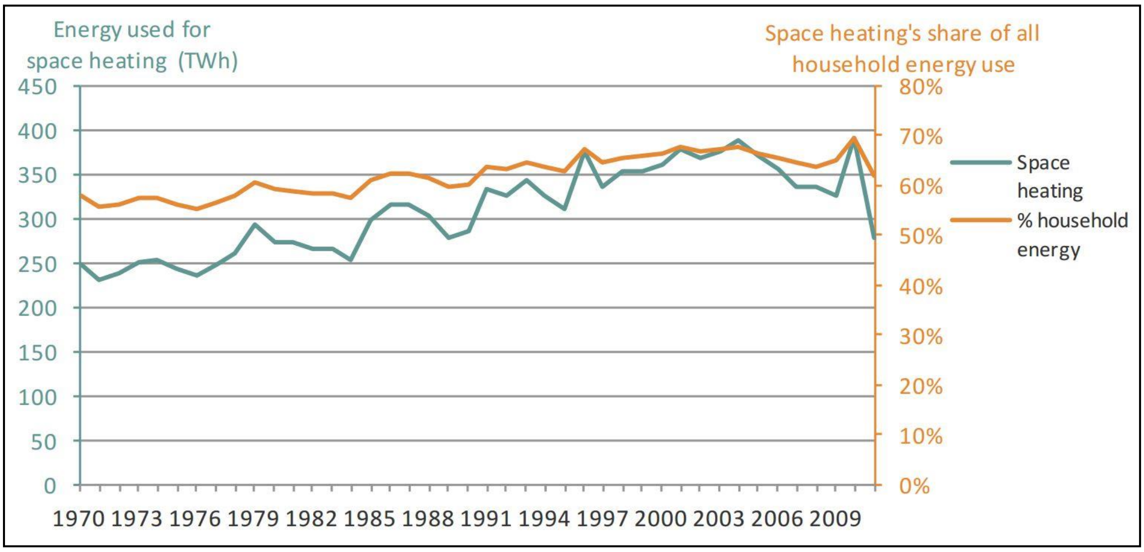


Figure 2-1: Space heating energy figures of the UK's houses (Palmer and Cooper 2012)

The total thermal energy demand within the UK (including space heating in residential buildings) accounts for 40% of the national thermal energy demand (Hawkes et al. 2011). Figure 2-2 demonstrates the share of thermal energy consumed in the UK in 2006. Hawkes et al. (2011) stated that the total residential thermal energy demand accounts for 50% of all annual thermal energy consumption for non-transport sectors.

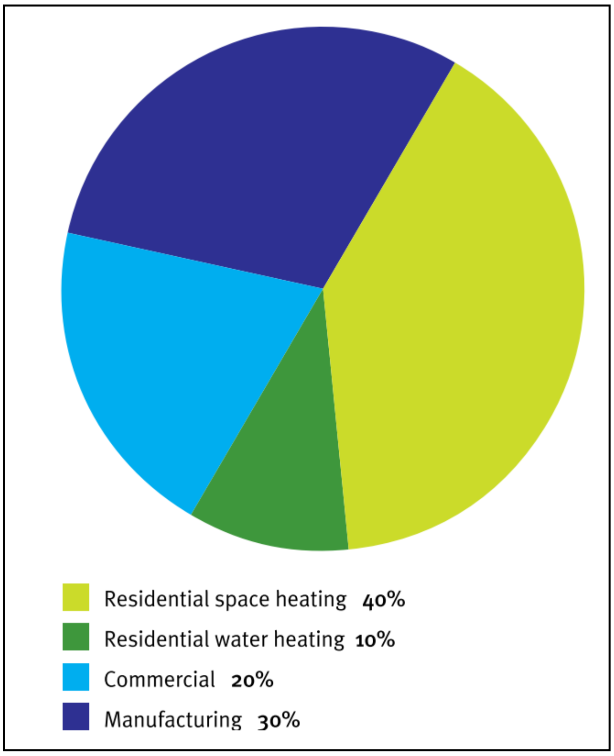


Figure 2-2: UK's national thermal energy consumption in 2006 based on demand type (Hawkes et al. 2011)

A number of factors contribute to the demand for space heating. Wei et al. (2014) stated that these include environment, buildings, and occupants. These factors primarily influence the demand for space heating through the behaviour of the occupants, but are also present in every domestic building in the UK. These factors are discussed in the following section.

1. Environmental factors

The impact of the environment on the demand for space heating has been frequently investigated over previous decades. In general, the greater the difference between indoor and outdoor temperatures, the higher the demand for heating. While this demand is also affected by the building and occupants, the environment has been established as the primary factor (Palmer and Cooper 2013; Wei et al. 2014). The majority of dwellings in the UK have an indoor temperature set to approximately 20°C, and therefore the colder the outside temperatures, the higher the energy demand to raise the indoor temperature to this set temperature (Palmer and Cooper 2013). At the same time, the demand for space heading in the UK has been reduced by milder winters since 2010 (ibid).

Zimmermann et al.'s (2012) report *Household Electricity Survey: A study of domestic electrical product usage* also considered seasonal change in outdoor temperatures as a significant factor, as the operation of space heating equipment is directly correlated to seasonal changes in weather. Figure 2-3 demonstrates the impact of seasonal change on the operation of heating equipment. The operational measure on the left of the graph (vertical axis) indicates the change from the normalised operation statues represented by the value of 1 (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012).

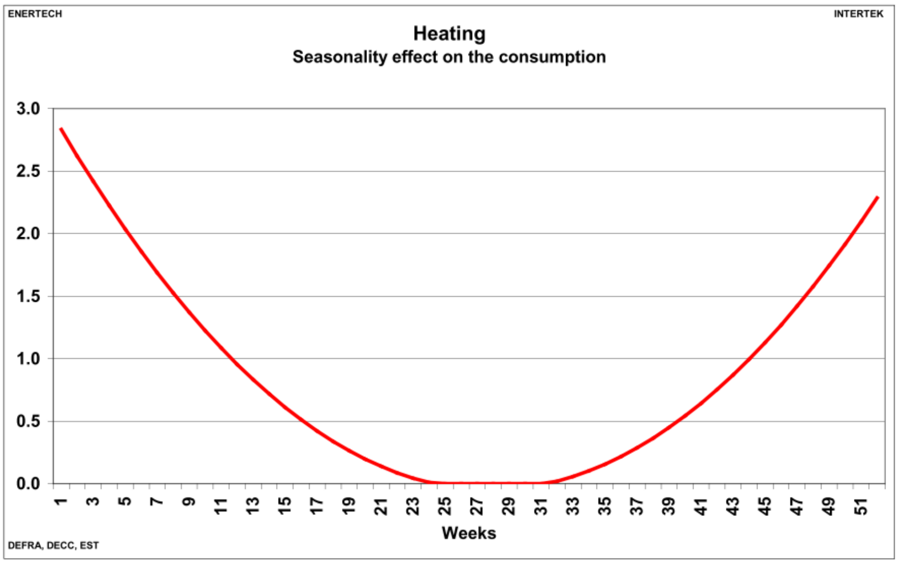


Figure 537 Heating – Seasonality effect for water and space heating

Figure 2-3: Seasonal operation of space heating and water equipment (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012)

2. Building and systems factors

A number of studies have established a correlation between building attributes and energy demand in general, and space heating demand in particular. This section therefore considers these attributes and space heating profiles in the UK as established by existing studies.

Palmer and Cooper (2013) stated that the two most important factors determining the demand for space heating and heating energy usage in general are the efficiency of space heating systems and insulation. They also considered that these two factors are closely related to the age of a building age, i.e. the older the building, the less efficient its heating system and insulation. Even older homes that have undergone improvements have a lower thermal performance than new builds (ibid). Table 2-1 demonstrates the average of the UK’s dwelling stock, based on type and floor area with average heat loss (Kelly et al. 2012).

Recent surveys commissioned by the Department for Communities and Local Government presented a key view of the current state of housing stock in the UK, in terms of age, type, condition, and tenure. In the report published in 2008, the most common type of dwelling was semi-detached, comprising 26% of the total housing share. The most noticeable figure in this report is the high percentage of buildings built prior to 1919 and between 1965 and 1985 (Department for Communities and Local Government 2010b). Further studies based on this survey have calculated that the U-values of the building components depend on the building age and construction type (see Table 2-2), with their aim being to consider the effectiveness of retrofitting old dwellings in order to increase the overall thermal performance. Dowson et al. (2012) noted that retrofitting poses a considerable challenge, since the majority of the buildings from these two eras are viewed by BRE's published reports as 'hard to treat' (BRE 2008), i.e. dwellings with: hard walls; no access to a gas network; lacking a loft; and high rise flats. Figure 2-4 demonstrates the percentage of hard to treat dwelling in the UK, based on type.

The most recent report reveals that a large proportion of the current housing stock in the UK is well below current thermal performance standards. New strategies must be devised by local governments to increase retrofitting, in order to meet the latest regulations from the UK government and the EU (Jones et al. 2013). Retrofitting an existing building in order to reduce carbon emissions by 80% requires a 'whole house' approach, rather than targeting individual elements of the building (ibid). Therefore, a near zero carbon reduction is highly dependable on the original state of the building, including its age and type, and whether it is economically feasible to retrofit. This study will therefore focus solely on new-built zero carbon homes. In addition, the feasibility of retrofitting is also related to fuel poverty and policy, which are beyond the scope of this current study.

Table 2-1: UK's dwellings by type, area and heat loss averages (Kelly et al. 2012)

Type	Detached	Semi-detached	Terraced	Flat	Other
% of housing stock average	28	28	19	16	9
Average floor area (m^2)	136	87	58	56	n/a
Average heat loss (W/°C)	342	265	235	167	n/a

Table 2-2: U-values targets in the historic building regulations (Dowson et al. 2012)

Building Regulations	Exposed walls (W/m2 K)	Roof (W/m2 K)	Floor (W/m2 K)	Windows (W/m2 K)	Air permeability (m3/m2h @ 50Pa)
1976	1.0	0.60	n/a	n/a	n/a
1982	0.6	0.35	n/a	n/a	n/a
1990	0.45	0.25	0.45	3.3	10
1995	0.45	0.25	0.35	3.3	10
2000	0.35	0.25	0.25	2.2	10
2006	0.35	0.16-0.25	0.25	2.0-2.2	10

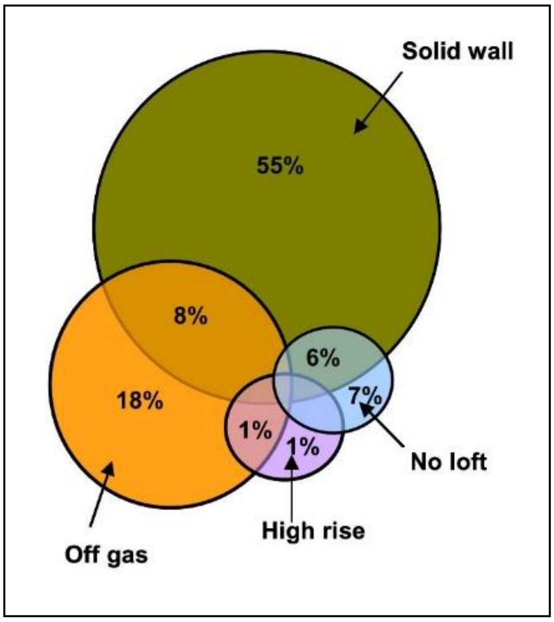


Figure 2-4: Percentage of hard-to-treat types of dwellings in the UK (BRE 2008)

Zimmermann et al. (2012) monitored energy consumption in 251 households in England, resulting in beneficial data relating to the demand for space heating and hot water, and demonstrating the average consumption rates per household, area, and also per individual (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012). While the primary aim of this survey is to monitor electrical energy consumption, the issue of the use of electrical energy for space heating is strongly related to this study. Figure 2-5 demonstrates the annual consumption values for space heating for all households, including the average value for the sample surveyed (equal to 2135 kWh/year). Furthermore, Figure 2-6 demonstrates the space heating energy consumption rate per area (i.e. square meter), establishing that the average rate for all households is 38 kWh/m^2/year. Finally, Figure 2-7 shows the average space heating consumption per person per household (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012).

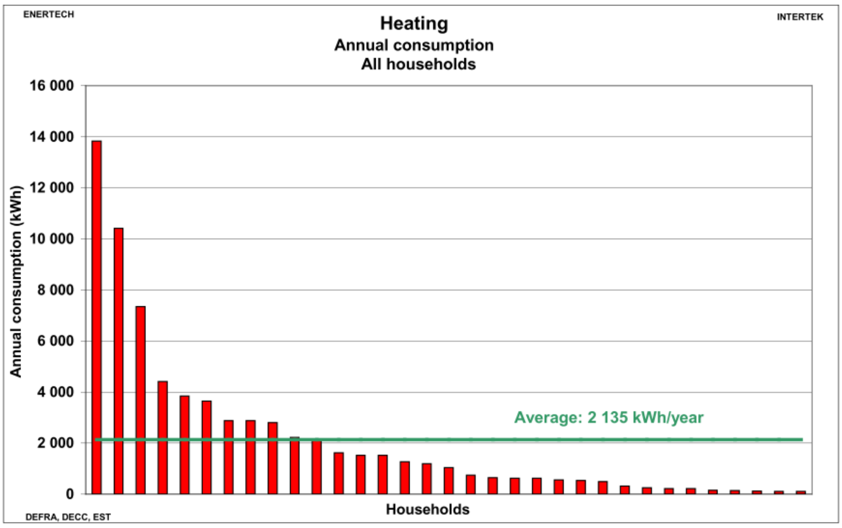


Figure 2-5: annual space heating consumption per household (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012)

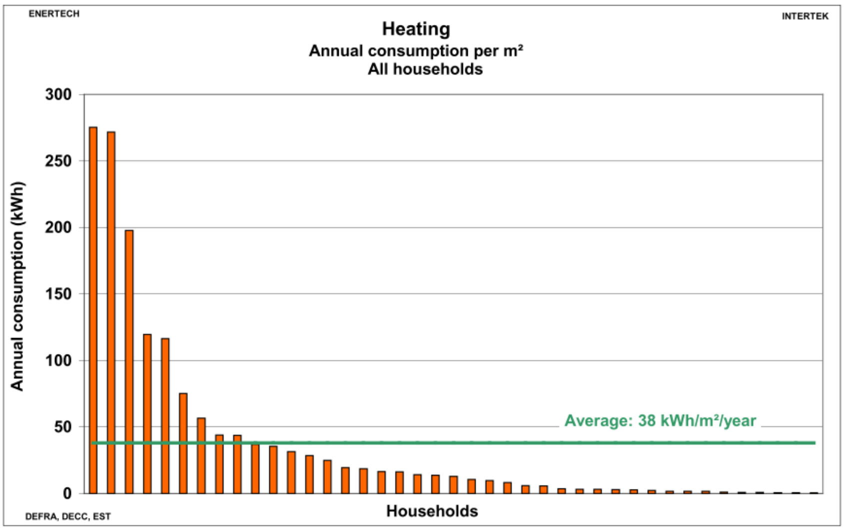


Figure 2-6: Annual space heating consumption per area (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012)

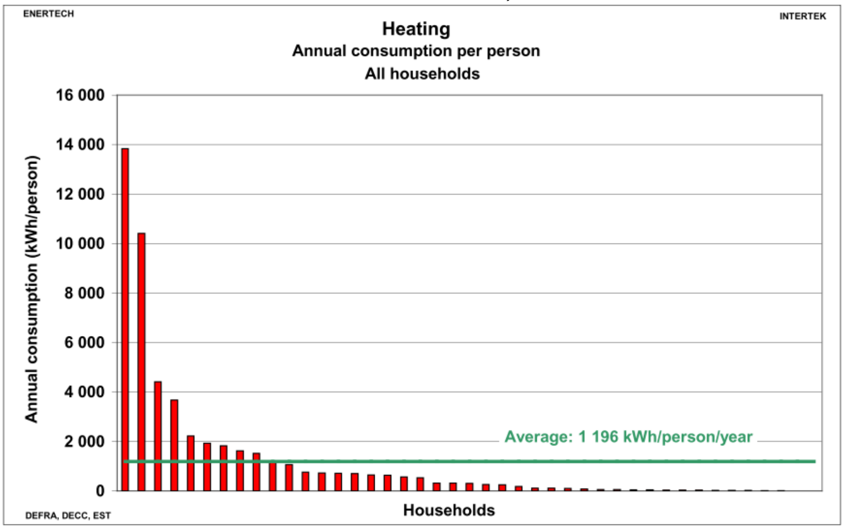


Figure 2-7: Annual space heating consumption per person (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012)

A number of previous studies have investigated the means of delivering heat into space, i.e. the equipment and type of fuel employed. BRE's (2005) reports on domestic energy demand in England identified three main methods of space heating: (1) central heating; (2) programmable; and (3) other. Central heating is defined by BRE (2005) as a system distributing heat to at least one room other than the one in which the boiler is located, and which utilises mains gas (91%) or other (9%) fuel sources. Programmable heating is operated automatically by a timer and is designated to heat an individual room, generally using electricity or hot water. The final system can be subdivided into fixed, and non-fixed, heating systems, and is designated to heat an individual room without being operated automatically (BRE 2005b). BRE also stated the ratio of these systems in the surveyed sample, as shown in Figure 2-8 (ibid). BRE's reports outlined the most common methods of delivering heat into UK houses, regardless of building type, age, and occupancy (ibid), which accords with Zimmermann et al. (2012). The average energy consumption rate for the central heating methods identified in the survey undertaken by Zimmermann et al. (2012) is equal to 1,202.3 kWh/year, in comparison to 1,076.3 kWh/year for individual heaters (i.e. programmable, fixed, and non-fixed heaters).

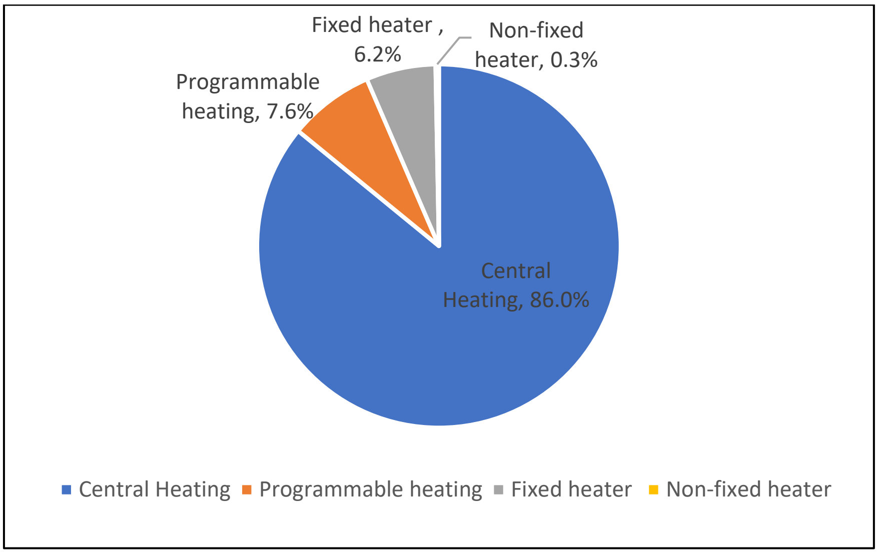


Figure 2-8: Space heating methods (BRE 2005a)

A further issue reviewed in a number of studies concerns the size and type of households in relation to space heating. The argument for an increased demand for energy as a result of increased volume was supported by *Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use* (Yohanis et al. 2008), which identified a strong correlation between the floor area of UK homes and the significant increase in energy demand, including for space heating (see Figure 2-9).

Yohanis et al. (2008) identified energy usage through the monitoring of twenty-seven UK houses, of different types, in order to determine the impact of the behaviour of the inhabitants on energy consumption levels. Although the study revealed a slight difference in annual energy consumption patterns between different types of dwelling, there was a significant difference in the daily energy consumption figures. The authors identified several conditions causing such differences, but referenced the main factors as being: (1) the behaviour of the occupants and (2) the number of occupants per dwelling (Yohanis et al. 2008).

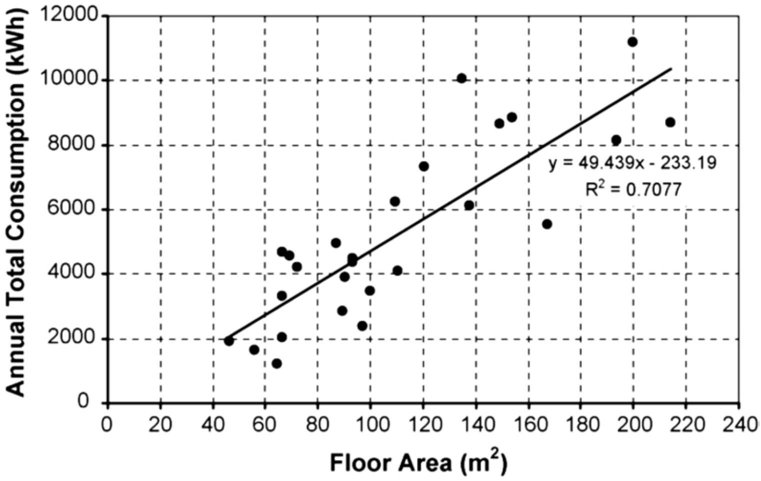


Figure 2-9: Electrical consumption in relation to floor area in the UK dwellings (Yohanis et al. 2008)

3. Occupants

The behaviour of the occupants played a considerable role in shaping current energy consumption figures, in particular the demand for space heating. A number of studies have observed different aspects of occupants' attributes and behaviour patterns, and the ways they can alter the total energy consumption figures. Yohanis et al. (2008) identified total household income as one of the main factors motivating occupants to expand the area of their dwelling, or having the ability to use a central heating system. This conclusion is also supported by multiple published works, including the study of Palmer and Cooper (2013), along with a series of reports entitled *Energy Use in Homes: A series of reports on domestic energy use in England* (BRE 2005b).

Further factors recently studied include the age of the occupants, i.e. *Keeping warm? Self-reported housing and home energy efficiency factors impacting on older people heating homes in North Wales* (Burholt and Windle 2006), and *The challenge to UK energy policy: An ageing population perspective on energy saving measures and* *consumption* (Hamza and Gilroy 2011). These researchers concluded that the age of occupants can significantly alter energy consumption levels, and in particular the demand for space heating. Hamza and Gilroy (2011) stated that 27% of all tenures of UK households are by older people (i.e. over the age of sixty), with 70% of all homeowners in the UK being aged sixty-five or older (original figures are from the Department of Communities and Local Government housing survey). These figures are expected to increase by the year 2026, to 75% of home ownership (ibid). The researchers suggested that the dwellings of older occupants are more likely to have an outdated heating system, and no (or inadequate) insulation, leading to issues concerning heat loss. In addition, the reduced income of older homeowners can also reduce the likelihood of improving the thermal conditions of the dwelling to meet current standards. A further issue for an older occupant concerns the degree of thermal comfort, since both their activity level and metabolism are lower than that of the average adult (Cena et al. 1988), and their perception of ambient temperatures differs from younger adults when all factors are taken into consideration, i.e. activity level,; clothing; body type; and ambient temperature (Havenith 2001). A number of studies employing surveys also concluded that older occupants (i.e. aged 70 and over) are more likely to increase their indoor thermal temperature to meet their comfort level (Tsuzuki and Iwata 2002).

A number of studies investigating energy consumption levels in UK homes have also observed the role of the behaviour of the occupants in shaping the demand profile. In the article *Evaluation of time series techniques to characterise domestic electricity demand*, McLoughlin et al. (2013) noted a variation in energy consumption profiles both for a single household and a number of households, i.e. diurnal, intra-daily, and seasonally. This change is due to irregularities in the behaviour of the occupants and their working/sleeping habits (see Figure 2-10). This was also noted by Yao and Steemers (2005) in their attempt to formulate a modelling approach to predict the daily energy consumption for an average UK household. The main factors contributing to demand profiles are: (1) the number of occupants; (2) working patterns; (3) the presence of children, and whether they attend school; and (4) unoccupied periods per household (Yao and Steemers 2005). Although previous studies focused on electrical demands rather than the thermal energy demand of a dwelling, the outcome of these studies relates to space heating, for the following reasons: (1) the operation of space heating is also effected by the daily routine of occupants; and (2) the operation of other appliances and lighting also effects the demands on space heating by adding to internal heat. The survey undertaken by Zimmermann et al. (2012) demonstrated similar patterns of space heating energy demands by occupants in relation to working days and holidays, as demonstrated in Figure 2-11 and Figure 2-12.

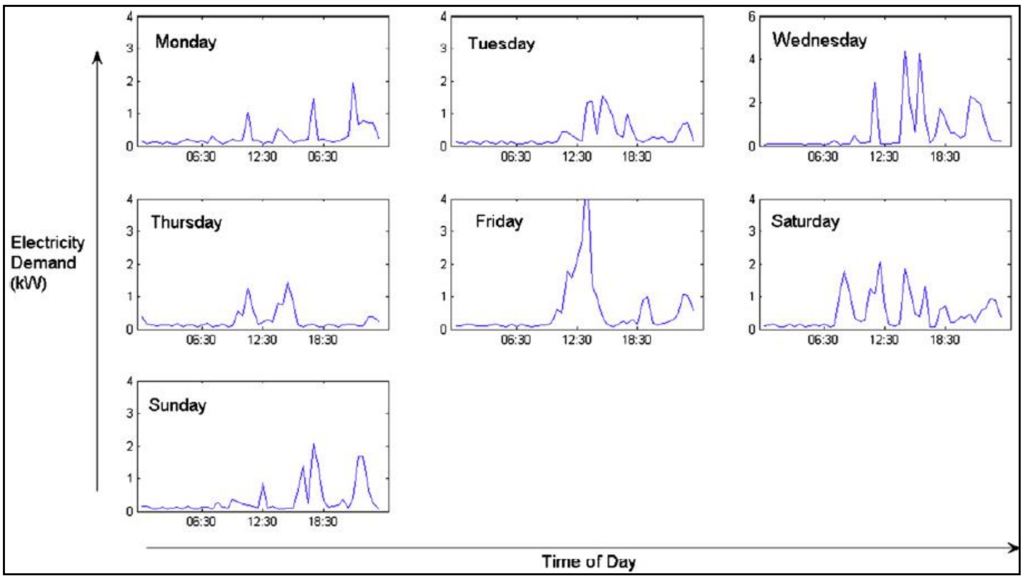


Figure 2-10: An intra-daily variation in electrical demand in a single household (McLoughlin et al. 2013)

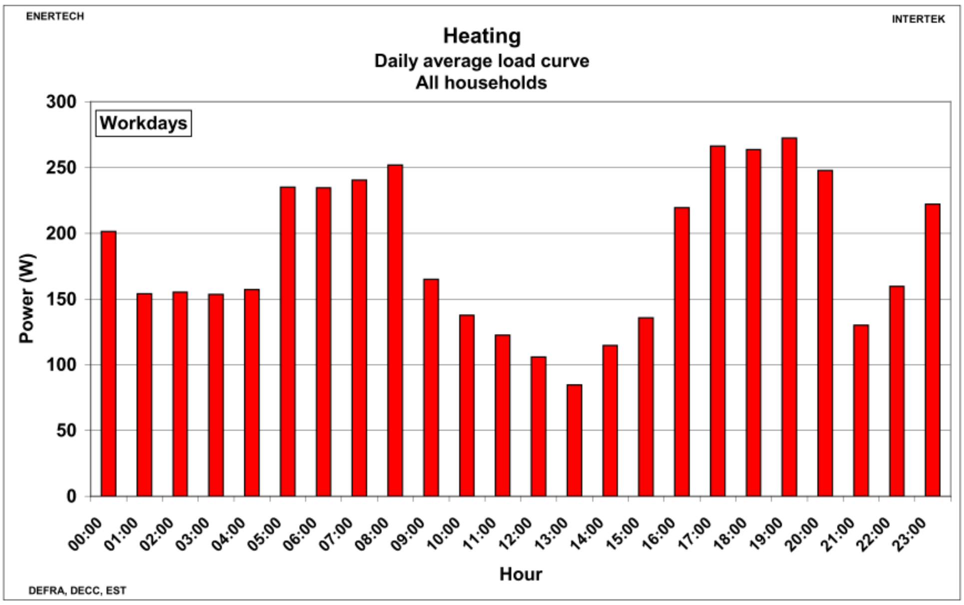


Figure 2-11: Average space heating energy demand during workdays (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012)

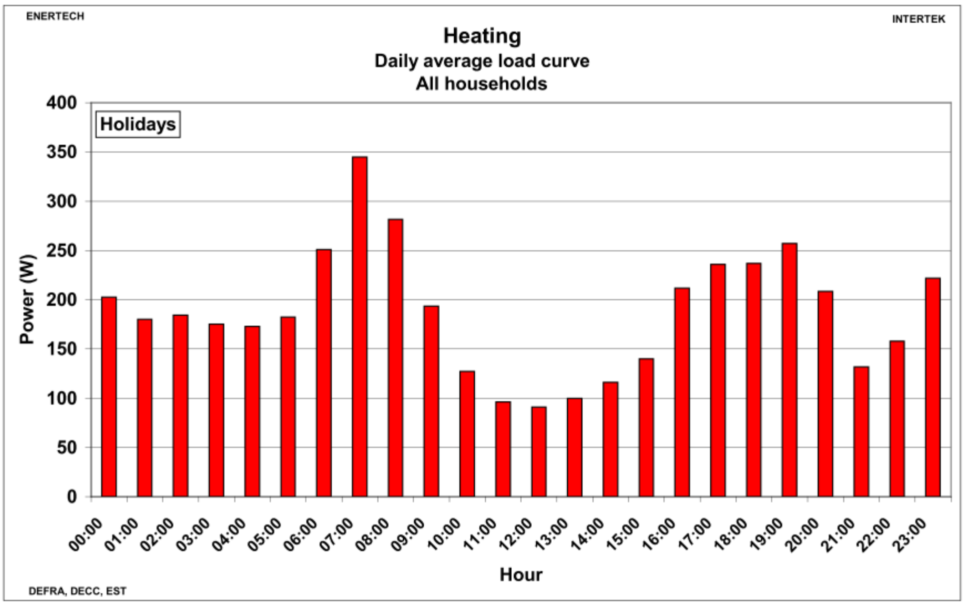


Figure 2-12: Average space heating demand during holidays (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012)

4. Other factors

Recent studies have also investigated a number of further factors. One of the main factors influencing space heating consists of the reaction of the occupants to the price of fuel. The amount of spending on space heating energy was studied by Wilhite et al. (1996) and Hitchings and Day (2011), who found that the occupants change their heating preferences according to fuel prices and energy costs (Wilhite et al. 1996; Hitchings and Day 2011; Wei et al. 2014).

2.1.1.2 Domestic hot water

Palmer and Cooper (2013) noted that domestic hot water (DHW) energy consumption has fallen dramatically over the past four decades. The share of energy consumed for heating water within a household has also decreased from 30% in the 1970's to approximately 18% in 2010 (see Figure 2-13). The reason for this decrease includes higher efficiency in energy utilisation by water heaters and dishwashers, and also the improvement of insulation for hot water storage tanks and pipes.

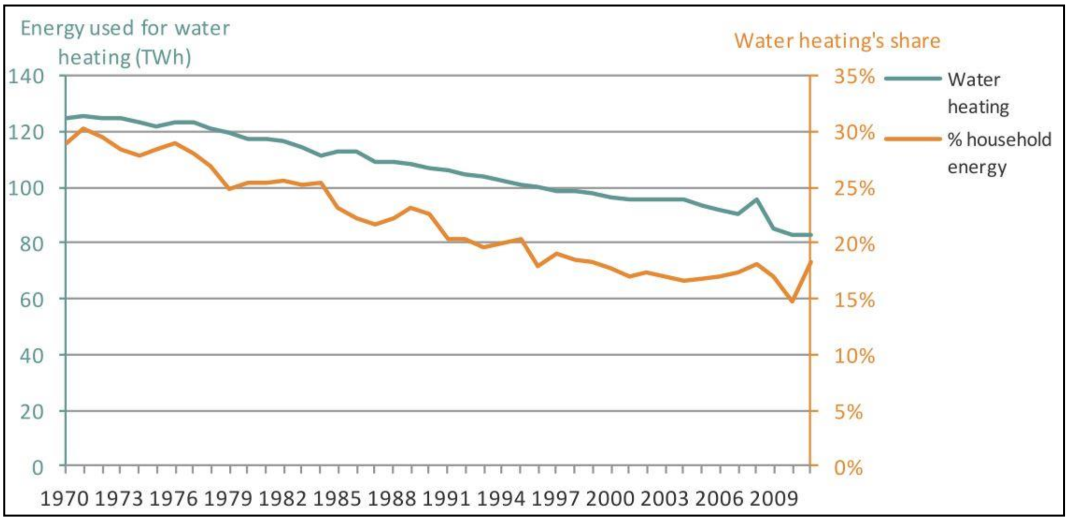


Figure 2-13: Water heating energy consumption in households in the UK (Palmer and Cooper 2013)

The Energy Saving Trust conducted a water consumption study in dwellings in the UK, based on survey of 124 households. The results were published in the report *Measurement of Domestic Hot Water Consumption in Dwellings*, and demonstrated an average consumption level of 122 litres of hot water per household per day (Energy Saving Trust 2008). The report also identified daily consumption profiles for hot water per household, in which a major factor in determining levels of demand was identified as the behavioural patterns of the occupants. The primary factor in levels of demand concerns the morning routine, which resulted in over 60% of the total daily demand (see Figure 2-14). These figures accord with the survey undertaken by Zimmermann et al. (2012), which revealed similar patterns of DHW energy demand. Figure 2-15 demonstrates the daily average water heating demand for a survey of 251 households in England, using an electrical heating system (ibid).

Energy used to heat water for dwellings is also affected by two further factors, i.e. inlet water temperature and the daily running time of the boiler. The average mean of daily time spent heating water, as reported by the Energy Saving Trust (2008), is approximately 2.6 hours, with the majority of the sample surveyed being between two and four hours per day (see Figure 2-16). The amount of energy needed to increase water temperature is also reliant on the initial temperature of the water, which is inconsistent throughout the year. The report presents the average figures of the inlet water temperatures where it fluctuates monthly, while the heated water is fixed around 52°C (see Figure 2-17). This seasonal change of inlet water temperatures can be estimated, but can be difficult to predict precisely for energy consumption calculations, due to relying on several factors inherited from main supply lines (Energy Saving Trust 2008).

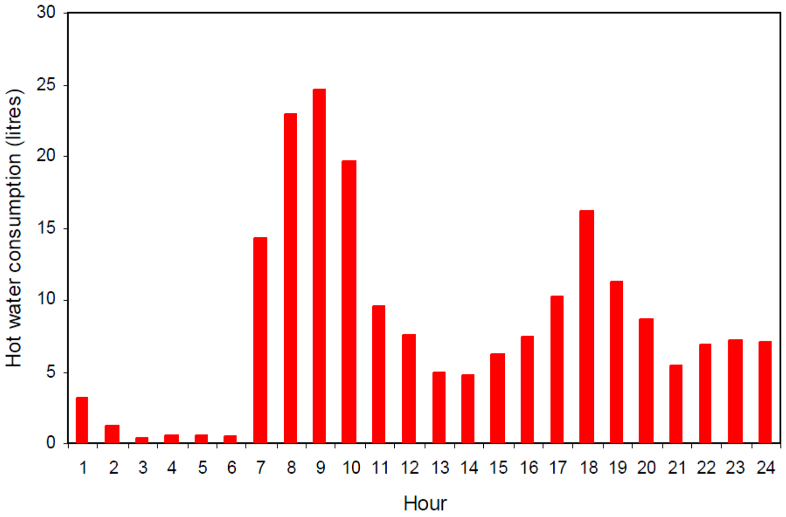


Figure 2-14: Daily hot water consumption profile per household (Energy Saving Trust 2008)

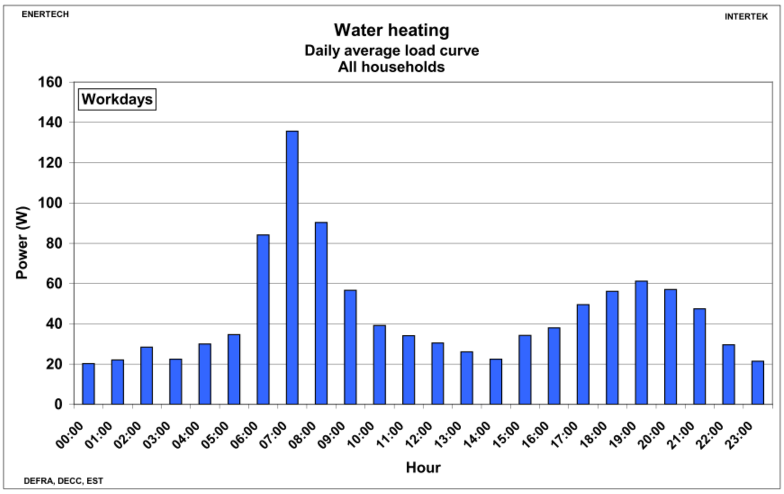


Figure 2-15: Daily average water heating energy demand (Zimmermann, Evans, Griggs, King, Harding, Roberts, Evans, et al. 2012)

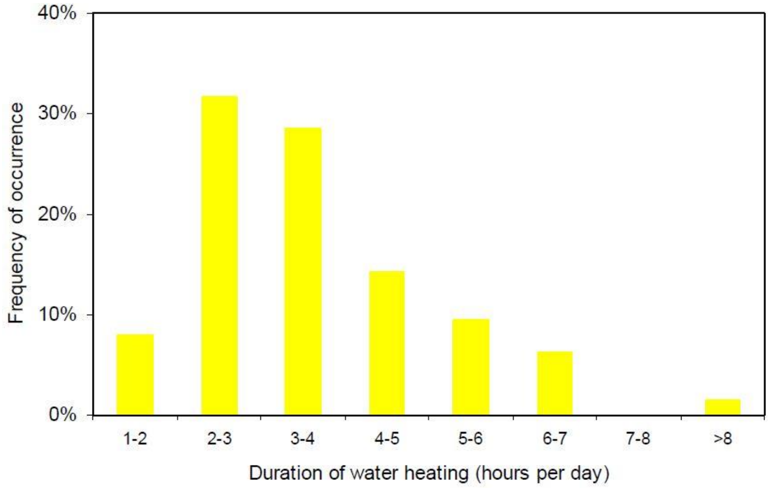


Figure 2-16: Water heating time in UK's dwellings (Energy Saving Trust 2008)

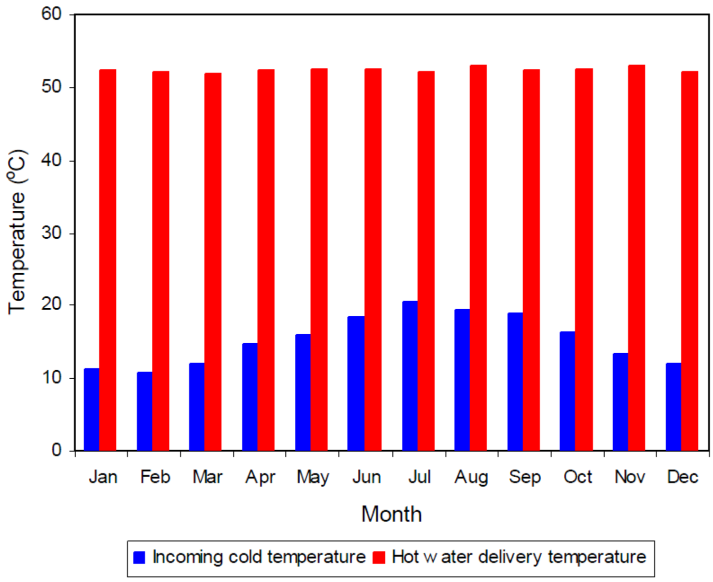


Figure 2-17: Monthly average inlet water temperatures (Energy Saving Trust 2008)

BREDEM (2006) formulated an equation to estimate the volumetric domestic demand of hot water as follows:

DHW (litres/day) = 38 + 25 N (N = number of occupants per dwelling)

This is considered a benchmark standard. However, the Energy Saving Trust has presented a modified version, with the new formula accounting for several factors drawn from the surveyed sample, i.e. differences in (1) boiler type; (2) inlet water temperature; and (3) system output (delivery) temperature (Energy Saving Trust 2008). The new formula is as follows:

DHW (litres/day) = 46 + 26 N (N = number of occupants per dwelling)

When N < 5, more accurate, results can be predicted via the formula:

DHW (litres/day) = 40 + 28 N (N = number of occupants per dwelling)

While the report of the Energy Saving Trust demonstrates a conflict with BREDEM regarding the DHW demand calculation method, both reveal similar and consistent segmented water demand figures within a household. The greatest demand on hot water is bathing, which represents over 55% of the total energy demand per household. Showers and the bathroom basin account for approximately 25% of total water consumption, which raises the bathroom share of the hot water demand to a total of 80% of the total household consumption (see Figure 2-18 and Figure 2-19). The report also noted that homes employing new and more efficient dishwashing machines have lower levels of hot water consumption, as reflected in daily profiles and annual consumption figures. Although the Energy Saving Trust report failed to include the input of renewable energy sources, further studies have investigated the input of such systems in the reduction of energy consumption. The main sources of observed renewable thermal energy were from solar thermal and ground source heat pumps, which were identified as benefiting both the performance and efficiency of the complete system, while maintaining the delivery temperature well within the desired range, i.e. as set by the UK’s Building Regulations Part G (Boait et al. 2012).

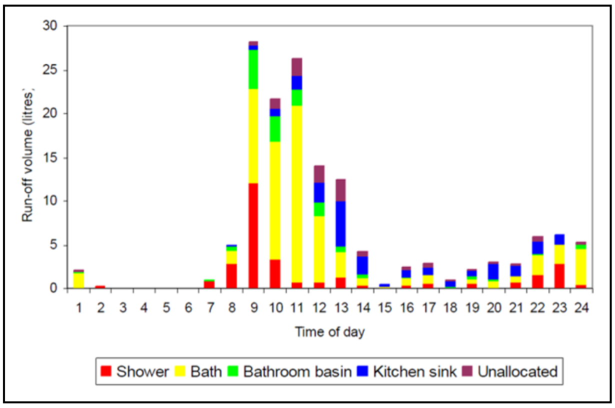


Figure 2-18: Daily hot water demand profile per household in litres (Energy Saving Trust 2008)

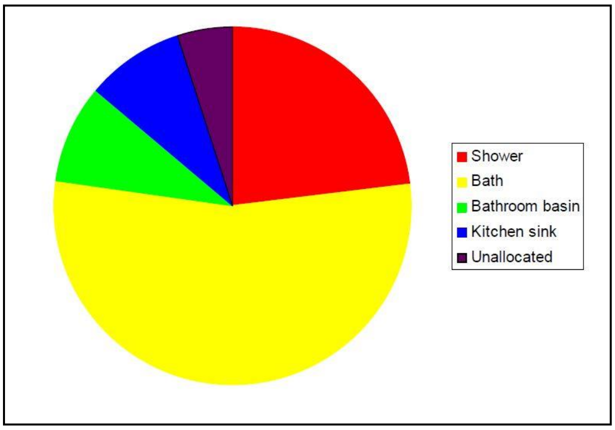


Figure 2-19: Energy demand for hot water by location within households (Energy Saving Trust 2008)

2.2 Potential sources of renewable energy in the UK

The following section discusses several renewable energy sources for domestic applications, as identified within the latest publications, and particularly in relation the UK and EU zone, in order to investigate the potential for meeting energy demands in domestic dwellings.

2.2.1 Solar energy

Over the previous three decades, methods and technologies to collect solar energy have been intensively developed to extract the highest levels of energy with the highest levels of efficiency. The most common energy outcomes from the majority of harvesting systems consist of electrical and thermal energy. The location of the system is considered a crucial factor in determining the applicability of the system. However, still higher efficiency systems can provide a substantial potential to reduce the overall carbon footprint of a building during its lifecycle (Duffie and Beckman 2013).

Data gathered by weather stations and satellites provide a good starting point to determine the feasibility of each location, and to predict possible outcomes, as this can give a rough estimate of the total sunshine hours available for the system (see Figure 2-20 and Figure 2-21). It also provides an estimated range for the tilt angle of solar collectors maximise its potential in acquiring direct sunlight (MacKay 2008). Studies have covered most aspects in considerable detail, due to their importance in developing new sources of energy while reducing the effect of carbon emissions.

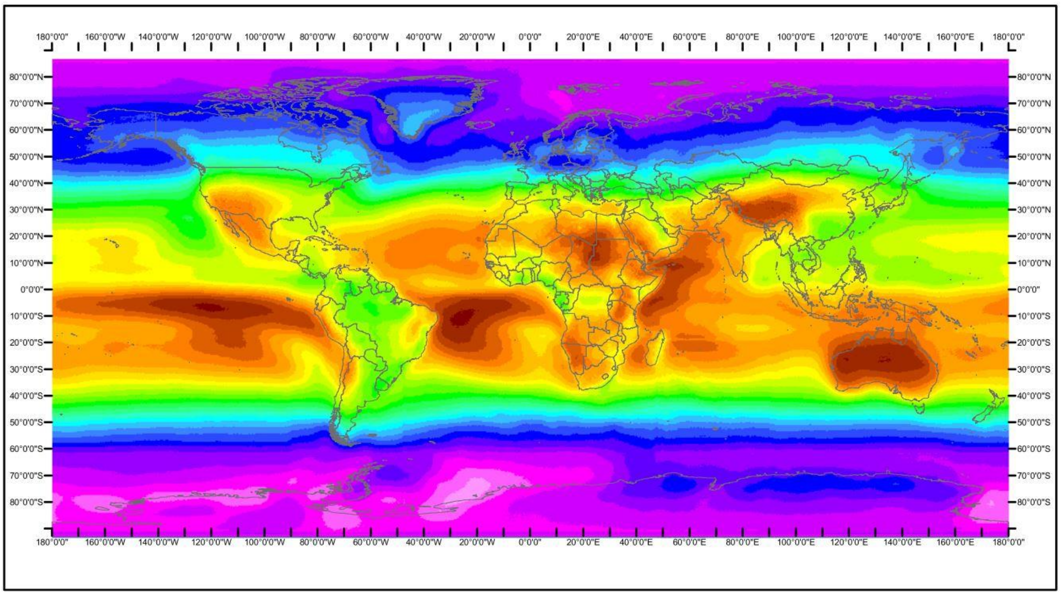


Figure 2-20: Global solar irradiance (Albuisson et al. 2006)

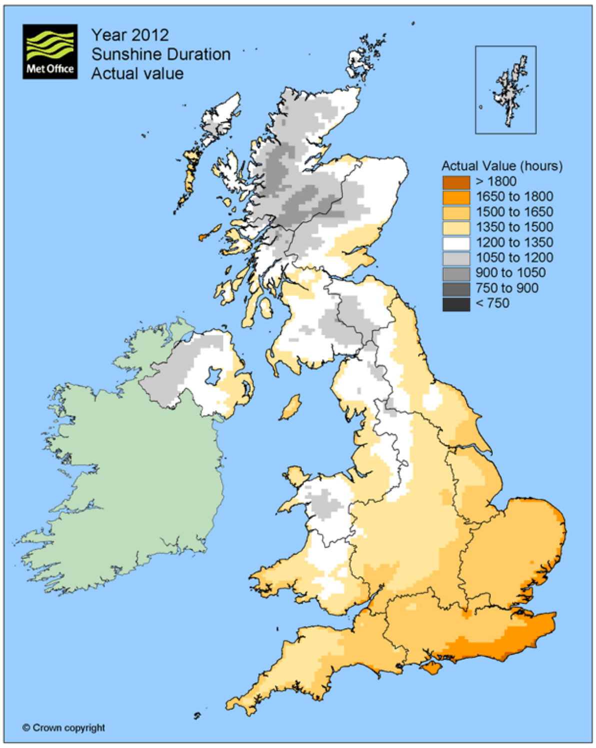


Figure 2-21: Average sunshine hours for the UK during 2012 (MET Office 2013)

2.2.1.1 Solar energy system types

Thermal collectors and PV panels are among the most popular systems used to harvest solar energy for domestic applications, due to construction and financial constraints. The secretariat of the European Photovoltaic Technology Platform technical report noted that European energy generation from solar PV has been increased as a result of: (1) the increasing number of installations and (2) the development of more highly efficient systems (The secretariat of the European Photovoltaic Technology Platform 2011). A further extensive analysis undertaken by the European Photovoltaic Industry Association (The secretariat of the European Photovoltaic Technology Platform 2011) based on the energy market of five EU countries (UK, Germany, Spain, Italy and France), revealed that, by 2050, the solar energy market could be able to compete with the main electrical grid market under the “right policy and market conditions” (ibid).

- ***Solar photovoltaic (PV) systems***

A Photovoltaic (PV) system consists of a number of silicon based cells capable of reacting to exposure to sunlight in order to produce electrical energy resulting from the release of negative electrons from the silicon crystals when struck by photons from sunlight. The type of silicon cell determines the efficiency, lifecycle and power output of the system, since different cells react to different wavelengths of light. The secretariat of the European Photovoltaic Technology Platform (2011) stated that a number of PV systems are widely available to the public, i.e. (1) wafer-based crystalline silicon; (2) thin-film PV; (3) concentrator photovoltaic; and (4) novel photovoltaic technologies (see Figure 2-22). Each one of these four types has its own properties offering a different energy output. They can be integrated with the building directly, or form land-based systems, frequently positioned on a remote site (Lynn 2010). However, all these systems produce Direct Current (DC), while the demands of domestic and commercial electrical usage require conversion into Alternate Current (AC). This conversion further reduces PV efficiency.

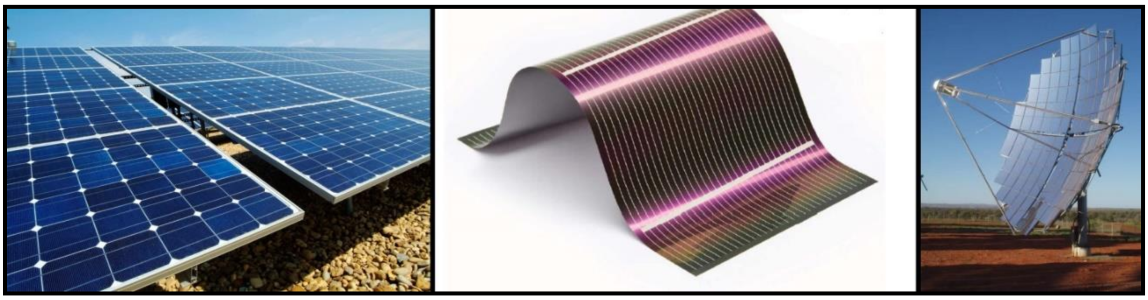


Figure 2-22: Solar PV systems: wafer-based panels (left), thin-film PV (centre), and concentrator PV (right) (Anderson 1990)

The oldest (and most commonly used) PV technology is wafer-based crystalline silicon technology, which employs either monocrystalline or polycrystalline silicon to generate power. These types of silicon crystalline require a rigid frame and are constructed on flat panels capable of being orientated towards a light source. Unlike thin-film PV (which uses amorphous silicon), this type can be deposited into thin film and can be site fixable. However, thin-filmed PV has a lower energy output, efficiency and a shorter lifespan. On the other hand, concentrator photovoltaic systems are more technologically advanced and require less area to generate the same amount of energy in comparison to the wafer-based and thin-film PV. This type of PV concentrates sunlight optically, into a multi-junction solar cell, through the use of a lens or parabolic mirror. These cells have a higher energy efficiency than alternative PV technologies, resulting in an output rate of 25-40% energy efficiency in direct sunlight. The sole disadvantage of this type of PV concerns the higher initial cost, which is further increased as the system gains additional complexity (Duffie and Beckman 2013).

- ***Solar thermal systems***

Thermal solar collectors have a considerably simpler architecture and technology. Duffie and Beckman (2013) stated that thermal solar collectors can produce far greater energy from the sun in comparison to PV. Thermal collectors function by harnessing heat from solar radiation, transferring it via mediums (e.g. water or air) to be used directly, or moved to an accumulator for later usage. It harnesses the heat generated from sunlight's long wave radiation, and the infrared part of the spectrum, in particular. Thermal energy can then be used in residential buildings to heat water, or in internal spaces, and can also prove beneficial for the heating of water in public and commercial buildings. On a larger scale, it can be used to generate electricity serving an urban environment. It can be categorised into: (1) flat solar panels; (2) evacuated tube collectors; and (3) parabolic collectors (Lynn 2010).

Figure 2-23: Solar thermal energy systems: flat panels (left), evacuated tubes (centre), and parabolic collectors (right) (Weiss 2003)

Flat solar panels were developed in the late 1950s, and are mainly assembled into four layers (see Figure 2-23 left). The first layer is transparent, allowing sunlight to pass. The second layer is a dark heat absorbent material, attached to the third layer, which carries heat to a reservoir via a fluid-based medium. The final layer is a heat insulator fixed to the back of the system, which prevents the heat from leaking through the back panels. This is the most efficient and cost-effective module of thermal solar collector systems, in particular those in use in moderate or hot climates (Lynn 2010).

Evacuated tube solar collectors are made of parallel glass tubes, with fluid pipes running through to collect heat in a heat exchange or reservoir tank (see Figure 2-23 centre). These glass tubes are air vacuumed in order to reduce heat loss occurring as a result of conduction and convection. This technology is most useful in colder climates, where the output of a solar thermal collector is limited by heat loss due to the surrounding environment. Both flat panels and evacuated tube systems have a life expectancy of over twenty-five years. In addition, the initial cost of both systems is relatively low, leading them to be more easily acquired for residential applications. On the other hand, both are restricted by obstacles such as clouds and snow cover (Lynn 2010).

Parabolic solar thermal collectors form a more advanced technology, which works by concentrating sunlight through means of curved mirrors into a point or a line containing a fluid to absorb the heat (see Figure 2-23 right). The heated fluid (e.g. water, air, anti-freeze, or salts) is then used to generate steam and operate an electrical engine, producing electrical power. Alternatively, the heated fluid can be used to deliver heat for hot water demand. This thermal collecting method can generate far higher temperatures, and is therefore more commonly used in large scale applications or urban scale power generators (Duffie and Beckman 2013).

2.2.1.2 Domestic solar energy applications in the UK

The UK housing sector (along with the majority of European homes) consume over two thirds of their total energy in providing hot water and heating living spaces. Solar thermal energy contains considerable potential to provide the heat required by homes, as this is categorised as *low-temperature* (Weiss 2003). Spain and Germany currently have the highest energy production rates from renewables among all EU nations, with the majority of the energy produced being channelled towards domestic energy consumption (Jäger-Waldau 2009). This increased production is accompanied by policies encouraging home owners and investors to place an increased reliance on renewables, including: (1) lowering energy bills for homes with renewable sources of energy; (2) reducing taxes; and (3) implementing a *feed-in-tariff* to sell excess energy back to the grid (Jäger-Waldau 2009).

Until recently, policy makers tended to consider that the UK would not sufficiently benefit from solar energy as a reliable source, however, recent research and new technologies have transferred attention back to solar energy as a main potential source. However, current policies have not yet convinced the population, with the latest report of the EU PV status noting that the only action taken by the UK has been to reduce VAT and require renewables to be put in place in new buildings, without providing specific details concerning the proportions, or the technical aspect. Furthermore, buildings constructed prior to 2000 (i.e. comprising over 80% of overall housing stock in the UK) are not obliged to improve their energy consumption (Palmer and Cooper 2012). The turnover of housing stock does not exceed 1% per year, and it has been estimated that 70% of the housing stock for 2050 has already been built (Roberts 2008).

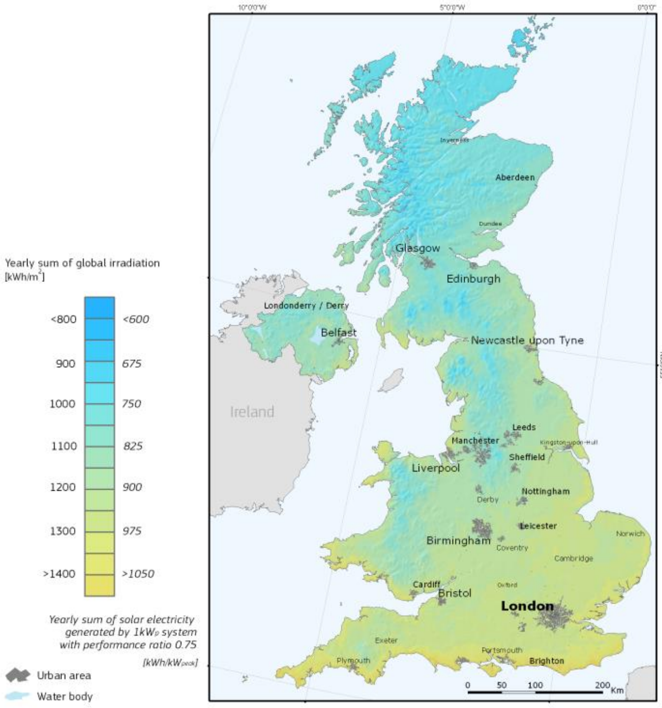


Figure 2-24: United Kingdom Global Irradiance and Solar Electricity Potential for optimally-inclined PV modules (Huld and Pinedo-Pascua 2013)

MET office data from between 1981 to 2010 noted an the average of 1373 hours of sunshine in the UK (MET Office 2013), with the average energy received per square metre on a horizontal plane being approximately 100W (see Figure 2-21), rising to 110W if the surface is facing south on an angle (MacKay 2008). Furthermore, (Prasad and Snow 2005) suggested that the optimum angle for the majority of UK locations is 45° south, allowing the surface to efficiently receive most annual energy. Although the suggested inclination angle of 45° is the most efficient on an annual basis, adaptable systems with an adjustable inclination are capable of yielding a higher sum of energy. The optimal inclination angle varies from month to month, resulting in variable energy output of any solar system (ibid). The European Commission, represented in the joint research centre in Italy, introduced a calculation tool for solar radiance and optimal inclination angle capable of being employed for any global location. This tool calculated the average optimal inclination angle in the UK to be from 38° to 40° south (European Commission 2012). Table 2-3 demonstrates the calculated irradiance on both the horizontal and optimally inclined planes of the city of London, based on monthly figures.

MacKay (2008) suggested a minimum requirement of $10m^2$ per person per dwelling for a domestic energy production system. Although an efficient rate of production is demonstrated by solar PV panels and thermal collector panels, energy tends to be produced during daylight hours and in the summer, i.e. at times when heat is least in demand. An energy (thermal or electrical) storage system is required to transfer energy produced by solar collectors until demand rises.

Table 2-3: solar panels annual figures including optimal inclination angle in London (European Commission 2012)

Month	Hh	Hopt	H(90)	Iopt	D/G
Jan	787	1460	1560	69	0.65
Feb	1420	2160	2040	60	0.63
Mar	2600	3400	2770	48	0.58
Apr	4210	4860	3290	36	0.49
May	5100	5180	2970	21	0.53
Jun	5550	5400	2870	15	0.52
Jul	5260	5220	2890	18	0.54
Aug	4300	4640	2930	29	0.54
Sep	3220	4020	3080	44	0.54
Oct	1870	2790	2550	57	0.57
Nov	1000	1790	1860	67	0.62
Dec	629	1250	1380	71	0.66
Year	3000	3520	2520	38	0.55

- **Hh**: Irradiation on horizontal plane (Wh/m2/day)
- **Hopt**: Irradiation on optimally inclined plane (Wh/m2/day)
- **H(90)**: Irradiation on plane at angle: 90deg. (Wh/m2/day)
- **Iopt**: Optimal inclination (deg.)
- **D/G**: Ratio of diffuse to global irradiation (-)

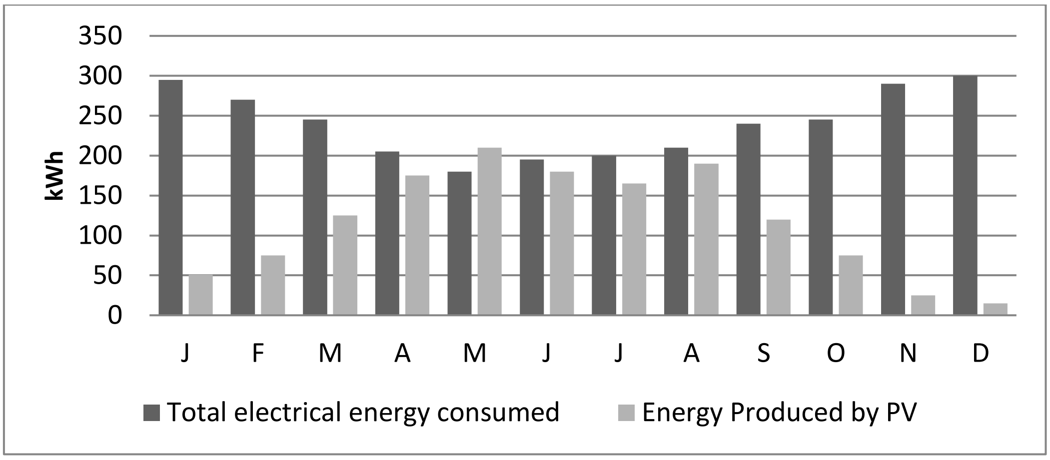


Figure 2-25: Energy demand of a five person household compared to 3kW PV solar panels (Thomas and Lovins 2001)

2.2.2 Wind energy

Wind energy can be considered a form of a solar energy, since the atmosphere is heated by solar radiation, which, combined with the earth’s rotation, generates both local and planetary wind patterns. The first recorded use of this energy was approximately two thousand years ago, when wind energy was harnessed by windmills to mill grains. According to the earliest descriptions of windmills, the Persians used a vertical type of windmill as early as 200 BC (Duffie and Beckman 2013). A number of different types and designs have subsequently been used for various applications. In general, there are two main types of wind turbines capable of harnessing wind energy, i.e. (1) a horizontal axis and (2) a vertical axis (see Figure 2-26). The scale of wind energy generation has also been extended by using multiple turbines with larger blades or diameters. A significant growth in wind farms globally has reduced the cost of wind energy production from 0.3 $US/kWh in 1985 to 0.05 $US/kWh in 2005 (Duffie and Beckman 2013). Denmark is currently the leading country in the production of wind energy, with 34% of total national energy produced from wind farms.

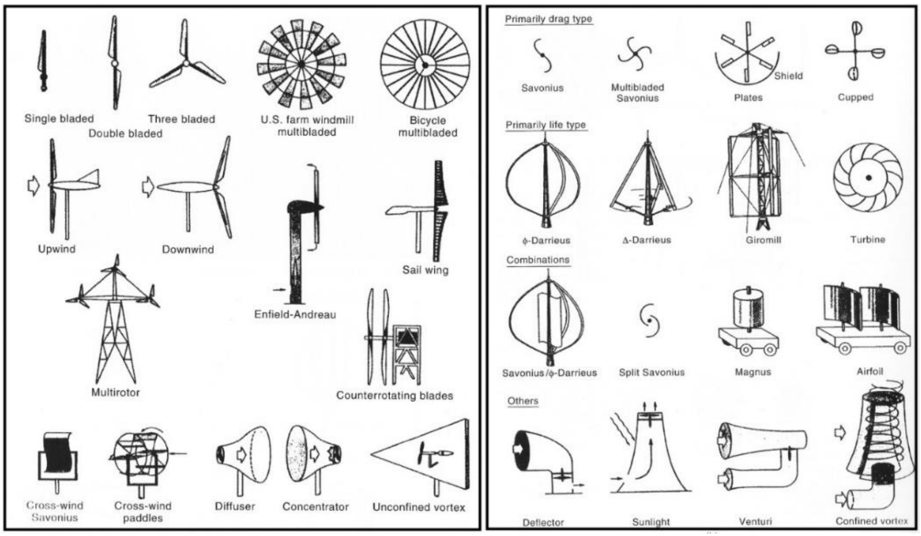


Figure 2-26: Horizontal axis wind turbine (left), and vertical axis wind turbine (right) (Duffie and Beckman 2013)

There has been an increase in the demand for the micro-generation of energy by the domestic sector, leading to a rapid development in micro wind energy generation. However, although, micro wind energy generation has been installed in dwellings, it is still considered a secondary source of renewable energy, due to its intermittency, irregularity and high levels of unpredictability in simulated models (Drew et al. 2013). Furthermore, the energy output of the system is highly dependent on on-site construction, environmental factors, and wind behaviour in relation to rooftops in an urban environment. The lack of detailed data concerning wind speed and direction for urban regions is also a major factor in the ability to predict system outcomes, while the development of wind turbines takes place under optimal conditions rather than in an actual environment. A number of studies have tested a modelling methodology to predict wind energy generation by using Met Office wind speed stations, with, in rare cases, the outcome being closer to the actual monitored data (Drew et al. 2013).

The first step in considering the potential use of wind energy in building design is by means of a mathematical calculation. Data gathered from an on-site location, or the nearest weather station, can be used to study the potential energy input of wind turbines. Although this method is considered to be basic, it does (to some extent) reflect the input potential of wind energy. A simple mathematical equation is applied to achieve an estimation of power generation with given variables, e.g. wind speed; the area of turbine perpendicular to wind direction; turbine efficiency; and air density. The equation is as follows:

$$P_w = \frac{\rho A U^3}{2}$$ (P_W is power output in W, ρ is air density, A is turbine area, and U is wind speed in m/s)

Although this equation has the ability to predict the wind energy outcome of a given turbine size, this outcome is considered theoretical only, and therefore not sufficiently accurate for use. In order to give a more accurate prediction, this equation needs to account for turbine efficiency rates and cut-in wind speeds. Current wind turbines are manufactured with efficiency rates of energy output between 20% and 40%.

Further considerations are required to include wind energy systems into building design, i.e. current regulations concerning the permitted location and noise level of wind turbines. The UK government has issued several guides for the installation and operation of wind turbines in an urban environment, with the first being focussed on roof mounted turbines, and the second on stand-alone turbines. These regulations dictate: (1) rotor diameter; (2) turbine height; (3) operation noise; (4) number of turbines allowed; and (5) vibration levels (Table 2-4).

Table 2-4: The UK regulations to on-site wind turbines applications (Peacock et al. 2008)

Roof mounted turbine	Standalone turbine
• <3 m above ridge (including the blade) and diameter of blades <2m	• <11 m (including the blade) high and diameter of blades <2m
• Internal noise <30 dB	• At least 12 m from a boundary
• External noise <40 dB	• Internal noise <30 db
• 'garden' noise <40 dB	• External noise <40 db
• Up to 4 turbines on buildings >15 m	• 'garden' noise <40 db
• Vibration <0.5 mm/s	• Vibration <0.5 mm/s
No roof top mounted turbines are permitted on buildings in conservation areas or world heritage sites.	Standalone turbines are permitted beside buildings in conservation areas or in world heritage sites, apart from in front of the principal elevation.

A study undertaken on wind energy tests, based on data gathered from on-site data from two locations in the UK, resulted in a series of significant outcomes. The calculation of the energy output for a 1.5kW wind turbine revealed a significant difference between the two sites, despite being only 1 km apart. The annual energy output of the studied system was 277kWh in the first location, and 254kWh in the second location (Peacock et al. 2008). The two locations had similar installation properties taken from the UK government's planning guidelines. A previous study had further investigated the size of the wind turbine propeller over a period of one year in both locations (i.e. low and high wind). Output energy from the turbines in both locations demonstrated a lack of output during a significant percentage of the year ranging between 25% in the high wind location to 51% in the low wind location. A summary of the findings is outlined in Figure 2-27 and Figure 2-28. The study concluded that the difference between the locations was due to a highly unpredictable change in urban wind speed patterns. Furthermore, the authors suggested that the performance advertised by wind turbine manufacturers required extensive research to determine the actual energy outcome (Peacock et al. 2008). This conclusion was also supported by Drew et al. (2013), who stated the necessity for on-site monitoring to determine actual system energy output. Moreover, while the theoretical calculation method has the potential to predict the energy output of a micro wind turbine at lower wind speeds, the actual turbine efficiency reduces the energy curve from 60% to 80%. Furthermore, design safety requirements force the turbine to shut down under higher wind speeds (i.e. from 25m/s and upwards) and to regulate the noise output of the router, which plays an important role in reducing the overall turbine efficiency (Drew et al. 2013).

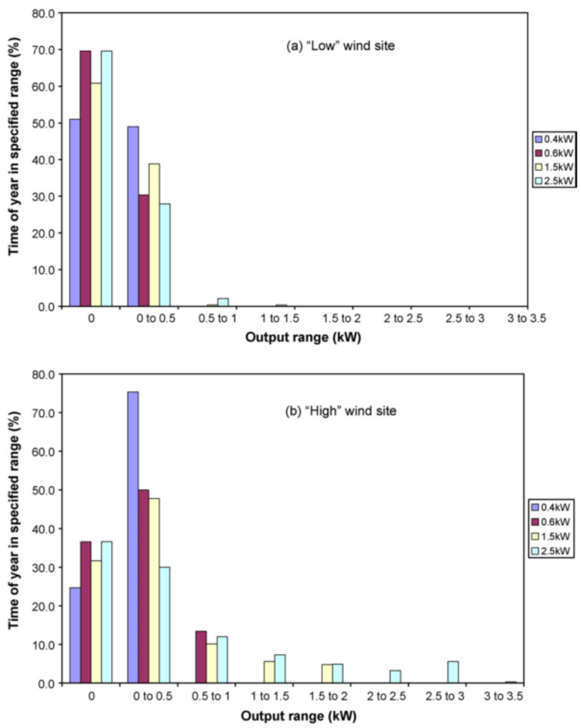


Figure 2-27: Power output from two different locations (low wind and high wind) from four types of wind turbines (Peacock et al. 2008)

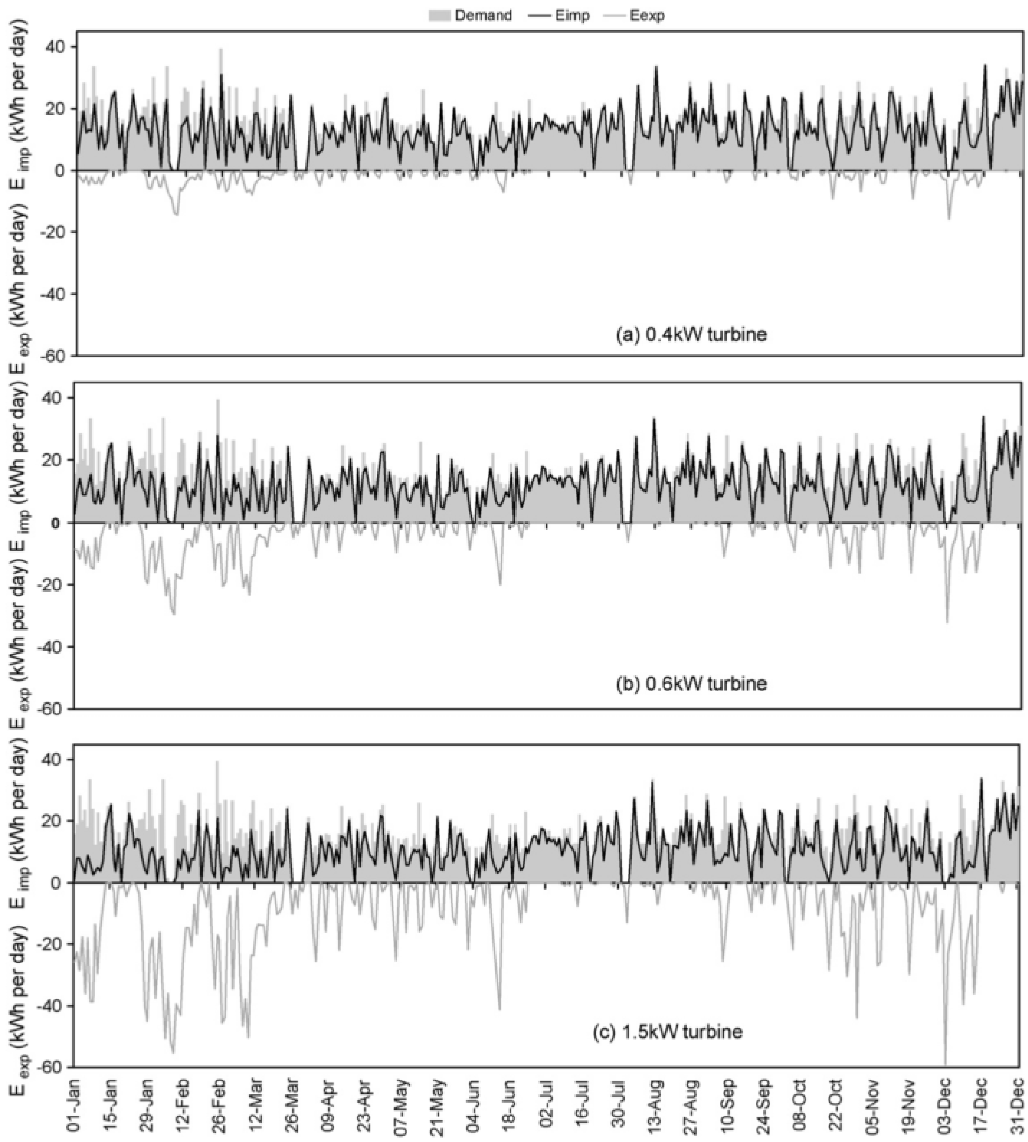


Figure 2-28: Annual energy supply and demand from a 5600kWh dwelling utilising three different sizes of wind turbine (Peacock et al. 2008)

2.2.3 ASHP and GSHP

Two systems using on-site energy sources to reduce thermal energy demand in domestic buildings are: (1) Air Source Heat Pump (ASHP) and (2) Ground Source Heat Pump (GSHP). Although these systems may require an auxiliary pump that operate with an electrical energy source, their energy production exceeds that which it consumes. While investigations continue into their efficiency in the domestic sector in the UK, the theoretical calculations and computed models note a positive potential.

A detailed energy analysis of eighty-three (83) residential heat pumps locations in the UK has been published by the Energy Saving Trust, from a study undertaken from April 2009 to April 2010. These locations included GSHP and ASHP standalone systems and/or combined with further systems (e.g. solar thermal panels). The monitoring analysis concluded that the mean ASHP efficiency for the total twenty-two locations was around 1.83 while the forty-nine GSHP locations demonstrated a higher mean of 2.39 (Dunbabin and Wickins 2012). Furthermore, the published report also noted that system efficiency is affected by the method of introducing heat to the space or DHW (see Figure 2-29).

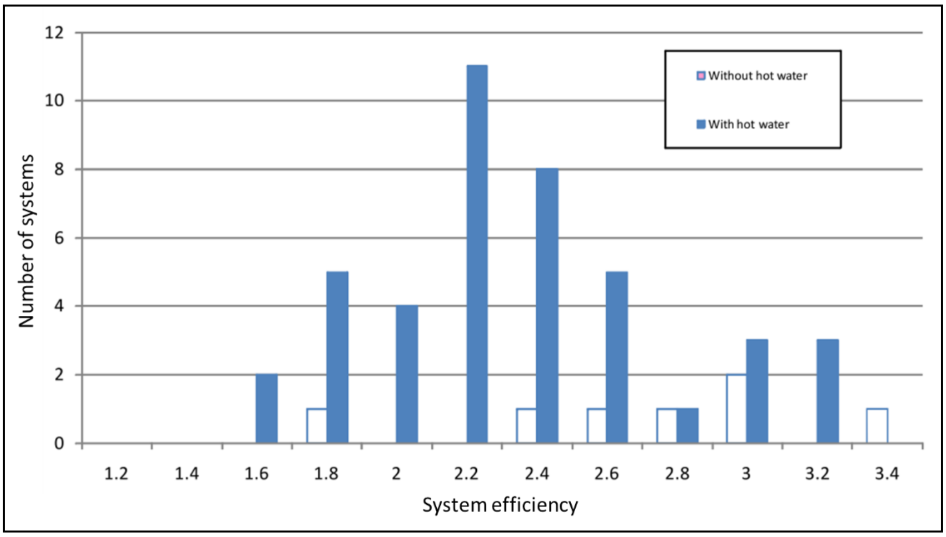


Figure 2-29: GSHP system efficiency in the UK monitored sites (Dunbabin et al. 2013)

The results revealed by the Energy Saving Trust were supported by studies based on site monitoring and system simulations. Kelly and Cockroft (2011) monitored and simulated an existing ASHP for a domestic building in Westfield, Scotland, and found that the Coefficient of Performance (COP) for the ASHP system was slightly higher than the data from the Energy Saving Trust (2.77 COP compared to a 2.65 COP from Energy Saving Trust). Agreement has also been found in comparisons between on-site data and simulation results. Underwood (2014) found the simulated GSHP outcome to also be in compliance with Energy Saving Trust data. It should be noted that two conclusions were commonly identified in all the articles reviewed: (1) the efficiency of the system was considerably influenced by the design and installation specification; and (2) the data provided by manufacturers did not prove reliable for system performance predictions.

2.3 Zero-carbon house

There has recently been a growing acknowledgment of the impact of global warming, including its threat to modern lifestyles, and a number of species, leading to the introduction of approaches to reduce this threat. One of the main approaches is to reduce the emissions of the greenhouse gases responsible, and in particular carbon dioxide. This has led to an initiative to reduce emissions from the built environment, which account for over 38% of total global emissions of CO_2 (EPA 2013). Two further attempts to create higher performance standards for buildings relate to low carbon and zero carbon buildings, established through: (1) improved building fabric; (2) the use of renewable energy sources; (3) improved energy efficiency; and (4) limiting the waste created by a building both over its life-span and subsequent demolition. The following section examines zero carbon buildings in the available literature, including a number of case studies.

2.3.1 General principle of zero carbon buildings

A building is defined as being zero carbon (or net zero-energy) when it consumes an equal (or less) amount than its annual production of energy (London Energy Partnership 2006). There are three levels for achieving a state of absolute zero carbon emissions in the built environment: (1) zero emissions from energy used for heating, cooling, hot water, appliances, etc.; (2) the ability to offset a building's embodied energy; and (3) a zero-carbon lifestyle, which impacts on the use of energy for transportation, food, and production. The combined purpose of these levels is to offset carbon-based energy (e.g. fossil fuels) by using on-site energy resources to achieve near total independence from the grid. These initiatives are also known as zero emission buildings or zero carbon.

The new concept of zero carbon was adopted as the target of all new constructions (domestic and non-domestic) in the EU zone, particularly in the domestic sector. In 2010, the UK government implemented the Energy Performance of Buildings Directive (EBPD), which requires all new domestic buildings to be classified as almost zero carbon by 2020 (Zero Carbon Hub 2014b). While the focus of the government (including targets) is on a zero-carbon environment, the level of emissions reduction is limited to offsetting energy demand, i.e. the first level noted above. Since this alone is incapable of eliminating carbon emissions, a new concept of a nearly zero carbon building was introduced in 2010, i.e. "a building that has a very high energy performance, as determined in accordance with Annex I. 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 p.6). This new concept allows for importing energy to the site from a renewable network in the form of heat (or cooling).

2.3.2 Fabric first approach

The fabric first approach focuses on maximising the performance of the fabric of a building. This can be in the form of improving the selection of materials and components, or the method of construction, to improve the thermal performance of the building without relying on mechanical service systems (Stenlund 2016). This principle can be applied to domestic buildings by optimising: (1) location; (2) orientation; (3) air tightness; (4) thermal bridging; (5) services; and (6) fabric (ibid). This approach has been implemented and developed in zero carbon buildings as a foundation for reducing carbon emissions and increasing energy efficiency (McLeod et al. 2012). Fabric First is also prioritised in the design of zero carbon buildings to reduce heat loss and conserve energy prior to applying carbon emission offsetting systems (Jones et al. 2013).

2.3.3 Performance of zero carbon buildings

In order to evaluate and classify any building as a zero carbon, it must be first assessed and rated based on its performance in relation to an existing set of standards. There are currently a number of methods from government or private initiatives for evaluating high performance buildings in relation to both environmental and energy requirements. There are four main methods of assessing building performance in the UK, as developed by the Building Research Establishment (BRE) over the past two decades while a fifth is still under development. The following section outlines the main assessment tools used in the UK to rate building performance.

2.3.3.1 Building Research Establishment Environmental Assessment Method (BREEAM)

The first tool is the Building Research Establishment Environmental Assessment Method (BREEAM), created in 1990. This is an environmental assessment method based on the scoring of points for new, and existing, buildings. The scoring and rating of a building requires a BREEAM licenced assessor to assist in the evaluation of the building's energy performance. The BREEAM rating method includes a number of schemes capable of being applied to different ratings, including: new builds; refurbishments; in-use buildings; and international schemes. Furthermore, this method is capable of rating a number of different types of buildings, i.e. industrial; commercial; residential; educational; and public. BREEAM's rating is based on a total of forty-nine criteria, including: transport; safety; water consumption; health and wellbeing; pollution;

materials; waste; energy; management; and ecology. BREEAM scoring systems also account for innovative credits for new technologies, and methods used to improve the energy performance of buildings (BREEAM 2012).

An energy category can impact the total environmental criterion score by approximately 15% for fully outfitted buildings. This category is intended to encourage the design of more energy efficient buildings, while supporting more sustainable systems and sustainable management.

BREEAM awards buildings with total credit scores based on performance in each criterion, followed by a comparison to its own performance level benchmarks. Currently, there are six benchmarks set by BREEAM: (1) Unclassified (<30%); (2) Pass (≥30%); (3) Good (≥45%); (4) Very Good (≥55%); (5) Excellent (≥70%); and (6) Outstanding (≥85%).

These apply to new builds following 2010, however, the minimum limit of the credit score was altered in 2010 to meet new EPBD requirements. The minimum limit for any building has thus increased from a credit score of 80% in 2010, to 85% or more following 2016 (BREEAM 2012).

2.3.3.2 Standards Assessment Procedure (SAP)

The Standard Assessment Procedure (SAP) was created by BRE in 1992 for the Department of the Environment. This method specialised in assessing and comparing energy and environmental performance for dwellings in the UK. The UK government considered this method to be the official tool for the provision of accurate and reliable assessments for the energy performance of dwellings, reflecting energy and environment policy initiatives.

The SAP method is based on the measurement of energy consumption in dwellings, in relation to a given level of comfort and services. The efficiency of performance is calculated in relation to three main aspects, i.e. (1) energy consumption per unit of floor area; (2) energy efficiency rating using the SAP system (based on fuel cost); and (3) CO2 emissions using the Environmental Impact Rating (EIR) method. All previous indicators were based on data gathered from annual energy consumption figures, drawn from: (1) space heating; (2) DHW; estimated energy consumption by appliances and lighting; (3) ventilation; and (4) cooling loads in cases of summer overheating. SAP also takes into account a number of factors to determine the fabric energy efficiency, including: (1) the size of the dwelling; (2) climate data; (3) internal heat gains; (4) solar gains; and (5) heating and cooling systems (Department of Energy and Climate Change 2013).

This method forms an official government tool, and has recently experienced a number of updates and modifications. The government planned a target of zero carbon homes for newly constructed homes from 2016, however, this tool does not reflect accurate results in relation to reductions in carbon emissions, due to its inability to account for both on-site and off-site supplies of energy from renewables. Therefore, the Department of Energy and Climate Change will address this issue in the next development of the SAP method (Department of Energy and Climate Change 2013).

2.3.3.3 Code for Sustainable Homes (CSH)

The Code for Sustainable Homes (CSH) was an environmental and energy assessment method for new homes, created by BRE Global in 2006 under contract from the Department of Communities and Local Government. It was intended to be a national standard for the design and construction of new homes in the UK, while encouraging continuous improvement in the building of sustainable homes (Department for Communities and Local Government 2010a).

The CSH assessment process was based on a scoring method in nine main categories. The building's performance was required to pass a minimum performance level in all nine categories, and award percentage points in each category. The assessment process was undertaken in two phases: (1) the design phase and (2) the post construction phase. The points credited reflected the building performance rating, or the 'Code Level', which was illustrated in a row of stars (see Table 2-5). There was a legal mandatory minimum requirement of code level three, while a total of six stars indicated a Code level six, which was defined as a net zero carbon emission (Department for Communities and Local Government 2010a).

Table 2-5: CSH code level for carbon emissions (Department for Communities and Local Government 2010a)

Code level	Minimum Percentage Improvement in Dwelling Emission Rate over Target Emission Rate
Level 1 (★)	0% (Compliance with Part L 2010 only is required)
Level 2 (★★)	0% (Compliance with Part L 2010 only is required)
Level 3 (★★★)	0% (Compliance with Part L 2010 only is required)
Level 4 (★★★★)	25%
Level 5 (★★★★★)	100%
Level 6 (★★★★★★)	Net zero CO2 emissions

Following the technical housing standards review, the UK government withdrew the CSH on March 27th 2015, excluding legacy cases and thus preventing local authorities in the UK from requiring the levels of the code. The initiative to withdraw CSH was undertaken during the Housing Standards Review process initiated by government to simplify regulations and standards into on key set driven by Building Regulations. The code remains valid for buildings with special conditions, e.g. legacy cases; existing contractual arrangements; and developments legally contracted to apply the code. Furthermore, BRE has announced a new method of evaluating the energy performance of buildings, known as the Home Quality Mark, which is still under development (BRE Global 2015).

2.3.4 Passivhaus standards

The term 'passive house' is derived from the German word 'Passivhaus', as this was initially introduced in Germany as a voluntary means of creating buildings with higher standards of environmental sustainability, and which relied on reducing carbon footprint and energy waste. The working principle of Passivhaus standards is primarily identified by limiting energy consumption while maintaining thermal comfort. Mead and Brylewsky's (2011) formal definition of Passivhaus, as presented in the literature, is as follows:

A Passivhaus is a building, for which thermal comfort can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air. (Mead and Brylewsky 2011 p.2)

Furthermore, construction standards in the Passivhaus guide include: (1) increasing the efficiency of heating and cooling; (2) using renewable resources; (3) optimising insulation; (4) minimising thermal bridges; (5) employing ventilation heat recovery; and (6) increasing the air tightness of the building (Sei 2007). Adaption of the 'Fabric First' approach, leads to the production of a higher building performance under Passivhaus standards (Mead and Brylewsky 2011). This concept has been adopted internationally, with many governments adopting the Passive House Institute's guide to identify and categorise a building as a 'passive house' (Athienitis and Santamouris 2002).

The current Passivhaus standards define a number of energy performance targets, in order to determine the compliance of the building design with the main scheme of Passivhaus. These energy targets govern the demands during an annual cycle for: heating;

cooling; general energy; and the air tightness of the entire building. Table 2-6 demonstrates the main energy demand targets, while Table 2-7 presents the construction and design requirements for a Passivhaus certificate.

Table 2-6: building energy performance standards for Passivhaus certification (BRE 2006)

Energy standard	Value
Annual heating demand	≤ 15 kWh/m^2.y
Maximum heating load	≤ 10 W/m^2
Annual cooling demand	≤ 15 kWh/m^2.y
Primary energy demand	≤ 120 kWh/m^2.y
Air tightness	≤ 0.6 ach

The guide for a designer of a Passivhaus, as published by BRE (2006), outlines several points to be considered by designers to achieve a Passivhaus certificate, and cover most of the design aspects, i.e. building location; orientation; building form; construction methods; thermal bridges; air tightness; MVHR; main appliances; glazing; shading; and solar heat gain.

Table 2-7: building components and construction values limits for Passivhaus (BRE 2006)

Design component	Value
Walls, Roof, Floor	≤ 0.15 (W/m^2K) (U-value)
Glazing unit	≤ 0.8 (W/m^2K) (U-value)
Installed glazing	≤ 0.85 (W/m^2K) (U-value)
Doors	≤ 0.8 (W/m^2K) (U-value)
Thermal bridges	≤ 0.01 (W/m^2K) (U-value)
MVHR coefficient	≥ 0.75 (η HR)
Ventilation electric limit	0.45 Wh/m^3
Appliances	High efficiency recommended
Lighting	High efficiency recommended
On site renewables	No requirement but SHW typical

BRE's Passivhaus designer's guide maps several approaches to achieve Passivhaus statues in newly constructed buildings, e.g. the need to consider the form of the building during the design phase, in order to reduce the surface-to-volume ratio and reduce any potential heat loss to the environment from the envelope. Furthermore, there is a requirement for the main mass of the building to be oriented towards the south in the UK and EU, with a roof inclination of 30° degrees in the UK.

While the thermal properties of the building's envelope are set by Passivhaus standards, and the guide suggests, but does not dictate, the construction methods. There are a number of options for walls and roofs, in addition to glazing and openings (see Figure 2-30). In addition, the guide emphasises the limitations of the thermal bridging within the building structure and envelope, in order to reduce heat loss. A detailed design is required when building geometrical connections and junctions, accompanied by significant insulation to minimise or eliminate thermal bridging. Although the final inspection is able to identify thermal bridging by means of thermal imaging, it is often too late to resolve any issues contained in the building, leading to a need for careful and accurate design and modelling prior to construction (ibid).

Since heat loss as a result of glazing can greatly affect the overall energy performance of a building, the Passivhaus guide specifies rules and guidelines to reduce glazing heat loss. In the EU region, double glazing windows are generally sufficient to achieve Passivhaus statues, while the guide specifies that, due to its climate, buildings in the UK require triple glazing, in particular due to the high level of heat loss during the winter months. Furthermore, the glazing ratio on south facing facades should not exceed 25-35% of the surface area. These conditions act to improve the thermal performance of a building, in addition to the increased air tightness of the glazing elements in particular, and in all construction parts in general (ibid).

The final issue identified in the Passivhaus designer's guide is the MVHR system, which is marked as a mandatory installation, aimed at reducing heat loss via ventilation, using recycling through either passive or active systems. Although the guide does not specify a particular method of MVHR, it requires a performance limit of 75% minimum recovery rate, based on testing, rather than relying on the manufacturers' specifications (ibid).

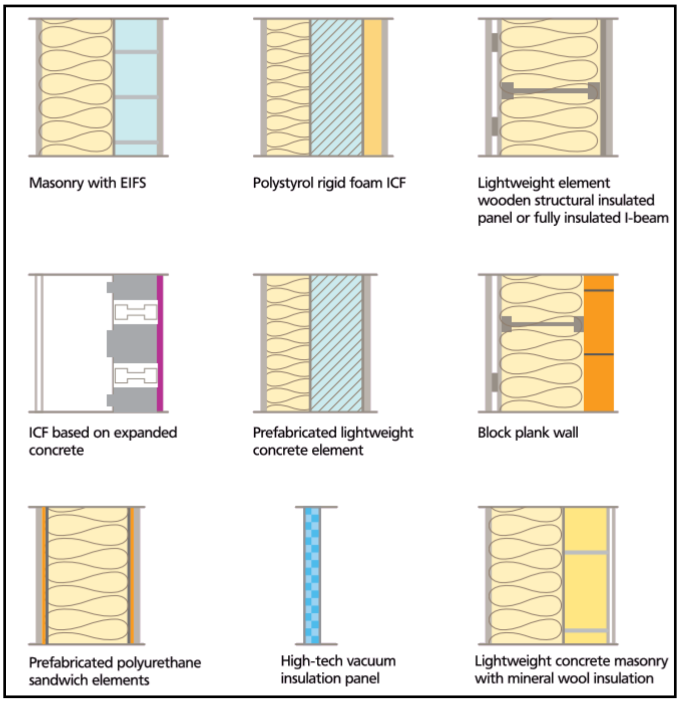


Figure 2-30: Wall construction methods suggested in the Passivhaus designer's guide (BRE 2006)

2.3.4.1 Zero carbon building and Passivhaus

There have been a number of attempts in the UK to link Passivhaus and zero carbon dwellings. The Passivhaus Trust has issued several technical briefings, suggesting that Passivhaus energy design targets can benefit zero carbon homes, both in terms of meeting the energy targets set by the Passivhaus energy consumption levels, and the regulatory emissions set by the government's 2016 zero carbon house (the date of this standard has been changed to 2020 in 2015 by the UK government) (Zero Carbon Hub 2014a). Although (due to emission rate changes), the direct link between carbon emissions and energy consumption standards can be misleading, it can be achieved with careful attention to energy efficiency details and reasonably simplified assumptions (Passivhaus Trust 2011). Furthermore, the energy requirements to ensure a dwelling is considered a Passivhaus meets the 2020 zero-carbon status without the need of on-site renewables (see Figure 2-31). These energy requirements are set by limiting the energy demand to $15W/m^2/y$ for space heating, while limiting the cooling demand to $15W/m^2/y$.

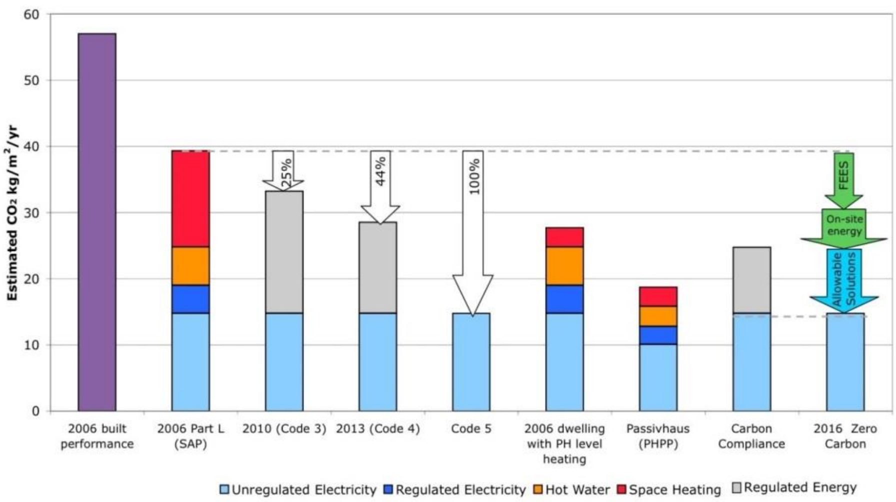


Figure 2-31: Comparison between zero-carbon houses and Passivhaus in carbon emissions (Passivhaus Trust 2011)

A number of further studies have accepted the concept of focussing on Passivhaus energy consumption standards, rather than on regulated carbon emissions (Williams 2012). In the journal article *An investigation into recent proposals for a revised definition of zero carbon homes in the UK*, McLeod et al. (2012) concluded that considering carbon emissions of homes as static (and capable of being offset by other means) as: "a dangerous and short-sighted argument, which is not supported by evidence on the efficacy of carbon offsetting mechanisms" (McLeod et al. 2012 p.33). They further suggested the use of Passivhaus standards instead of current zero carbon limits to produce more efficient energy and limit carbon emissions.

2.3.5 Zero carbon buildings and the issue of overheating

There have been a number of investigations into the overheating of dwellings, as this poses a difficulty in minimising energy consumption in both zero carbon, and Passivhaus, dwellings. CIBSE guide A defines overheating in dwellings as a living space temperature of 28°C, at least 1% of the occupation time, or by a bedroom temperature of 26°C for at least 1% of the occupation time (Three Regions Climate Change Group 2008).

The issue of overheating has been noted in monitored studies or simulated models for a number of new UK dwellings (Peacock et al. 2010). Several Zero Carbon Hub reports have recommended two main points to be considered in newly designed dwellings: (1) improving overheating treatments; and (2) undertaking performance monitoring to compare the design claims for a building against actual performance. These reports stated that the current design energy predictions do not perform as expected, particularly in relation to a demand for higher energy, improved air quality and overheating (Passivhaus Trust 2011).

Furthermore, climate change and global warming are also impacting on the energy demands and carbon emissions of dwellings in the UK. There is currently an annual increase in the demand for cooling in UK dwellings, while current energy and carbon emissions targets are fixed. The journal article *Investigating the potential of overheating in UK dwellings as a consequence of extant climate change* (Peacock et al. 2010) concluded that, based on prediction models relating to climate change projections for 2030, overheating will prove a significant issue for UK houses. Figure 2-32 demonstrates the cooling requirements of three dwellings between 2005 and 2030 in two different UK cities (i.e. London and Edinburgh) Although the modelling approach has taken climate change into consideration, there remains a need for performance monitoring to verify the projected figures for 2005 up to 2010 (i.e. time of publication). On the other hand, Ampatzi and Knight (2007) produced similar figures for the cooling energy demands of a newly constructed dwelling in Cardiff city (Wales), i.e. approximately 1472 kWh/yr. Furthermore, the conclusions of the study suggested that 9 m^2 of thermal solar collector powering an absorption chiller would prove sufficient to meet this cooling energy demand without the need to depend on the grid (Ampatzi and Knight 2007). However, although this might prove feasible for the majority of domestic applications, there remains a lack of monitored case studies to validate the simulation results in order consider this solution.

In addition, the issue of overheating is not exclusive to zero carbon buildings, being shared across most efficient energy performing buildings (Energy Saving Trust 2005). The Passivhaus designer's guide indicates the potential for overheating to also exist in Passivhaus certified buildings, particularly those with south facing maximised window glazing. Suggested solutions include introducing cross ventilation and night purge ventilation, along with the inclusion of solar shading devices to reduce solar heat gain during the summer months (BRE 2006).

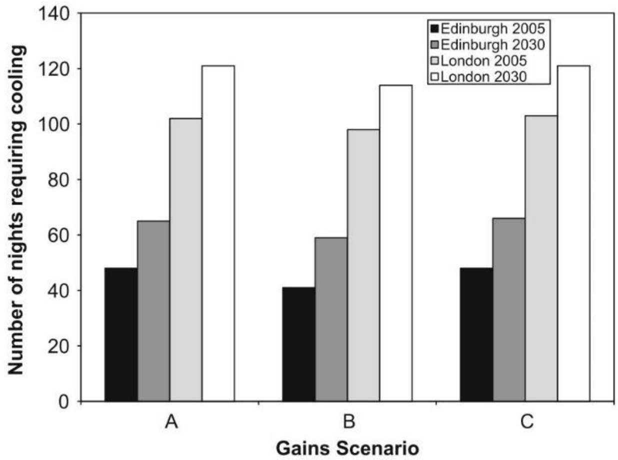


Figure 2-32: Cooling nights demand over three dwelling types in 2005 and 2030 (Peacock et al. 2010)

2.3.6 Zero carbon building design process models

A number of design process models have been developed for efficient energy performing buildings to provide a guideline for new low carbon emission building designs. These design process models aim to meet the new building regulations, while reducing carbon emissions from the built environment. Mainly there are three major design processes: Integrated Design Process by IEA SHCP (2003), Integrated Design Process in PBL by Knudstrup, Denmark (2004), and Low/Zero Carbon Design by Professor Jones, UK (2007). The first method focuses on the observation of the impact of decision- making during the design process, i.e. while it is relatively easy to make design changes during the early stages of development (International Energy Agency 2006). The second method by Knudstrup (2004) utilises the engineering method of problem solving for the architectural design process (Knudstrup 2004). Both of these methods focus on the decision-making process rather than the design elements of the zero-carbon building which falls beyond the scope of this research.

The third method named as Low/Zero Carbon Design process was developed by Professor Jones from Cardiff University in 2007. This method focused on establishing low carbon emissions from the building environment, and could be applied to individual buildings, or on an urban scale. It commenced with climate data analysis, in order to establish the project objectives, followed by: processing the site planning, building form and building fabric; establishing efficient building services and renewable energy systems; taking into consideration the waste generated before, during, and following construction. Furthermore, this method needed to be applied during the early design stages, followed by being tested periodically by means of an analysis simulation (Jones et al. 2014). The complete process can be summarised into four main stages (see Figure 2-33 and Figure 2-34):

1. **Energy demand reduction:** This includes reducing internal heat gain and energy loads, through reducing electrical energy loads, i.e. lighting, small power, and incidental energy loads.
2. **Passive design:** This is achieved through several building technology techniques. One of the most effective practices during this stage is the development of a heat loss building envelope with solar heat gain control properties.
3. **Efficient mechanical systems:** These are achieved by employing energy efficient heating, cooling, and ventilation systems. Alternative methods of delivering thermal energy in (or out) of the living spaces can influence the outcome of this stage of the design, along with the subsequent stages.
4. **Renewable energy supply:** during this stage, it is possible for the remainder of the energy demand to be met via renewable energy sources from onsite generation (i.e. electrical or thermal), with the amount of energy generated depending on the building type, location, orientation and occupation. Furthermore, excess energy from active renewables can be stored on site, or within the development network. The amount of energy generated offsets carbon emissions from energy consumption from the grid, and building embodied energy.

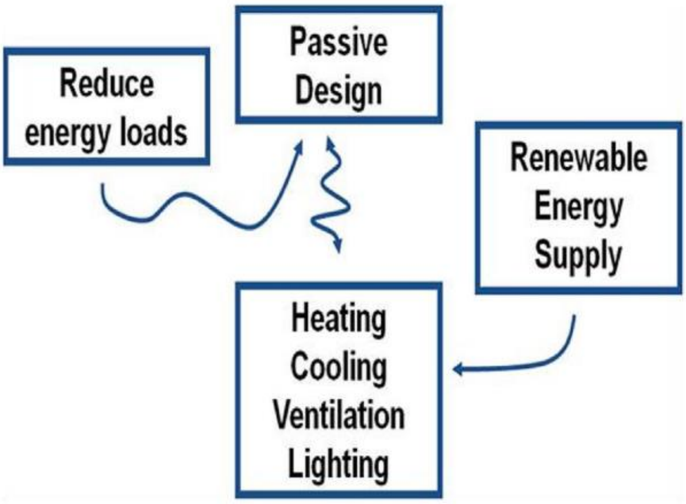


Figure 2-33: Design process simplified from Low/Zero Carbon method by Jones et al. (2014)

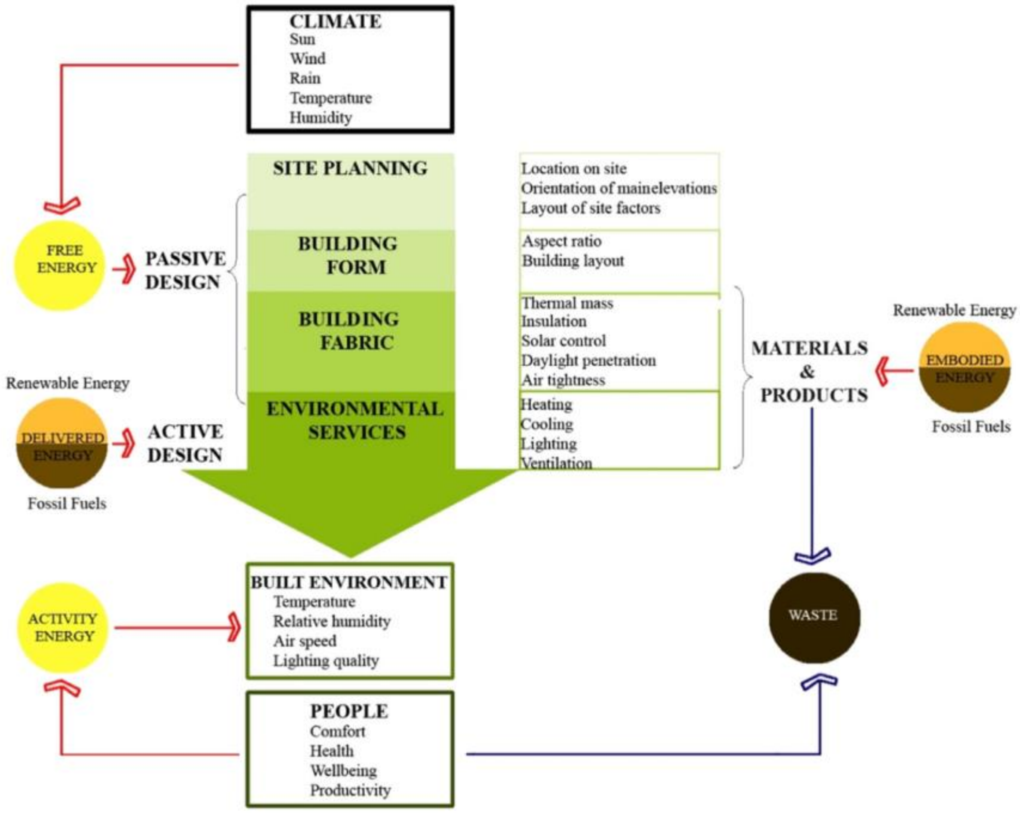


Figure 2-34: The design process of Low/Zero Carbon by Jones et al. (2014)

2.3.7 Zero carbon case studies in the UK

The UK has played an important role in forming the EU's energy policies, and thus paving the way to a more sustainable built environment. The new targets set by the European Parliament to reduce emissions by 80% in 2050 pose a particular challenge to the UK, due to age and condition of the current housing stock (Zero Carbon Hub 2009b). Building compliance to the new regulations has been monitored and rated by a number of tools developed by BRE, with the most common tools being SAP (the official government tool) and the CSH rating system. The most recent report from the Department of Communities and Local Government is *Cumulative and Quarterly Data for England, Wales and Northern Ireland*, in which 354 buildings in the design phase have been given a rating of six stars (i.e. zero carbon level) and 142 buildings in the post-construction phase also have been given a rating of six (Department for Communities and Local Government 2012).

The following sections discuss a number of case studies found in the published articles and reports, focussing on the physical details presented within a design and application concerning the building, energy performance, and innovative solutions.

2.3.7.1 The Renewable Energy Centre at Kings Langley

Figure 2-35: The Renewable Energy Centre (RES Globe 2004)

The Renewable Energy Centre building in Kings Langley was established in 2003. It was introduced as the first commercially-developed net zero carbon and energy self-sufficient building in the UK. Furthermore, the centre was planned as a retrofit to an egg farm used by local industries since the 1920's (REFocus 2004). The design principles on which the entire centre was developed focussed on:

1. Providing fully operational head offices for the centre's staff.
2. Providing an exhibition, conference, and supporting facilities for the centre's users and visitors.

3. Minimising energy consumption, while supporting the local economy and community.
4. Generating energy locally, from on-site renewable sources.
5. Seamlessly integrating social, technical, and aesthetic aspects into the building.

Table 2-8: The renewable Energy Centre development properties (REFocus 2004)

Area	2,500 m^2
Type	Commercial – offices - exhibition
Annual energy consumption	85 MWh (34 kWh/m^2): space heating 115 MWh (46kWh/m^2): electric
Annual energy generation	187 MWh: thermal energy 248.7 MWh: electrical
Renewable sources	PVT: 54 m^2 Solar thermal panels: 116 m^2 Wind turbine: standalone 225kW turbine, 29 m rotor, 36 m hub height Biomass: 100kW boiler with 5 hectares of elephant grass Ground water cooling: 75m deep bore
Energy storage	Seasonal thermal: 1100 m^3 of water tanks storage

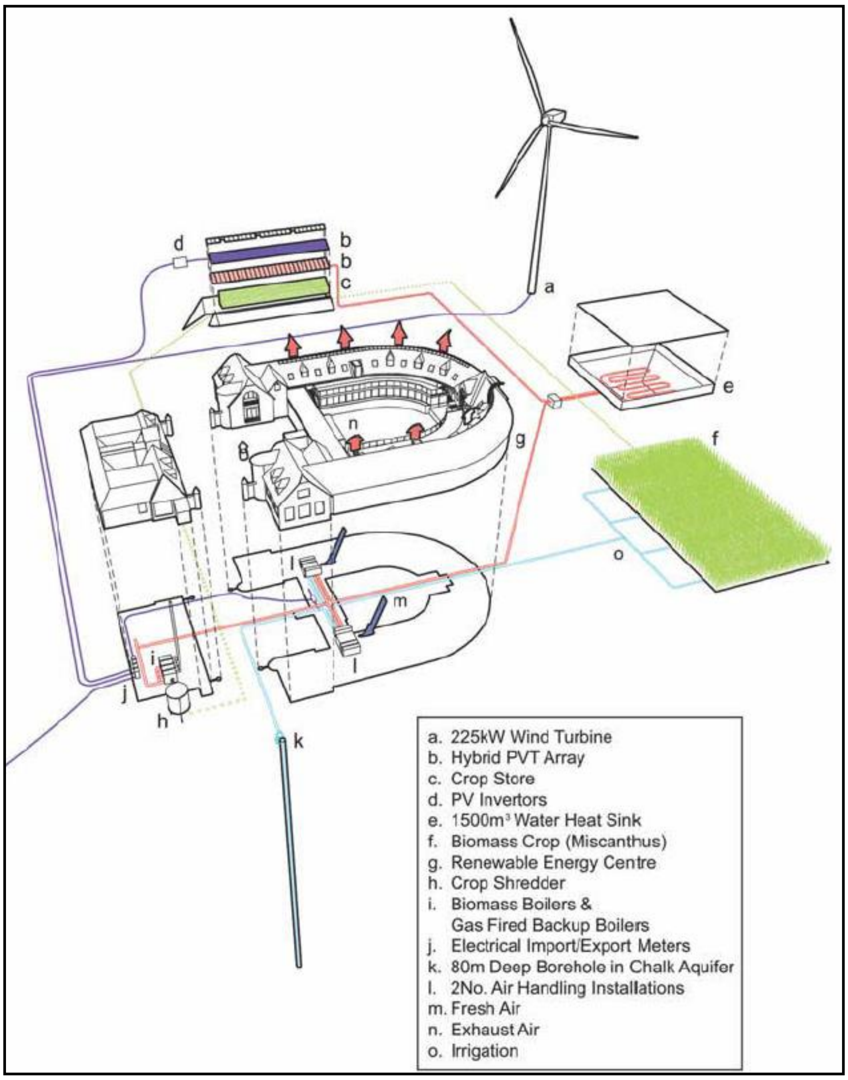


Figure 2-36: Schematic of the building renewable energy flow (REFocus 2004)

RES Globe, the owner and developer of the Renewable Energy Centre, claimed that the generation of the project exceeded demand, with published figures indicating the annual averages during two years of monitoring under operation. A net potential for exported energy produced annually by the centre consists of 133.7 MWh of electrical and 102 MWh of thermal energy. The systems implemented in this development are versatile and have a considerable generational capacity. A total of 170 m^2 of solar panels primarily produces sufficient thermal energy to supply seasonal storage during the summer months, in addition to a commercially sized wind turbine, which is estimated to produce 250 MWh of electrical power. These combined systems generate above the total energy demand of the building, with the excess being stored or exported to the grid network.

The thermal storage system also has a large capacity, and takes the form of a water tank. The container for the 1100 m3 of body of water is constructed from 500mm of expanded polystyrene insulation in order to reduce heat loss, which is estimated to remain approximately within 50% of the total annual storage. It is primarily employed for thermal (heat) storage for demand during the winter months, while cold water is extracted from a local aquifer to meet the centre's demand for cooling during the summer months. The water has a temperature of approximately 12 C° and is pumped through a 75 m borehole to cool the centre's offices. Following its use in the cooling cycle, the extracted water is used to irrigate energy crops, including five hectares of elephant grass used to supply the biomass boiler, with an annual expected yield of approximately sixty tons of dried hay, resulting in 17 GJ/tonnes in the facility 100kW boiler. While all these systems produce energy on site, an additional gas boiler has been installed as a backup, and is attached to mains gas.

2.3.7.2 Greenwatt Way development in Slough

The Greenwatt development was built in 2010 by Scottish and Southern Energy (SSE), and consists of ten dwellings of various sizes, designed as a zero-carbon level six on CSH. The dwellings consist of: two one bedroom flats; a terrace of two bedroom houses; a terrace of three bedroom houses; and two three bedrooms detached houses. Furthermore, this development was intended as a showcase for the developer while leased to its employees. The development has been occupied since 2010, being monitored for energy performance and the comfort of the residents.

Figure 2-37: The Greenwatt development (Energy Saving Trust 2012)

Table 2-9: The Greenwatt way district properties (Energy Saving Trust 2012; Welsh Government 2012)

Area	800 m^2
Type	Residential
Construction	3 timber frame – 7 traditional masonry
TER (Target Emission Rate)	From 20.71 to 32.32 ($kgCO_2/m^2$)
DER (Dwelling Emission Rate)	From -19.71 to -58.89 ($kgCO_2/m^2$)
Renewable sources	PV panels: 63 kW photovoltaic array Solar thermal panels: within a district heating network ASHP: within a district heating network GSHP: within a district heating network Biomass: within a district heating network MVHR: with heat recovery efficiency of 92%
Energy storage	Stratified thermal storage Hydrogen fuel cell CHP

The design aim of the Greenwatt development was to investigate several methods of achieving CSH code level six with various technologies. The developer focused on the issue of heat loss parameters from the building envelope, with a reduction in heat loss leading to a mean low base energy demand and a shorter winter heating window (Welsh Government 2012).

Solar energy was utilised in this development through both PV panels and solar thermal energy panels. The PV panels primarily provide the district with its demand for electrical energy, while providing grid access to export excess energy. The solar thermal panels were installed on the energy centre of the district, and provide heat to the thermal storage. Wind energy was not implemented in this design and construction, due to it being located within a dense urban location (Welsh Government 2012).

The heating system installed in this development is an advanced system, providing low-grade heating. All dwellings are connected to the central energy building in series, with each dwelling supplied with space heating by means of an under-floor single radiator in the living area, and a single heated towel rack. The hot water supply is also connected to the energy centre, circulating hot water of 55 C° (Energy Saving Trust 2012). Furthermore, a total of three heat generating systems are installed within the district’s energy centre. These systems were designed to cover the heating demand for the entire compound, with an air source heat pump (ASHP) and ground source heat pump (GSHP) implemented and tested specifically for that purpose. The preliminary studies demonstrated that GSHP operating alone would cover the entire annual heat demands of the development (Welsh Government 2012).

Each dwelling was also fitted with a mechanical heat recovery system (MVHR) collecting heat from vented air, and recycling it into the space, or sending it for storage in the energy centre. While the required heat recovery rates for code six buildings are set as approximately 85%, the Greenwatt design has a more efficient system, which runs on a 92% heat recovery rate (Energy Saving Trust 2012).

2.3.7.3 The Camden Passive House in London

The Camden Passive House in London was listed as the UK's first certified passive house. Constructed in 2010, it consists of a single-family dwelling of 118 m^2, being a two-storey building with a timber frame construction and a south facing facade. Research undertaken on this building was carried out over two phases, both of which were funded by the UK government (Bere:architects 2014).

Figure 2-38: The Camden Passive House in London (Ridley et al. 2013)

Table 2-10: the Camden Passive House properties (Bere:architects 2014)

Area	118 m^2
Type	Residential
Construction	Timber frame
Energy consumption	12.1 kWh/m^2 heating demand 124 kWh/m^2 primary energy demand
CO_2 emissions	23.6 kg (PHPP estimated)
Renewable sources	Solar evacuated tubes MVHR: with heat recovery efficiency of 90%
Energy storage	None
supportive systems	Green roof Rain water collection Adjustable shading devices

The potential of the Camden passive house has attracted the attention of many leading members of the UK building industry. The developer implemented several currently available technologies, while the design was assessed by the Passive House Planning Package (PHPP) tool. The design strategies of this house were primarily developed to ensure the comfort and health of the residents, while complying with the standards of a passive house (Bere:architects 2014).

The construction of the Camden house implemented a number of highly efficient systems to reduce primary energy demand. (1) The mechanical ventilation recovery system. This extracts heat from the exhausted air, supplying it to the solar hot water tank, which stores the domestic hot water. (2) The solar hot water tank is connected to solar evacuated tubes, in order to further meet the demand for hot water during the summer months. (3) An auxiliary gas boiler is used during the winter months, to fill the gap between hot water supply and demand (Bere:architects 2014).

Although the Camden house is an example of good practice in creating an efficient and comfortable living environment, the performance study revealed a number of issues, in need of being addressed in later developments. Firstly, there was the issue of overheating during the summer, which failed the CIBSE, PHPP and EN 15251 overheating criteria. Secondly, there was the issue of exceeding the maximum energy demand per area per year. The first phase of monitoring the study revealed the total energy demand as slightly higher than the passive house requirement of 120 kWh/m^2/year (see Figure 2-39). Thirdly, there was the issue of the occupants' behaviour during the monitoring period, with residents preferring to close the main window blinds for reasons of privacy, thus limiting the solar heat gains during winter months (Ridley et al. 2013).

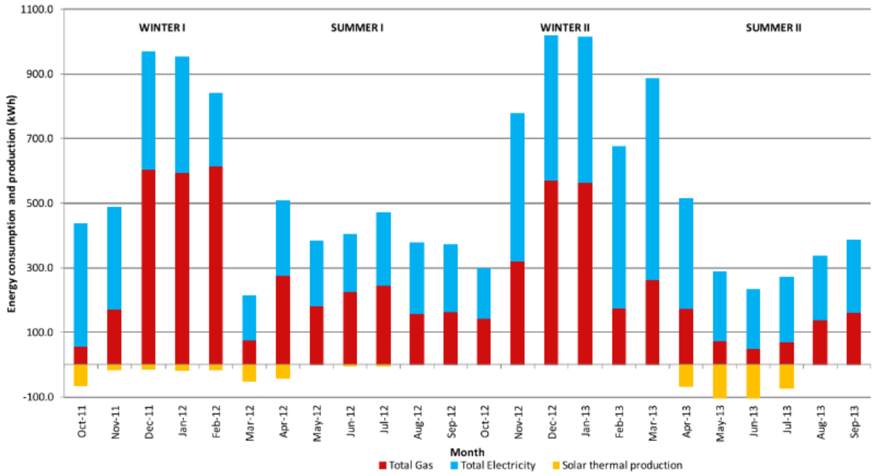


Figure 2-39: Energy use and production in the Camden house (Bere:architects 2014)

2.3.7.4 The Barratt Green House in Garston

Figure 2-40: The Barratt Green House (Barratt Developments PLC 2007b)

The Barratt Green House was built in 2007 on the BRE Innovation Park, as a demonstration project. It is a semi-detached house consisting of three storeys, containing three bedrooms, constructed primarily of a light concrete (aircrete) for the walls, and a ventilated hollow core concrete floor slab. The house design and performance was awarded code level six on the CSH scale.

Table 2-11: The Barratt Green House properties (Zero Carbon Hub 2009a)

Area	129 m^2
Type	Residential
Construction	Medium density concrete
Code level	Code level 6 (CSH)
CO_2 emissions	-133%
Renewable sources	PV: 4.1 kWp on-site, 3.4 kWp off-site Solar thermal: 3.34 m^2 MVHR: with heat recovery efficiency of 85% ASHP
Energy storage	None
supportive systems	Hollow core concrete with passive ventilation Rain water harvesting External openings shading devices

The on-site micro energy generation used in this project includes: (1) solar PV panels; (2) solar thermal panels; (3) a mechanical ventilation recovery system; and (4) an air source heat pump. The energy generated is primarily used to heat the space and domestic hot water, while the PV panels fulfil the low power energy demands.

The design of the house envelope has a high degree of air tightness (0.97 $m^3/m^2/hr$ at 50 pa), with the risk of overheating during summer reduced through a number of strategies. Firstly, there are operable windows to create natural ventilation. Secondly, shutters were installed on external doors and windows to prevent solar heat gain. Finally, the design allowed the floor's hollow core concrete to passively ventilate. These measures further reduce the emissions associated with mechanical ventilation and air conditioning.

2.3.7.5 SOLCER House

Figure 2-41: SOLCER House (LCRI 2015)

Table 2-12: SOLCER House by LCRI in Pyle, near Bridgend, in Wales (LCRI 2015)

Area	100 m^2
Type	Residential (3 bedroom)
Construction	Structural insulated panels (SIPS)
Code level	Passivhaus
Embodied CO_2	340 kg CO_2/m^2
Renewable sources	Solar PV panels: 40 m^2 provide 4.3 kWp of energy Mechanical ventilation heat recovery unit (MVHR) Transpired solar collector: 17 m2
Energy storage	Thermal for (DHW) + electrical
supportive systems	450 W heat pump LED lighting

The SOLCER House was built in 2015 in Pyle, in Wales by the Low Carbon Research Institute (LCRI). It was designed by the Welsh School of Architecture in Cardiff University, and had a construction cost of £125,000, with construction taking place over sixteen weeks. The aim of this project was to build affordable housing with positive energy solutions and low carbon emissions. The house consists of two main storeys, with three bedrooms and an attic space for energy storage and monitoring equipment. A separate storage space on the ground floor was designated for thermal energy storage utilising a bulk phase changing material TES system.

Figure 2-42: Plans and a 3d section showing demand, supply and storage locations (LCRI 2015)

A number of on-site renewable energy generation sources were integrated into the design of this project: solar PV; a transpired solar system; and a MVHR system, all of which are designed to reduce grid demand to a minimum during high demand periods, in combination with energy storage systems and heat pumps. The predicted energy performance of this building was estimated to be approximately 70% autonomous, with a ratio of 1.75 grid export-to-input (LCRI 2015).

Although the house was built to Passivhaus standards, its energy performance registered higher than the Passivhaus benchmark. Furthermore, low energy demand systems (e.g. LED lighting and the MVHR system) significantly reduced the overall consumption levels. Although the TES system used in this project was aimed at meeting DHW demands, auxiliary electrical storage system (batteries) were also used for both space heating and DHW.

2.4 Summary of findings

This literature review outlined a number of beneficial points for the scope and objectives of this current research, i.e. domestic thermal energy demand; patterns for on-site renewable energy sources; and understanding the current state of high energy performance buildings in the UK, and in the EU.

Firstly, UK domestic energy demand was considered by means of a number of governmental reports and surveys. In general, thermal demand dominated the overall domestic energy demand in the UK for space heating and DHW. Furthermore, this demand accounted for approximately 78% of the total energy consumed by UK households, with the consumption rate fluctuating, depending on factors such as: building type; the number of residents; the behaviour of occupants; and the building's thermal performance. However, general figures of consumption remained within the surveyed national domestic energy demand. These figures are used in this research as a benchmark for the simulated thermal energy demand of the modelled building.

Secondly, UK studies concerning on-site energy generation indicated the potential for implementing solar and wind energy, due to their abundance and affordability. At the same time, these sources demonstrate issues related to intermittency and irregularities in output levels, leading to energy deficiencies for the end user and a reduction in overall efficiency. Solar radiation can be harvested by several methods, with different levels of efficiency. Furthermore, solar energy can be accurately predicted and estimated manually, or by means of modelling tools, according to the location of the building. In this study, the solar energy generation (from PV panels) is used as an on-site potential main source of energy for the building. Wind energy, however, is restricted by a number of factors, e.g. technological, regulatory, and environmental. A number of studies have also indicated a high level of unpredictability within the built environment, due to the complexity in predicting paths and turbulence generation. A supplementary system of energy storage should therefore be included to overcome these obstacles and match the peaks of energy production to those of energy demand. The coverage of these systems is discussed in the following chapter.

Thirdly, the literature review of high energy performing buildings resulted in the conclusion that implementing the standards of Passivhaus as a design reference can assist in achieving the goal of a zero-carbon building, including the limitation of carbon emissions and the use of on-site renewables. Although both solutions could experience overheating during the summer months, a number of remedies were suggested, including increasing cross ventilation and solar shading for south facing facades. In addition, the design approach employed to reach zero carbon statues can differ depending on the module used. The final results may not change the performance of a building but achieving the goal method differs in each module reviewed in this chapter.

Finally, this chapter reviewed a number of case studies focussing on energy efficient buildings. All case studies included the utilisation of solar energy, with the majority also including some form of energy storage system to reduce energy demand and increase the potential output of on-site renewables. A number of case studies identified further sources of on-site energy, i.e. ground source heat pumps and air source heat pumps. In addition, the case studies included a wide variation of construction methods, indicating the potential for achieving a high-energy status using commercially available construction methods. The energy performance of some of these case studies (Camden passive house and SOLCER house) are used later in this study to compare the results with the simulated model over annual and diurnal figures.

3 Thermal Energy Storage (TES) Systems

This chapter will investigate several aspects of thermal energy storage (TES) methods, technologies, applications, limitations, and system designs. In addition, this chapter will introduce modelling and basic thermal energy capacity calculation methods and describe the most common applications and the most popular methods used in domestic and energy efficient buildings. Furthermore, this chapter will present several case studies of active TES systems in the UK and in the EU.

3.1 Thermal energy storage

Thermal energy storage is one of the oldest methods of conserving energy registered in human history. One good example is when people harvest and store ice in colder regions to be used in times of need. Ancient Greek architects used to orient buildings toward the sun so that the building envelope could store solar heat, which would be welcome on cold nights. Although all applications use the same principle, the term 'thermal' is used to refer to heat and cold storage depending on the energy source interaction with the storage medium (Athienitis and Santamouris 2002; Parameshwaran et al. 2012; Duffie and Beckman 2013). Over time, larger and more varied applications were developed to accommodate different energy demands. Currently, TES has been developed to a point where it can contribute to the solution posed by the mismatch between the supply and demand of energy (Dincer and Rosen 2010). There are several benefits to using TES systems over electrical energy storage systems in buildings, most of which have been listed in a number of reviewed articles. The benefits include: energy cost reduction, energy consumption reduction, flexible operation, low initial cost, low maintenance demand and carbon emission reduction over time (Dincer and Rosen 2010; Parameshwaran et al. 2012).

Understanding the general operational principle of TES systems will be an essential step in following this review since all TES systems share the same principle of operation. Furthermore, reviewing each technology in detail will help build a better case study for that technology and help discover how to achieve the technology's maximum potential. The general principle behind any TES system comprises three steps: charging, storing and finally discharging. During this process, thermal energy will be subjected to some energy loss either in the form of heat or mechanical loss. Furthermore, heat loss during the storage period occurs either through heat leakage or through the intake of heat from the surroundings (Ataer 2006; Faninger 2010; Kalaiselvam and Parameshwaran 2014). Figure 3-1 illustrates the thermal energy storage process in its simplest form.

The amount of energy stored within any given TES system depends highly on the storage medium and its thermal properties. Each storage medium can store a certain amount of thermal energy per volume, known as the volumetric energy capacity. Moreover, the storage duration of thermal energy is also a key characteristic of the TES system, affecting its performance (Parameshwaran et al. 2012).

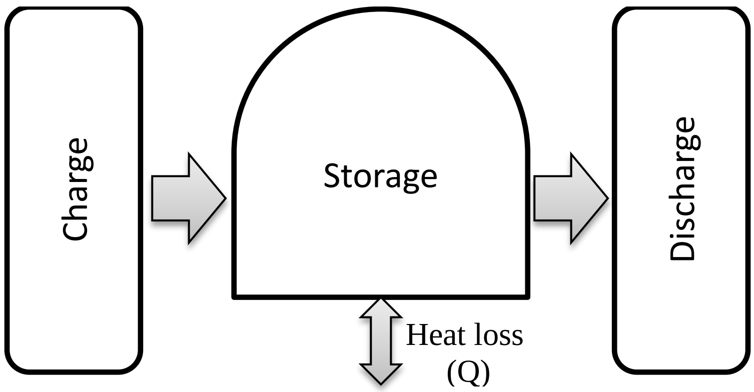


Figure 3-1: The TES system's basic working principle

Thermal energy storage systems working principle is based on the first and the second laws of the thermodynamics. Wherein the first thermal dynamics law refers to energy gain and loss, the second law refers to the exergy content of entropy and irreversibility (Kalaiselvam and Parameshwaran 2014). While exergy has been given considerable attention and analysis by scientists, engineers, and research groups, exergy concept has a wide variety of definitions (ibid). In the work of Dincer and Rosen (2010) exergy is defined as the amount of work or availability that can be produced by a steam of energy (or heat in the case of thermal energy storage) as it comes to equilibrium with a reference environment (Dincer and Rosen 2010).

However, estimating the thermal storage efficiency in relation to energy and exergy can be conducted by the following formula (ibid):

$$\psi = \frac{exergy\ recovered\ from\ TES}{exergy\ input\ to\ TES} \quad \text{and} \quad \eta = \frac{energy\ recovered\ from\ TES}{energy\ input\ to\ TES}$$

Where ψ is the overall exergy and η is the overall energy efficiency of the TES system.

There are currently three main types of TES systems used in buildings, namely: sensible, latent heat, and thermochemical storage (Figure 3-2). While sensible heat storage cycles occur when the storage medium temperature is changed while releasing or absorbing energy, the latent heat storage cycle will include a change in the storage medium's phase or state. Finally, thermochemical storage relies on the reaction of two pairs (or more) of reactants to store and release heat (Dincer and Rosen 2010; Parameshwaran et al. 2012; Kalaiselvam and Parameshwaran 2014).

These three types of thermal storage mediums vary according to a multitude of factors which affect their performance. This variation creates the potential for a spectrum of applications, ranging from an urban scale centralised storage system to a limited domestic application. The general advantages and disadvantages of each type of TES system are summarised in Table 3-1 (Parameshwaran et al. 2012). In addition, most thermal energy storage systems that are intended for domestic applications are coupled with a renewable energy source. This coupling accommodates the energy reduction and load peak shifting target of the TES system (Dincer and Rosen 2010). The next section presents an overview of each technology, including each technology's properties, capacities, and application to domestic buildings.

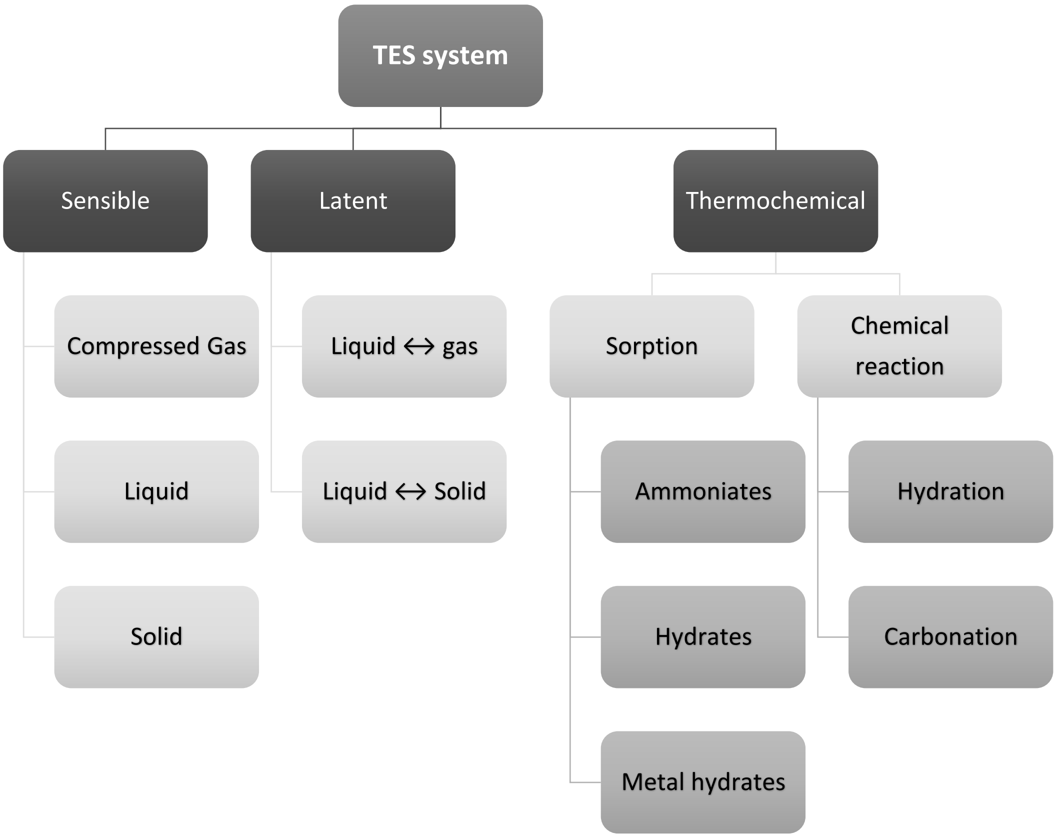


Figure 3-2: Thermal Energy Storage (TES) system types

Table 3-1: Seasonal TES technologies comparisons (Kalaiselvam and Parameshwaran 2014 p.63)

	Sensible	Latent	Thermochemical
Medium	Water, gravel, pebble, soil, concrete etc.	Organics, inorganics	Metal chlorides, metal hydrates, oxides etc.
Advantages	Environmentally friendly, cheap materials, simple installation and operations, easy to control, reliable	Higher energy density than sensible, provide thermal energy at constant temperature	Highest energy density, compact system, negligible heat losses
Disadvantages	Low energy density, huge volume requirement, self-discharging, heat loss presents, high cost of site construction	Lack of thermal stability, crystallisation, corrosion	Poor heat and mass transfer property under high-density condition, uncertain cyclability, high cost storage material
Present status	Large-scale demonstration plants	Material characterisation, laboratory-scale prototypes	Material characterization, laboratory-scale prototypes

3.2 Sensible thermal energy storage systems

Sensible TES systems depend on transferring heat by conducting it into storage mediums and altering their sensible heat. This method is the most commonly used in buildings as it is inexpensive to install and is based on a simple operation process (Tatsidjodoung et al. 2013). It relies highly on the specific heat of the medium material and the temperature change. In addition, the amount of energy stored is highly dependable on the storage medium in terms of properties and storage duration (Dincer and Rosen 2010). In ancient Greece, houses were made facing south to benefit from the solar heat gain to help with fuel shortages (Sukhatme and Nayak 2008). The same principle is applied in Passivhaus design and in most energy efficient buildings. By turning the whole building into a massive sensible heat TES system which utilises the internal heat gains to reduce energy demand (Chan and Russel 2011). What makes this TES method significant is the storage material's ability not to change phase or state during the storage process or within the intended storage temperature range. The determining factors of the system's performance and efficiency are mainly how energy is introduced to the storage, the storage medium itself, and the system's insulation from the surroundings. The amount of energy (*E*) required to change the temperature of the storage medium or any other substance of a volume (*V*) and density (ρ) from temperature (*T1*) to temperature (*T2*) can be calculated using the following equation:

$$E = mC\,(T_2 - T_1) = \rho VC\,(T_2 - T_1)$$

where C is the storage medium specific heat value.

3.2.1 Storage materials and methods

Sensible heat storage systems mainly consist of input/output devices, a container, and a medium. The container's main functions are to retain the storage medium while preventing thermal energy loss. Additionally, the storage medium's properties have to meet the storage energy requirements since different materials can differ hugely in terms of the amount of energy they can store. For example, storing heat in water bodies such as lakes and water tanks is a very common practice in TES as water has the highest specific heat for a liquid at ambient temperatures. Solid mediums, such as rocks and concrete, will yield a higher energy storage capacity due to their higher specific heat, although liquids have the advantage of being able to be transferred (Dincer and Rosen 2010).

The amount of energy stored by any material as sensible heat storage can be estimated by calculating ρC, where ρ is the material's density and C is the specific heat of the same material. The most common materials used in sensible heat storage systems are shown in Table 4 along with their thermal properties at 20C°. Another important parameter of the material chosen as a storage medium is thermal diffusivity, which determines the material rate of heat that can be extracted or released from the material per volume of size. Iron is a good example of a material with a high thermal diffusivity rate and thermal capacity; though the enormous amounts that would have to be stored and the sheer cost renders it highly impractical to apply to domestic buildings. On the other hand, rock, which only has half the thermal capacity of water, has commonly been used since it can hold temperatures above 100C° and has a low initial cost (Dincer and Rosen 2010; Parameshwaran et al. 2012; Kalaiselvam and Parameshwaran 2014).

Table 3-2: Common materials used in TES systems and their thermal capacities at 20C° (Dincer and Rosen 2010)

Material	Density (kg/m^3)	Specific Heat (J/kg K)	Volumetric thermal capacity (10^6 J/m3 K)
Clay	1458	879	1.28
Brick	1800	837	1.51
Sandstone	2200	712	1.57
Wood	700	2390	1.67
Concrete	2000	880	1.76
Glass	2710	837	2.27
Aluminium	2710	896	2.43
Iron	7900	452	3.57
Steel	7840	465	3.68
Gravelly earth	2050	1840	3.77
Magnetite	5177	752	3.89
Water	988	4182	4.17

The various types of sensible thermal heat storage systems are dependent upon the method used to store energy in the material and how the heat is introduced into and from the storage tanks. There are currently five main types of storage systems which are commonly used (Dincer and Rosen 2010), namely:

1- Thermally stratified storage tanks:

This is one of the most common storage systems and is gaining widespread application in domestic buildings. This method employs water as a storage medium. The water is stored in several chambers or cavities within the storage tank. Heated water (or cooled for cold thermal storage) will move passively to the next chamber or cavity due to its lighter mass and it is replaced by colder water. Figure 3-3 shows the levels of stratification in a hot water thermal storage system. In addition, there are multiple storage tank designs that have purposely used stratification as a method of increasing the duration of the storage (Dincer and Rosen 2010) with or without internal wall separations (see Figure 3-4).

This method of storing sensible heat is considered simple yet effective, while the output efficiency relies on several considerations such as the geometrical form of the tank, the temperature of operation, and the insulation of the tank. The use of a dual medium storage system which uses water and phase changing materials or other fluids (e.g. thermal oils) is also feasible when using this method. The use of a heat exchanger together with this method is also common practice since the heated fluid can be transferred from and to the tank.

Although the heat exchange method concept offers more flexibility, it presents a greater potential of heat loss and requires extensive piping (Dincer and Rosen 2010). The use of different tanks to separate cold from hot fluids is also common practice, although its application is better suited to larger centralised systems rather than small scale domestic applications (ibid).

To determine the stratified thermal energy storage system efficiency accurately, an exergy analysis must be conducted. This analysis evaluates and calculate the heat injected, recovered, holding of heat during storage periods, and temperature degradation within the TES tank (Dincer and Rosen 2010). The advantages of performing exergy analysis rather than energy analysis only; are mainly the recognition of the temperature change of the storage tanks, and quantitatively accounts for heat losses due to degradation of storage temperatures compared to the surrounding environment (ibid).

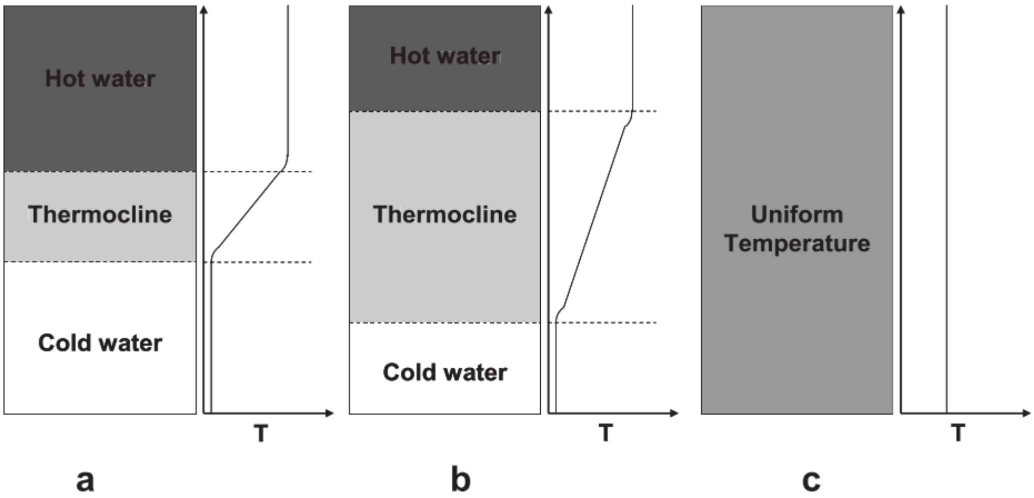


Figure 3-3: Hot water storage stratification levels: a) high stratification, b) moderate stratification, and c) fully mixed (Arteconi et al. 2013)

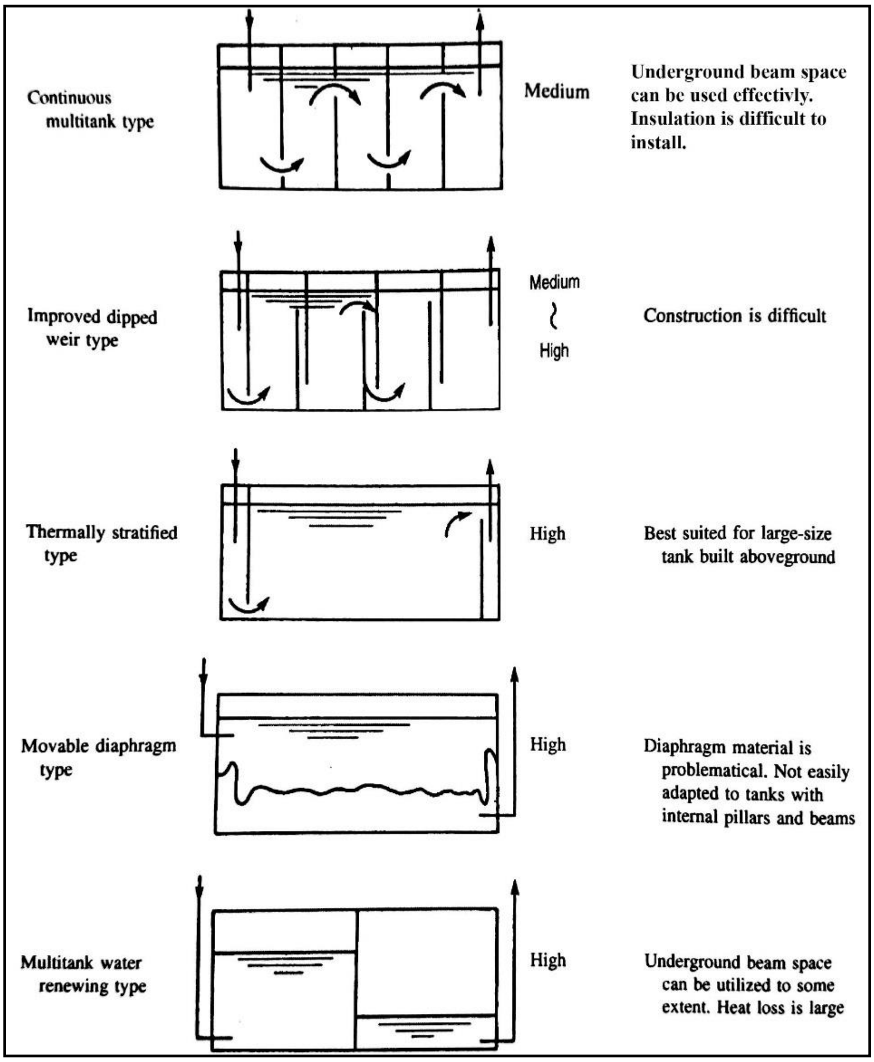


Figure 3-4: Types of stratified thermal storage tanks (Dincer and Rosen 2010)

2- Concrete thermal storage:

Concrete storage tanks have gained popularity in domestic applications because of their low cost, availability, and ease of implementation. Furthermore, the thermal property of concrete gives it several advantages as a storage medium, including high specific heat, good mechanical properties, a high thermal expansion coefficient, and a high mechanical resistance to cyclic thermal loading (ibid). It can store heat well over 100C° but this will cause the internal water to evaporate, thus causing it to lose density, which leads to a reduction in the specific heat. The dehydration of concrete will most likely occur between 30C° and 300C°. Dicer and Rosen have estimated that concrete thermal properties can be reduced by up to 20% at 400C° when compared to the material's properties at normal ambient temperature (ibid). Dehydration can also cause the concrete mass to lose structural strength through cracking, which effect can be countered by adding steel reinforcements. This would cause an up to 15% increase in the concrete's overall thermal conductivity at 100C° (ibid).

3- Rock and water/rock combination:

The appeal of using rock as a thermal storage medium originates from its low cost, availability, and ability to store higher temperatures (above 100C°). Although these advantages are tempting for small scale applications, the volumetric thermal capacity of rock is much lesser than that of water (ibid). The method of combining water storage with rock is known as the Harry Thomson method (Figure 3-5). This method utilises solar heated water and introduces it into a storage tank from the top to cool down and exit the tank from the bottom to be circulated once again. The heated water tank is surrounded by river rock with an air cavity that circulates hot air and introduces it to the building. This method combines the advantages of the high thermal capacity of water and the extensive area with the volume of the rock's container which creates an efficient heat to air transfer (ibid).

The reviewed literature on rock thermal storage systems points to several design requirements for the use of this material as a storage medium. The main aspect is the volume of the storage tanks required which is estimated to be three times the size of the storage tanks required for water with the same thermal capacity. While size is a major consideration, the shape of the storage tank can also play a major role in the system's performance. Cubical and rectangular tanks generally perform well with rock storage systems. Furthermore, the size of the stone particle is also an important factor to consider since size determines the air flow resistance. Dincer and Rosen recommend the use of 2.5 cm diameter size particles and washed gravel instead of crushed rocks (ibid).

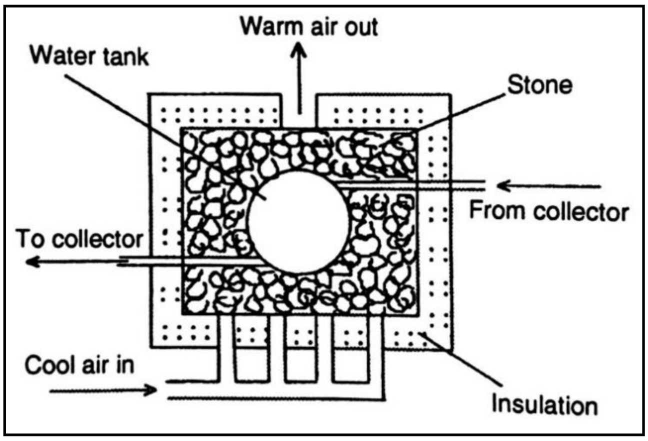


Figure 3-5: Harry Thompson's method of TES with rock and water as a storage medium (Dincer and Rosen 2010)

4- Aquifer thermal storage:

Aquifer thermal energy storage or the ATES concept is a well-known method of thermal storage which was first used several decades ago. It depends on using underground water as a storage medium. The natural boundaries of these water bodies are either one or more of the following: rock, limestone, sandstone, and clay. The water itself is usually fresh since it originates from remnant underground ice from the Ice Age. Northern Europe and Canada are known to have these aquifers of different types and sizes. Their employment as thermal storage reservoirs can be extended to large, regional, or central applications. Several studies have been conducted over the past three decades to understand the maximum potential of this storage method. The studies indicate that there are several advantages to employing this system, one being its high capacity storage. Another advantage is the flexibility of the system to store energy for different duration cycles (diurnal, weekly, or seasonal). Furthermore, the aquifer's environmental surroundings, such as rocks and clay, also work as an extended thermal storage medium. Lastly, since the volume required for storage in this method is located outside the property boundaries and is naturally provided, this system is much more economical and location feasible than other systems and has low operational maintenance costs. On the other hand, this method of storing thermal energy does have several disadvantages. Firstly, it is highly dependable on geographical location. Secondly, it can operate only at low temperatures (from 0C° – 40C°); higher temperatures may cause any number of problems. Thirdly, it requires a mechanical and auxiliary power source to operate which reduce the system's overall efficiency. Finally, this method requires the presence of several wells to be drilled within the operating property while maintaining a fairly large distance between them. This makes this system less suitable for small applications.

5- Solar ponds storage:

Solar ponds have been used and applied in several regions of the world, mainly in Israel since the 1960s (Dincer and Rosen 2010). The basic principle of this method relies on the gradient heat transfer in a solar exposed body of water (such as lakes). In lakes, generally, the heated water rises to the surface until it is cooled down by the atmosphere when it then sinks back down. In this method, however, dissolved salt is released in the bottom layer of the lake, which makes this layer heavier than fresh water thus keeping it from rising even if it is heated (Figure 3-6). The most commonly used mineral salt used in this method are sodium chloride, sodium carbonate, magnesium chloride, potassium nitrate, ammonium nitrate, urea, and natural brines of sodium, potassium, magnesium and chlorine (Kalaiselvam and Parameshwaran 2014). This method is suitable for regions where the temperatures rarely drop below freezing point. Furthermore, it requires a large land area and also works better with longer storage duration cycles such as weekly or seasonal storage cycles (Dincer and Rosen 2010).

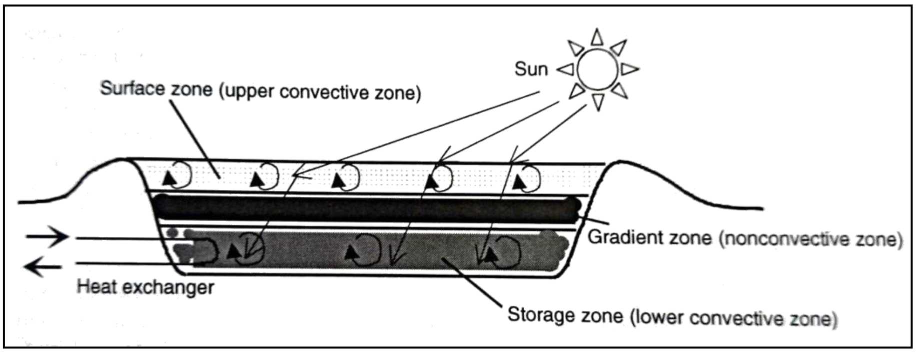


Figure 3-6: Solar ponds thermal storage systems (Dincer and Rosen 2010)

3.3 Latent thermal storage systems

The latent thermal storage method utilises materials that respond to temperature change by either changing phase or breaking down into different compounds. This method of storing thermal energy has been used for decades but has only lately started to gain popularity in domestic buildings since new technologies made this method much more compact and economically feasible. In the following section, latent heat storage methods and materials will be reviewed in addition to storage applications into domestic buildings.

3.3.1 Phase changing materials (PCM)

The PCM method relies on changing the material phase by applying or extracting heat from it. When the stored heat (energy) in the storage medium increases beyond the melting point of the medium, phase change phenomena occur and the medium stores a certain amount of energy without rising in temperature. The storage of energy between phases of the storage mediums is known as heat of fusion (Dincer and Rosen 2010). The process of increasing the internal energy of any storage medium beyond the phase change point will transfer the storage type from a sensible to a latent heat storage system. The phase changing process of any substance is illustrated in Figure 3-7, where A-B marks the rise of the initial temperature of the solid material; B-C marks the phase of change of the crystallisation structure within the solid state; C-D marks the rise of the internal temperature of the solid medium; D-E marks the phase change from solid to liquid; E-F marks the sensible heat storage and temperature of the liquid medium; F-G marks the phase change from liquid to gas and, finally, G-H marks the continuous rise of temperature of the gas medium as a sensible heat. The system's capacity and maximum temperature is dependent upon the heat of enthalpy of the storage medium used in the TES system. The following equation is used to calculate the medium energy storage capacity throughout the phase changing process (Regin et al. 2008):

$$Q = m[\int_{TA}^{TD} C_{ps}\,(T)dT + L_p + L + \int_{TE}^{TF} C_{pl}(T)dT + \,L_g + \int_{TG}^{TH} C_{pg}(T)dT]$$

Where: m is storage medium mass; C_{ps} is the specific heat of the medium in its solid state; C_{pl} is the specific heat of the medium in its liquid phase; C_{pg} is the specific heat of the medium in its gas phase; L_p is the latent heat of the material in its solid-solid phase; L is the latent heat of the material in its solid-liquid phase and, finally, L_g is the latent heat of the medium in its liquid-gas phase (Regin et al. 2008).

The capacity of the internal thermal energy storage of any storage medium is highly dependable on the material's thermophysical properties. The total energy storage capacity of a certain medium can be calculated using the initial energy storage state and the heat of fusion of that specific medium.

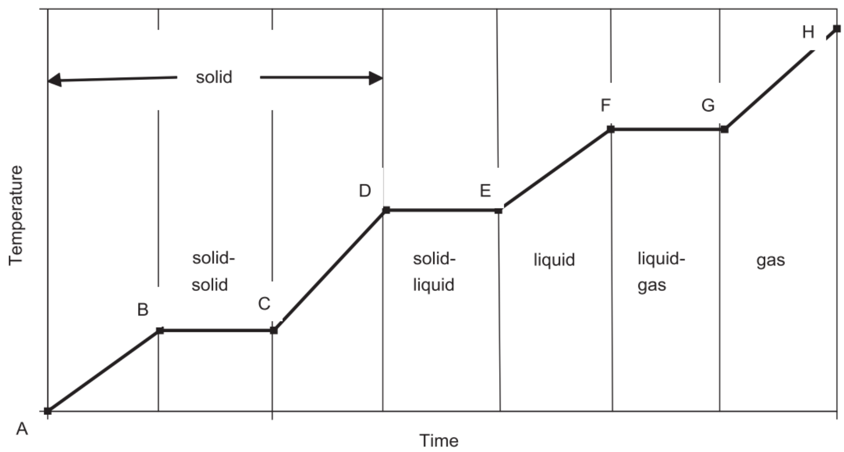


Figure 3-7: Temperature change over time in thermal storage medium (Regin et al. 2008)

The most common use of a basic PCM storage system is the water change from ice to water or water to vapour. In general, PCM materials have a higher energy density than any other sensible material, thus storage devices are much smaller, more compact, and have less storage heat loss. It is also important to know the thermal cycle of the material used and the physical properties of each phase change. For example, paraffin waxes usually melt at 37°C which make them more suited to small-scale applications (Zhou et al. 2012). Another example is salt, which melts at 131°C but has to be kept at 288°C to be efficiently used. Such high temperatures can mostly be found in larger scale applications that serve an urban scale demand. Currently, there are several materials, from both organic and inorganic sources, with different thermal properties that be applied as PCM storage mediums (see Table 3-3) (Dincer and Rosen 2010).

1. ***Organic PCM***

Organic PCM materials include paraffin, fatty acids, esters, alcohol, and glycols. Although most of these materials are used in cooling applications, paraffin and fatty acids have a melting point that can be used in heating applications. Fatty acids have been recently developed and used in energy storage systems since they have a mid-range melting point (50°C - 70°C). Some of the most common fatty acids used today are Myristic acid, Palmitic acid, and Stearic acid. These acids originated from an organic natural source with minimal environmental impact and low carbon emissions (Biçer and Sarı 2013). They possess a high heat of fusion that is close to paraffin without the super-cooling effect (Chan and Russel 2011). On the other hand, the cost of fatty acids is more than three times the cost of paraffin and are less available commercially (Regin et al. 2008).

Paraffin (alkanes) is commonly used as a PCM thermal storage material due to its high heat of fusion, insignificant super-cooling effect, lack of phase change segregation, thermal and chemical stability, abundance, low cost, and safety (non-poisonous, and non-corrosive) (Regin et al. 2008; Chan and Russel 2011). Several studies demonstrated that paraffin can store seven times the energy that can be stored in rocks and eight times the $Na_2SO_4.10H_2O$ for the same given mass (Ghoneim 1989; Chan and Russel 2011).

The main disadvantage of paraffin is its inconsistency with fatty acids, which have low thermal conductivity and flammability. While thermal conductivity can be increased by applying a fast heat distribution design in the storage container, flammability risk can be reduced by implementing fire retardant techniques (Chan and Russel 2011). Furthermore, paraffin is rarely found in its pure form which can be expensive, thus a mixture of different grades of paraffin and carbon hydrates is generally used, resulting in a range of melting temperatures instead of a sharp melting point (ibid).

2. Inorganic PCM

Inorganic materials used as PCM thermal storage are mostly synthetic materials that change phase on a low to a mid-range of temperatures (Dincer and Rosen 2010; Chan and Russel 2011). In their main, these types of inorganic PCMs are eutectic materials. These materials consist of several inorganic substances to form an alloy with a single melting point. Eutectic alloys usually form a single crystal when crystallised, reducing phase change segregation. In most cases these eutectic alloys consist of salt hydrates and/or other organic materials (Tatsidjodoung et al. 2013). In general, inorganic PCMs have several advantages over organic PCM materials, which include a higher heat of infusion thus yielding a higher energy density and the fact that they are non-flammable. They also have several disadvantages that reduce their efficiency and applicability, including phase separation, thermal instability, chemical instability, sub-cooling effect, corrosive hazard, and thermal degradation due to dilution over time (Chan and Russel 2011).

3.3.2 Selection of PCM material for TES systems

The implementation of the PCM method in domestic buildings largely depends on the energy demand of a particular building. In general, the literature reviewed classifies PCMs based on their melting point, their storage duration, and how the material can be utilised to meet the energy demand. Dincer and Rosen (2010) categorised PCM materials according to their melting point and thus their applications, as follows:

- 5C° - 15C°: mainly for applications using cool thermal energy storage where cool thermal energy demand is required.
- 20C° - 35C°: near room temperature melting point, which is applicable in buildings with heat and cold thermal demand or for energy storage with a diurnal cycle. A good example for this material is $CaCl_2.6H_2O$, which can be incorporated into the building structure to further delay diurnal temperature changes. Furthermore, it can be joined with a solar thermal collector to store heat for longer periods.
- 40C° - 60C°: suitable for most applications with solar energy as a heat source to store thermal energy on a diurnal basis.
- 55C° - 70C°: suitable for producing domestic hot water using grid energy or solar energy as a heat source.
- 60C° - 95C°: mainly used to produce domestic hot water on a diurnal basis or for space heating with seasonal cycles.
- 100C° - 175C°: reaching this high range of temperatures is not feasible for regular solar thermal collectors; this range of temperatures requires concentrated solar panels to meet high heat demand (for both space heating and DHW) or for seasonal storage.

There are several criteria that should be considered when selecting a suitable PCM material for domestic application during the TES system design. These criteria include: (Regin et al. 2008; Chan and Russel 2011)

- A melting temperature that meets the operational temperature.
- A high heat of fusion (the higher the heat of fusion the more desirable the material).
- High specific heat, thus higher sensible heat storage and higher storage capability.
- High thermal conductivity for a higher rate of thermal exchange.
- Minimal phase-change volumetric expansion to reduce system complication.
- Chemical and thermal stability during heat exchange cycles over time.
- Storage unite pressure stability (less pressure change is more desirable).
- Low to zero super-cooling effect below freezing point.
- High safety properties (non-poisonous, non-flammable, and non-corrosive).
- Low cost and high availability.

Table 3-3: Thermophysical properties of commonly used PCM materials (Dincer and Rosen 2010; Tatsidjodoung et al. 2013)

Compound	Melting temp. (C°)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)	Density (kg/m^3)
Inorganics				
$MgCl_2.6H_2O$	117	168.6	0.570 (120C°)	1450 (120°C)
$Mg(NO_3)_2.6H_2O$	89	162.8	0.490 (95C°)	1550 (94°C)
$Ba(OH)_2.8H_2O$	78	265.7	0.653 (85.7C°)	1937 (84°C)
$Zn(NO_3)_2.6H_2O$	36	146.9	0.464 (39.9C°)	1828 (36°C)
$CaBr_2.6H_2O$	34	115.5	-	1937 (84°C)
$CaCl_2.6H_2O$	29	190.8	0.540 (38.7C°)	1562 (32°C)
Organics				
Paraffin wax	64	173.6	0.167 (63.5C°)	790 (65°C)
Paraffin C20-C33	48-50	189	0.21	912 (20°C)
Paraffin C22-C45	58-60	189	0.21	920 (20°C)
Polyglycol E400	8	99.6	0.187 (38.6C°)	1125 (25°C)
Polyglycol E600	22	127.2	0.187 (38.6C°)	1126 (25°C)
Polyglycol E6000	66	190.0	-	1085 (70°C)
Fatty acids				
Stearic acid	69	202.5	-	848 (70°C)
Palmitic acid	64	185.4	0.162 (68.4C°)	850 (65°C)
Capric acid	32	152.7	0.153 (38.5C°)	878 (45°C)
Caprylic acid	16	148.5	0.149 (38.6C°)	901 (30°C)
Aromatics				
Biphenyl	71	119.2	-	991 (73°C)
Naphthalene	80	147.7	0.123 (83.8C°)	976 (84°C)

3.3.3 PCM storage methods

A coherent development of the PCM thermal energy storage system and its storage method will improve the overall performance of the whole system and its use (Regin et al. 2008). In general, the PCM storage container must meet several requirements to operate successfully, namely, it must:

1. Have strength, flexibility, corrosion resistance, and be thermally stable.
2. Protect the storage medium from environmental elements.
3. Provide an adequate heat transfer surface.
4. Be structurally stable and be easily handled. (ibid)

The literature reviewed indicated several methods of containment in a PCM storage system, the three main types being bulk storage tanks, macroencapsulation, and microencapsulation (ibid). Bulk storage tanks are similar to the sensible heat storage tanks except for one major point, which is the ability to deliver higher heat exchange due to the fact that PCM materials have a higher density than sensible mediums, which means less area for heat exchange (ibid). Several approaches have been used to achieve this extensive heat exchange, including insertion of fins, the use of high conductivity particles, the use of a metallic structure, the application of fibres from the PCM side, direct contact with the heat source, and the use of a rolling cylinder (ibid).

The macroencapsulation approach involves storing the PCM substance in small containers within the storage tank and using a fluid to circulate heat within the storage system (usually water or air). The stored PCM media can range from a few grams to a kilogram. The most used materials for the capsules are polyethylene (both high and low density), polypropylene, tin plated cans, and lacquer finished mild steel cans (see Figure 3-8). The benefits of implementing this method are several but, in general, this method will provide a better heat exchange rate than the bulk storage system and provide a self-supporting structure (ibid).

Microencapsulation, on the other hand, involves imbedding the PCM substance into a structural mesh of matrix on a molecular level. The impregnated material will provide structure and thermal conductivity (see Figure 3-9, Figure 3-10, and Figure 3-11). While this approach is constantly being developed, it has a high initial cost due to the complicated manufacturing process. Furthermore, the implementation of this method in building structures to increase the thermal mass of a building’s envelope has also been under development for the past decade. Domestic applications of this method are limited and some researchers think that incorporating PCM into building structures may affect the mechanical strength of the structure (Regin et al. 2008; Parameshwaran et al. 2012; Zhou et al. 2012; Heier et al. 2015).

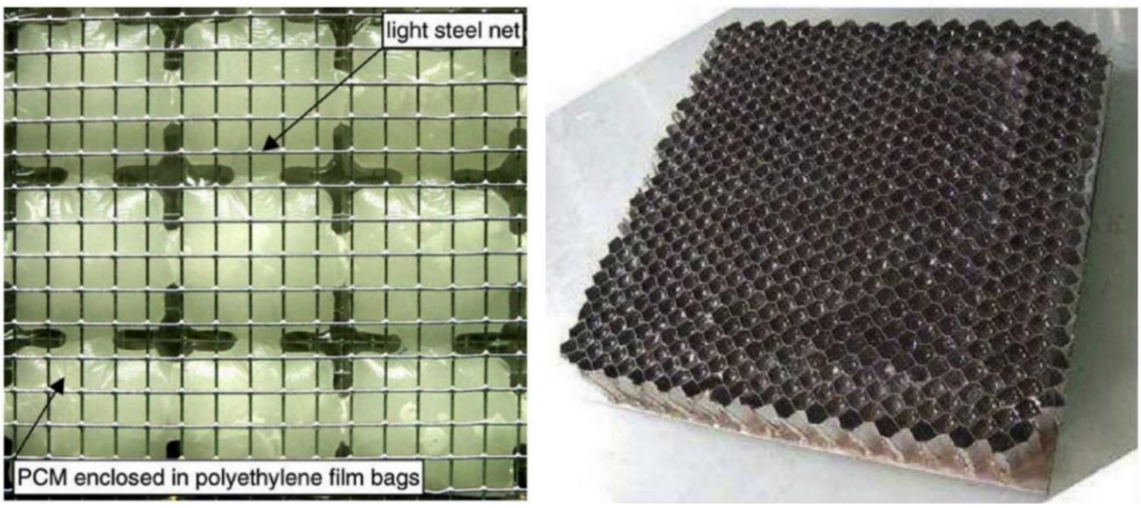


Figure 3-8: Some macroencapsulation methods: (left) polyethylene bags; (right) tin-plated honeycombs (Parameshwaran et al. 2012)

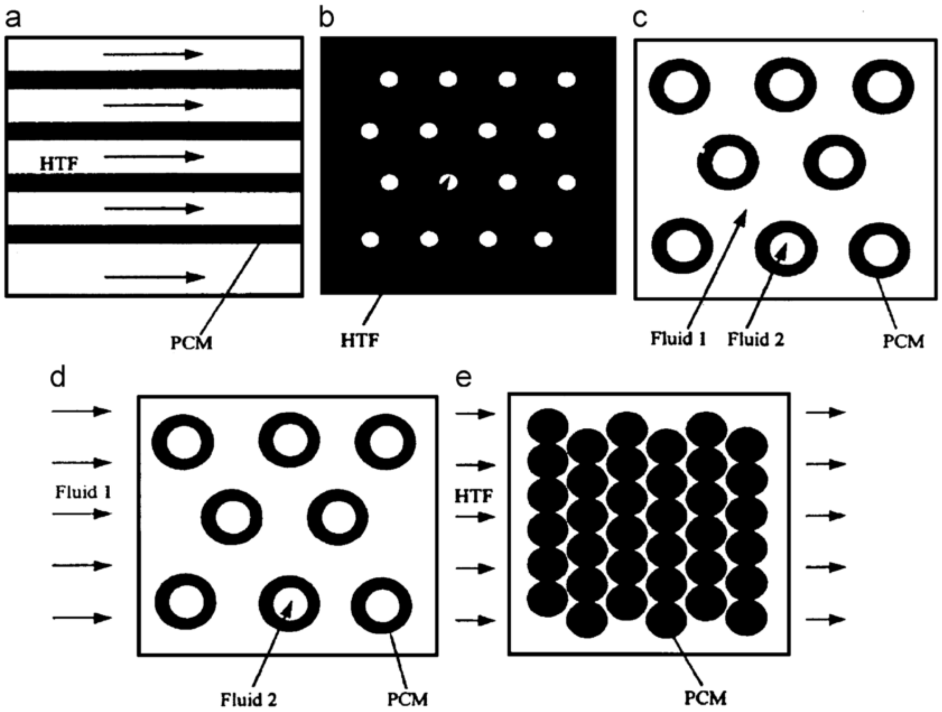


Figure 3-9: Several approaches to storing PCM materials in TES systems: a) flat-plate, b) shell and tube with internal flow, c) shell and tube with parallel flow, d) shell and tube with cross flow, e) sphere packed bed (Regin et al. 2008).

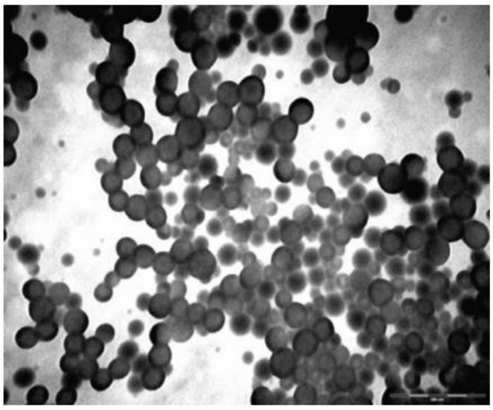


Figure 3-10: Encapsulated PCM with polystyrene shell and n-octadecane core (Parameshwaran et al. 2012)

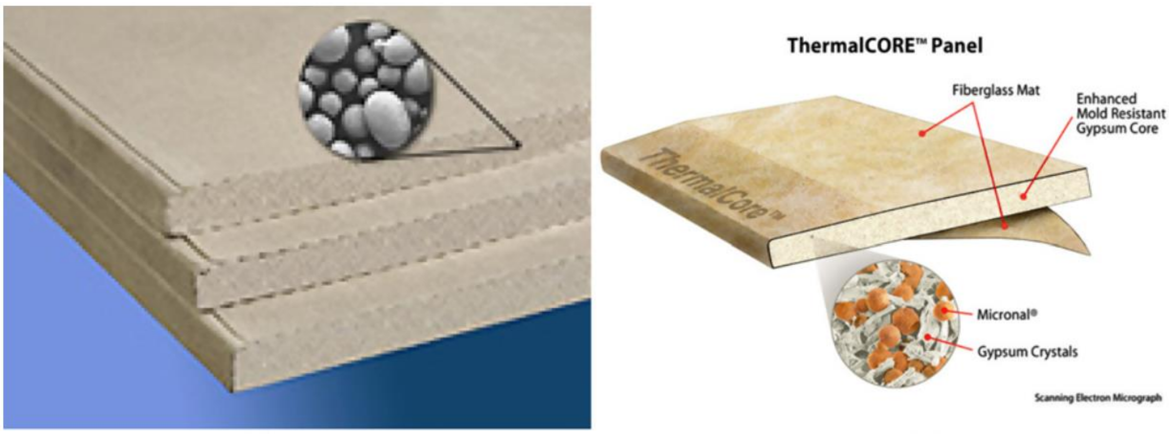


Figure 3-11: Microencapsulated PCM integrated into building materials. (left) Micronal® PCM imbedded into gypsum panels; (right) thermalCORE phase-change drywall (Zhou et al. 2012)

3.3.4 Heat transfer enhancement for PCM TES

In general, PCM materials used in thermal storage suffer from low thermal conductivity (organic PCMs specifically) that can prolong the charging and discharging time leading to some energy waste or loss (Li and Zheng 2016). Several methods and techniques have been developed to counter and enhance the thermal conductivity of these materials (illustrated in Figure 3-12) (ibid). In general, reducing the volume of PCM containers and increasing the conductive surfaces between the storage container and the thermal energy source are among the solutions that have regularly been implemented. Although there are several other approaches that offer high conductivity and thermal capacity (such as micro encapsulation and nanoparticles impregnation), these solutions are expensive and difficult to fabricate.

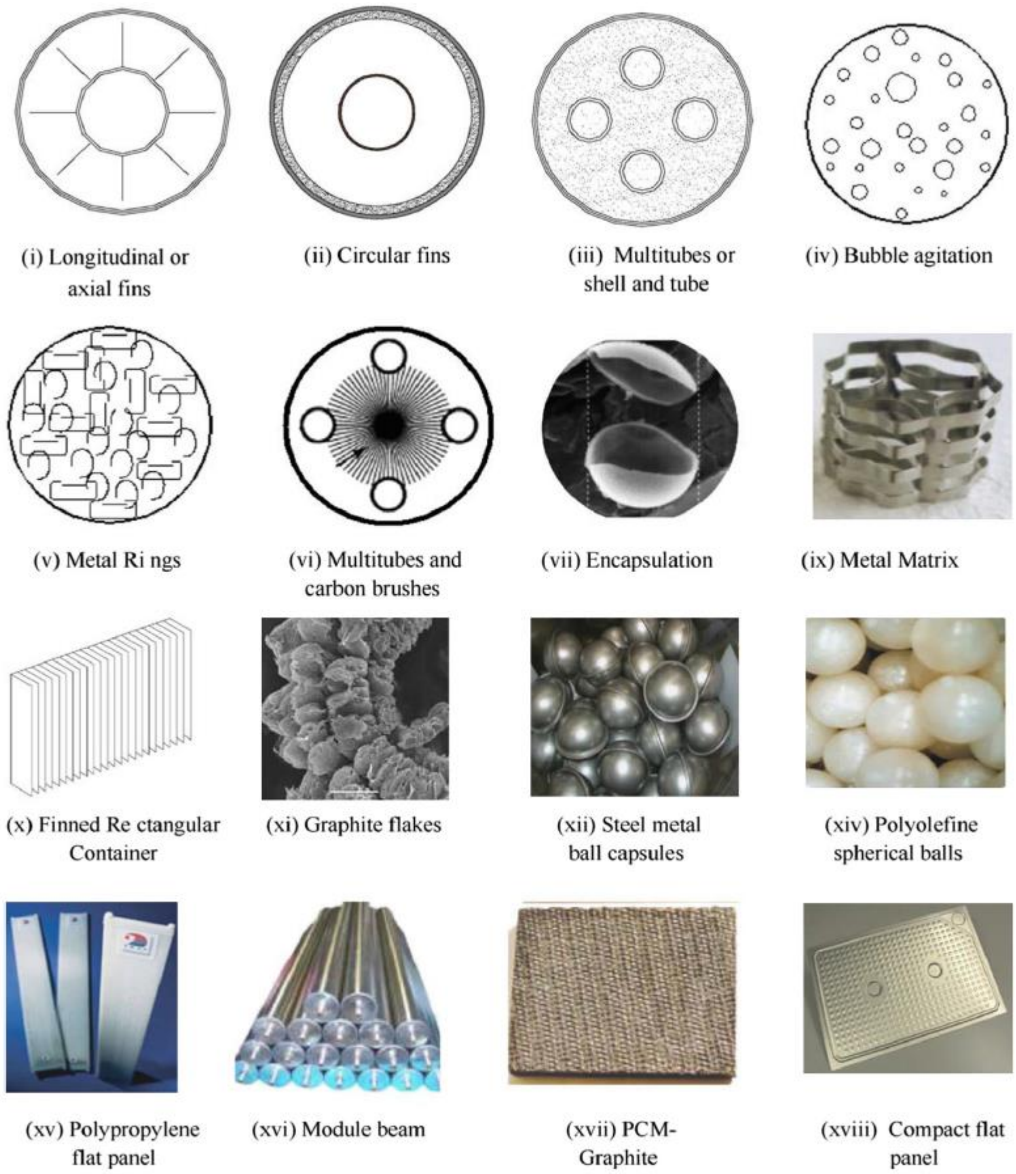


Figure 3-12: PCM heat transfer enhancement methods (Li and Zheng 2016)

3.3.5 PCM TES application in domestic buildings

PCM applications in domestic buildings for cool or heat storage can be classified into two main categories (Kalaiselvam and Parameshwaran 2014): passive and active applications. Passive application of PCM material refers to the process of implementing PCM into the building envelope, internal walls, glazing, ceiling, or furniture to regulate internal space temperature fluctuation on a diurnal basis. Active PCM applications involve a PCM storage medium connected to a pumping system and mechanically assisted heat exchanger or fan/blower (ibid). This method has a higher heat transfer rate and energy storage efficiency than the passive method. Furthermore, this method can be used for both diurnal and inter-seasonal storage. Figure 3-13 shows the PCM applications within domestic buildings.

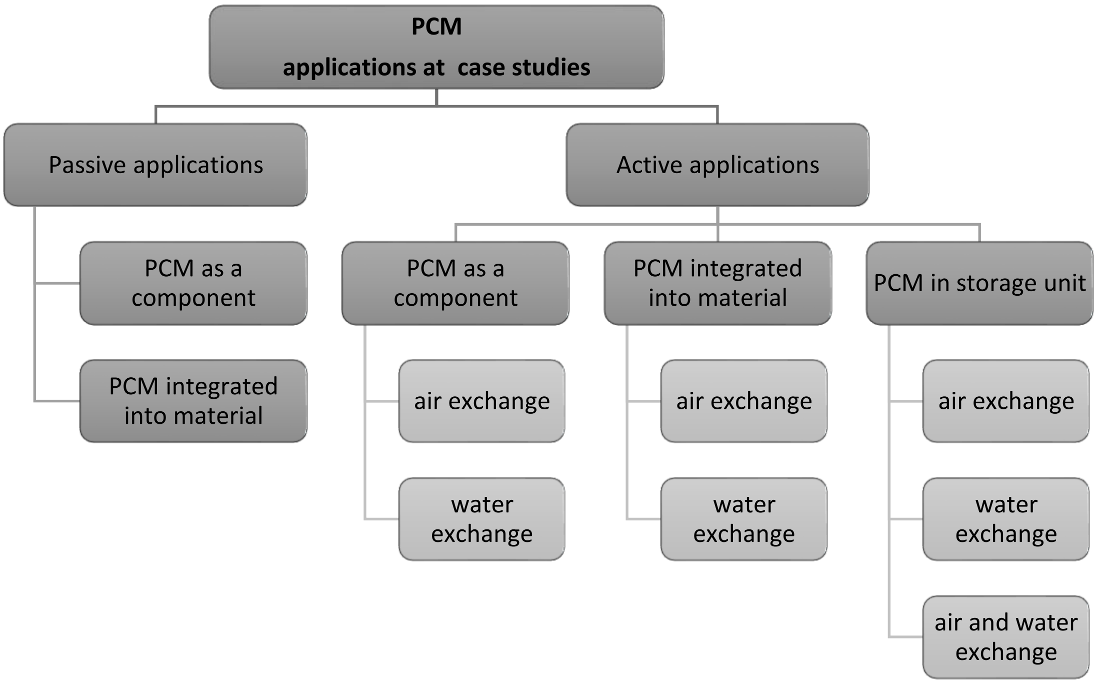


Figure 3-13: PCM application methods in domestic buildings (Kalaiselvam and Parameshwaran 2014)

3.4 Thermochemical energy storage

Chemical energy storage is a method based on endothermic-exothermic chemical reactions between two or more components (reactants) in which heat is generated or absorbed. What makes this method of thermal storage significant is that the reaction can be reversed with negligible heat loss. The basic principle of reaction can be illustrated through the equation: (Duffie and Beckman 2013)

$$(AB + Heat \rightarrow A + B)$$

The process of storing energy in a chemical energy storage system comprises three stages: reaction, storage, and separation (Figure 3-14). The reaction phase can be referred to as the discharge phase while the separation phase is the charging phase. The charging phase requires an energy source that causes the separation of the reactants thus storing thermal energy whether the energy source is thermal, electrical, or electromagnetic (Tatsidjodoung et al. 2013). The components of the reaction would also have separate storage units while the reaction is carried out in one or more tanks with a heat/energy applicator and/or extractor (Dincer and Rosen 2010; Kalaiselvam and Parameshwaran 2014). The stored energy is expressed in terms of wattage while the system capacity is determined by the size of the storage and chemical components. The thermal energy capacity of the thermochemical storage system depends mainly on the materials used as reactants. Furthermore, the efficiency of the system is also determined by the charging and releasing temperatures needed to complete the reaction. The following Table 3-4 demonstrates some of the commonly used reactions with the required temperatures of charge and release (Dincer and Rosen 2010).

Table 3-4: chemical storage system reactions and the charging/discharging properties (Dincer and Rosen 2010)

Reaction equation	Charging Temp.	Releasing Temp.
Salt hydrates reactions		
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	780°C	610°C
$SO_3 \leftrightarrow SO_2 + ½ O_2$	1025°C	590°C
$NH_4HSO_4 \leftrightarrow NH_3 + H_2O + SO_3$	498°C	435°C
Thermal decomposition reactions		
$Ca(OH)_2 \leftrightarrow CaO + H_2O$	450°C	200°C
$2PbO_2 \leftrightarrow 2PbO + O_2$	350°C	300°C
$4KO_2 \leftrightarrow 2K_2O + 3O_2$	300-800°C	

This method can store energy in the form of heat, cool, and can be used to control humidity. The most common practices of this type are sorption, thermal decomposition of metal oxides, and salt hydrates. Additionally, this type of energy storage is used in applications that require medium to high temperatures (Dincer and Rosen 2010). The terms chemical storage, thermochemical storage, and sorption storage are used interchangeably in the studies which were reviewed regarding the same chemical reaction energy storage method (Tatsidjodoung et al. 2013).

According to Sukhatme and Nayak (2008), thermochemical energy storage systems have several advantages over other storage systems. For example, the system is idle for storing energy in ambient temperatures without insulation to the medium reservoir. Which means that there is no heat gain or loss from the surrounding environment.

Furthermore, there is no need of a catalyst during reactions as long as there is an auxiliary energy input, for example a solar energy source. The authors also point out some disadvantages, such as the hazardous storage of some components of the reaction, for example oxygen and SO_4, since they pose safety and corrosion problems and will require continuous maintenance. Although Sukhatme and Nayak's (2008) statement is considered to be true for most thermal decomposition reactions and salt hydrates, it does not apply to the thermochemical sorption method. Finally, according to various studies, thermochemical energy storage systems theoretically present higher yields of thermal energy storage than sensible and latent storage systems (for building applications) (Tatsidjodoung et al. 2013; Yu et al. 2013; Kalaiselvam and Parameshwaran 2014).

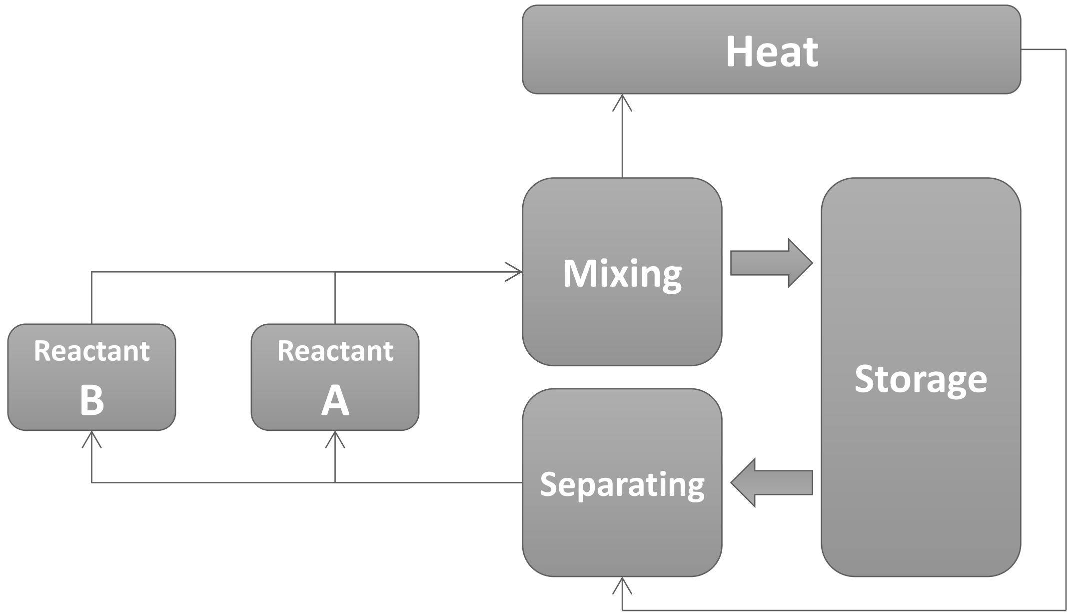


Figure 3-14: Chemical energy storage process (Kalaiselvam and Parameshwaran 2014)

3.4.1 Thermochemical sorption phenomena

Thermochemical sorption energy storage is based on storing heat in the form of a chemical binding force between the sorbent and the sorbate. The process of storing heat requires breaking this chemical bind by introducing heat that evaporates the sorbate and releases it in the form of gas or vapour (Chan and Russel 2011; Parameshwaran et al. 2012; Kalaiselvam and Parameshwaran 2014). This reaction method is also referred to as physicochemical reaction in the literature due to the use of thermophysical and thermochemical processes (N'Tsoukpoe et al. 2009; Chan and Russel 2011; Fraunhofer 2012).

In general, thermophysical reaction is referred to as 'absorption' and involves the endothermic process of the reaction. This reaction occurs to the bulk of the substance where the gas or vapour is absorbed by the liquid or solid substance. On the other hand, thermochemical reaction occurs with an exothermic process and is referred to as 'adsorption'. Therefore, the adsorption reaction involves the binding of a gas or vapour to the surface of a solid porous substance rather than the bulk of it, which signifies the difference between the two types. Furthermore, if the adsorption binding force is based on the Van der Waals forces then the reaction is identified as physical adsorption (physisorption). However, if the binding reaction is due to the Valency force, then it can be identified as a chemical sorption (chemisorption). Generally, chemisorption reactions yield more thermal energy as heat of sorption than a physisorption reaction (Yu et al. 2013; Kalaiselvam and Parameshwaran 2014). The classification of the sorption storage is illustrated in Figure 3-15.

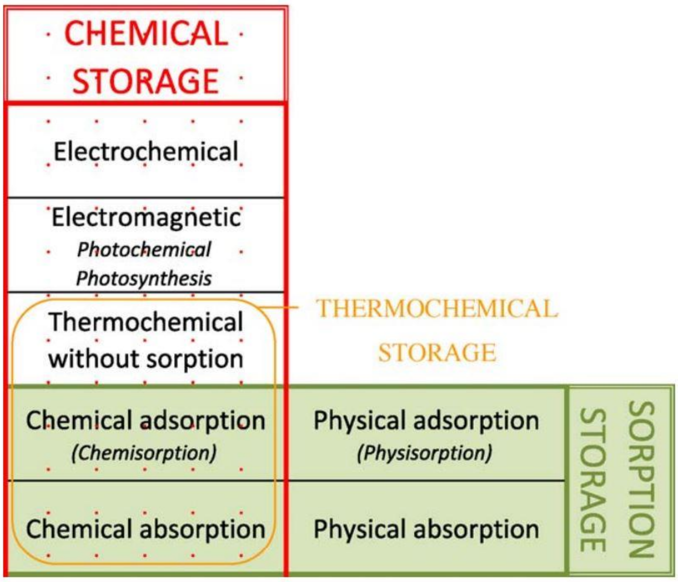


Figure 3-15: Sorption thermal energy storage classification (N'Tsoukpoe et al. 2009)

The basic method of calculating the thermal energy capacity (energy density) of thermochemical sorption storage material is by using the following equations (Aristov 2015):

$$A_{max}^{mas} = \Delta H_{des} \times w_{max} \text{ (for 1 kg of dry adsorbent)}$$

or

$$A_{max}^{vol} = \Delta H_{des} \times w_{max} \times \rho \text{ (for 1 m}^3\text{ of adsorbent)}$$

Where A_{max}^{mas} is energy density per unit of mass; A_{max}^{vol} is energy density per unit of volume; ΔH_{des} is average heat of water desorption; w_{max} is maximal mass of water adsorbed per 1 kg adsorbent; and, ρ is adsorbent density.

The variation of materials used as both sorbent and sorbate can determine the overall operational loads and heat capacity of the storage (Yu et al. 2014). The advantages of implementing the thermochemical sorption method in TES are: 1) it stores heat as a chemical potential that cannot occur unless there is direct contact between the sorbent and the sorbate. As a result, there will be no heat loss during the storage cycle nor will there be material degradation; 2) it can be used for heating and cooling applications with higher flexibility than other TES types; and 3) the desorption heat in the storing process will be higher than the evaporation heat of the sorbate alone (e.g. water requires 140°C to complete this process instead of 100°C in combination with artificial zeolites). This will increase the storing heat capacity and energy density of the storage system (Yu et al. 2014).

3.4.2 Thermochemical sorption materials

The sorption method can be established with a variety of combinations of sorbate and sorbents which can be referred to as ‘working pairs’. To build thermal storage applications water is mostly used as a sorbate while several other hosting materials were investigated as sorbents in the literature reviewed. Zeolites, silica gel, and activated carbon are among the most commonly studied working pairs for their low evaporating temperatures and high energy density (Yu et al. 2014).

Zeolites are a type of puros aluminosilicate mineral that exists in nature and can be synthetically produced to meet specific requirements (Chan and Russel 2011). Different commercially available zeolites have been developed to be used in thermal storage applications and other experimental fields (e.g. molecular sieves and chromatography). Zeolites’ performance in TES systems depends on the porous properties of the material itself which determines the contact surface with the sorbate. Therefore, the higher the surface area the higher the energy density the TES system can hold. While natural zeolites have less surface area than artificial zeolites, both can be utilized in TES systems depending on the storage capacity required and the TES system design (Srivastava and Eames 1998; Hauer 2007; Henninger et al. 2012; Aristov 2015). In general, natural and artificial zeolites can tolerate higher heating temperatures than most sorption materials (to about 500°C) without causing damage to the adsorption and regeneration properties (Chan and Russel 2011).

Figure 3-16: (left) Loose zeolite pellets (Fraunhofer 2012); (right) closed sorption system zeolite (De Boer et al. 2014)

The process of using zeolites in TES system does not differ from the main principle of the sorption method where the sorbate (mostly water vapour) is introduced to the zeolite's (sorbent) storage tank which leads to the adsorption reaction between the sorbate and zeolite, releasing heat in the process. Consequently, the released thermal energy from the reaction is transferred into the surrounding environment or extracted via the heat exchanger (Chan and Russel 2011; Henninger et al. 2012). Figure 3-16 shows zeolite pellets manufactured specifically for a thermal energy storage system.

Artificial zeolites have different thermal properties depending on the manufacturing specifications and intended application. For example, zeolites type A, B, and Y from Sigma-Aldrich are designed for energy storage and as a molecular sieve (Sigma-Aldrich 1999). There are no studies to date involving the use of these types of zeolites in domestic scale applications, although there have been several laboratory experiments and mathematical calculations carried out on them. Mitsubishi Industries has developed a zeolite for water thermal sorption under low evaporate temperatures called AQSOA™ (Mitsubishi Plastics 2008; Youssef et al. 2015). There was no documentation found on the performance of this material in domestic applications.

Silica gel and water are the second common working pair commonly studied as a thermochemical energy storage medium. The chemical form of silica gel is $SiO_2.xH_2O$ where silica oxide is bonded with traces of water molecules (Chan and Russel 2011).

Moreover, silica gel has been reported in numerous studies where it has been used in thermal storage systems for heat storage, cool storage, chillers, and humidity controllers. The main advantages of using silica gel in thermal storage systems are due to its availability, low cost, and fast charge/discharging times. Although silica gel has a highly porous surface and good maximum sorption capacity (typically 650 m^2/g), its use in thermal storage systems has its limitations (Henninger et al. 2012). The first limitation concerns its low hydrophilic characteristic, which leads to a great reduction of water exchange within the storage cycle (ibid). The second limitation is the requirement for the charging temperature limit to be below 150°C. Since silica gel contains about 5%-20% water within its structure, raising charging temperatures higher than the boiling point of water will cause the internal water content to escape, thus damaging the structural integrity of the gel (N'Tsoukpoe et al. 2009; Chan and Russel 2011). This low temperature limits the silica gel energy density to a level below water's sensible heat storage rendering obscure its potential as a sorption storage material (Yu et al. 2013). The third disadvantage of the silica gel is the low thermal conductivity and heat transfer rates within the storage confinement (Jähnig et al. 2006).

Activated carbon has been used in thermal energy storage due to its ability to store energy and react at lower temperatures (100°C when paired with water) (Chan and Russel 2011). It can be used in heating and cooling on small scale applications (ibid). Furthermore, it can be paired with different sorbates such as methanol, ammonia, and water. Activated carbons are made by carbonising and pyrolysing of carbonaceous minerals at temperatures ranging from 700°C to 800°C (ibid). When used in thermal energy storage systems, activated-carbons can be in the form of powder, micro-porous, granulated, or carbon fibres (ibid).

Calcium chloride, or CaCl2, is another type of medium used in thermal energy storage in medium to large scale applications. This method is generally preferred because of the availability and abundance of calcium chloride (Chan and Russel 2011). It can be paired solid with ethanol and methanol vapours or solid to liquid with water. It will remain solid until the point of saturation at which point it will dissolve. When dissolved in water, it can be transferred without losing its stored energy and can be used as a desiccant (ibid).

The final type of thermochemical energy storage material is the composite salt porous matrix (CSPM) which combines both sorption and salt-hydrates methods. It uses the sorption material (e.g. zeolite or silica gel) as a host matrix impregnated with hygroscopic material such as LiCl, CaCl2, and MgCl2 (Henninger et al. 2012). This method was developed in the past decade to be used primarily in cooling, heating and energy storage applications. Although the energy performance for some combinations such as silica gel–$CaCl_2$ composite were extensively studied (Yu et al. 2013), these studies were based on mathematical calculations and ignored a crucial problem concerning the carryover of salt solution droplets from the impregnated host during operation (see Figure 3-17) because of the swelling and agglomeration phenomena (Yu et al. 2014). As a result, non-vermiculite host matrixes sustain pore structure damage and reduced sorption rates. However, this damage was not observed in most mineral vermiculite hosts which presents a viable thermal storage with medium potential (Aristov 2015). In conclusion, this method requires further development and research to be deemed applicable and sustainable (Yu et al. 2014).

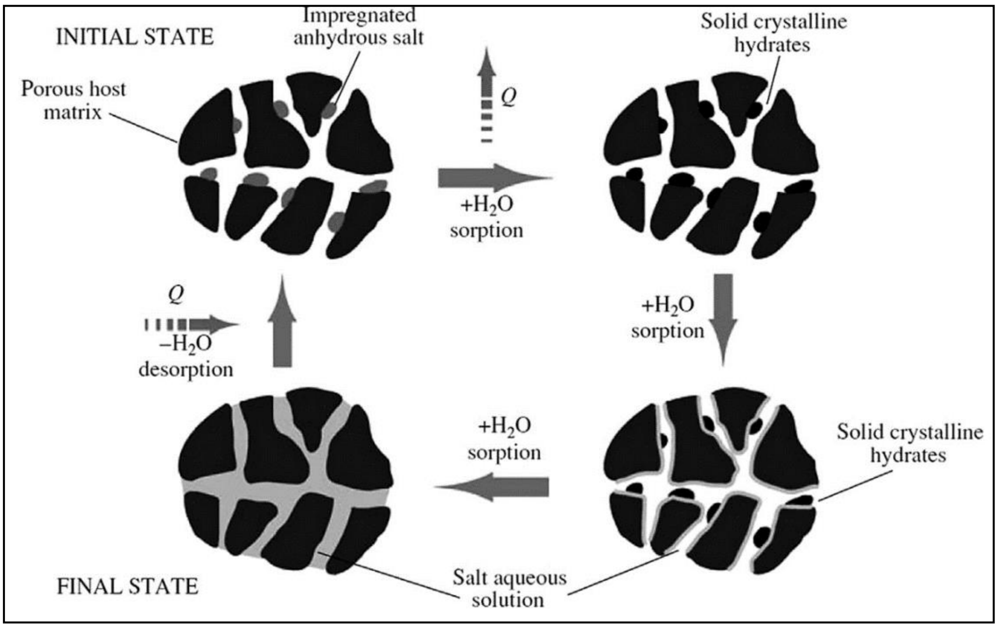


Figure 3-17: Water sorption in a composite salt porous matrix (Yu et al. 2013)

Figure 3-18 shows different thermal energy storage densities based on the storage medium used in various studies (Yu et al. 2013). It also shows the different working pairs and the related reaction temperature (adsorption heat).

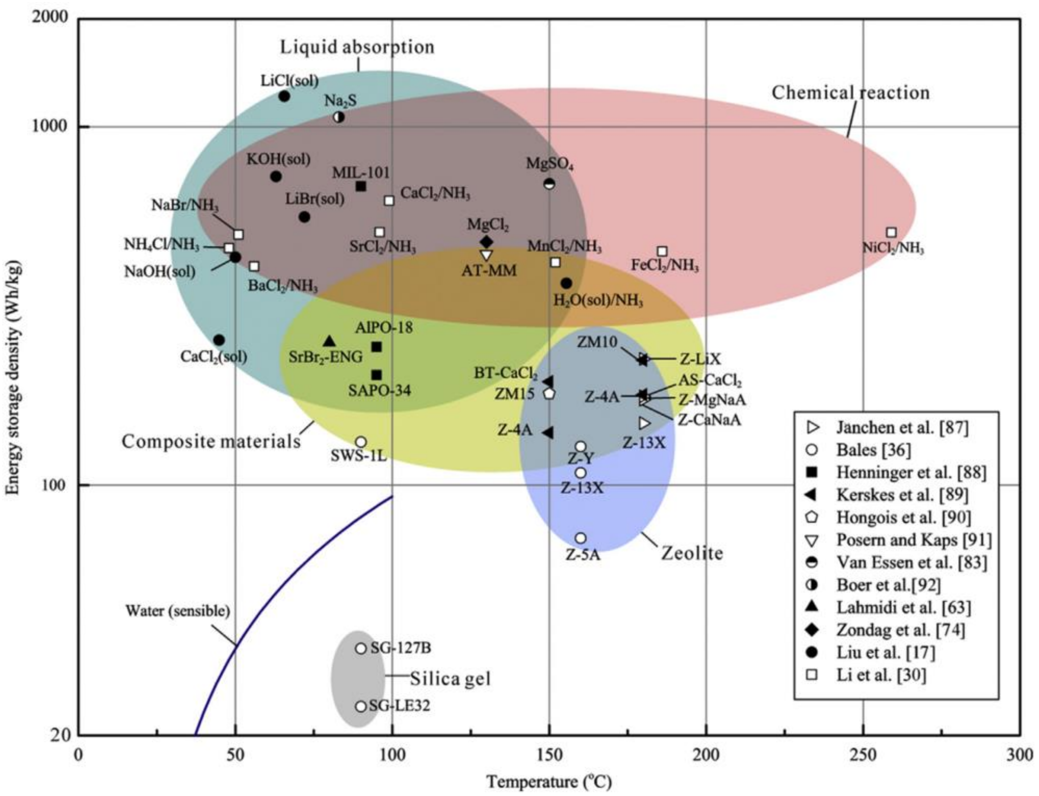


Figure 3-18: Thermochemical energy density and storage temperature of different working pairs based on the literature reviewed (Source: Yu et al. 2013)

3.4.3 Thermochemical energy storage system design

Since the effectiveness of any thermochemical energy storage system is highly dependent on the reactants and the reversible thermochemical reaction itself, how the storage system design handles the reaction plays an important role in the overall performance of the system. The two main types of thermochemical storage system designs that have been studied and tested in the literature reviewed are the open system and closed system design (see Figure 3).

The open system design usually involves moving the working fluid within the storage system in a gaseous form, then releasing it into the environment or into the building's space, depending on the heat flow (see Figure 3-19 left). This method can be coupled with a solar energy system to work in small scale buildings and help with energy peak load shifting in the short term (diurnal) (Kalaiselvam and Parameshwaran 2014). Usually the sorption material is trapped or impregnated within a matrix structure that allows for the exchange of heat and humidity while it remains stable. The cycle of charging and discharging starts with the introduction of hot air (from solar energy or the environment) through the system. Then, heat is stored while cool and humid (moist) air is released from the system either to the environment or into the building's space. This process is known as the desorption phase. On the reverse cycle, discharging of the system is initiated by reintroducing the humid air into the system to release the heat and trap humidity within the storage matrix.

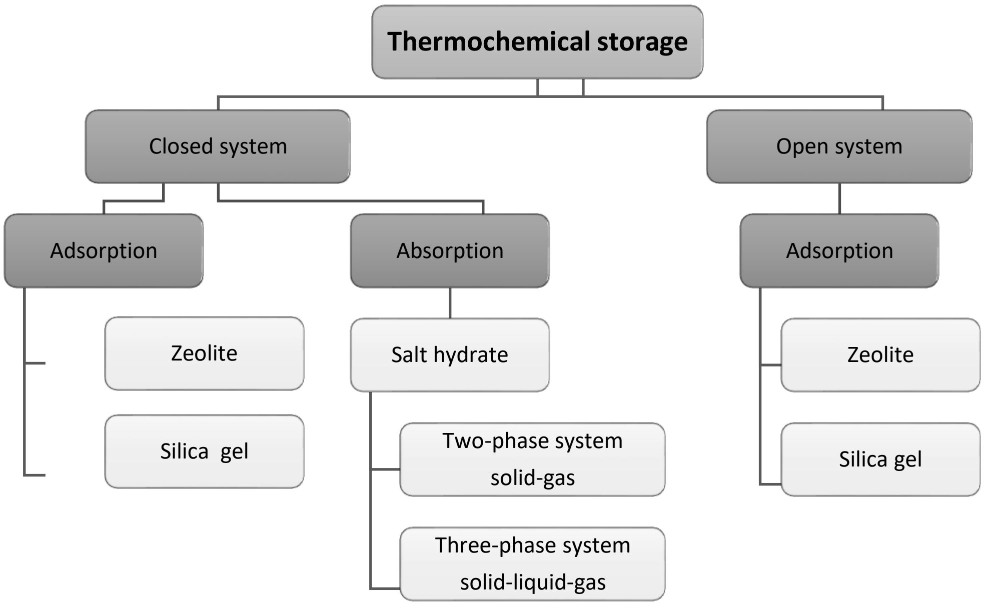


Figure 3.19: Thermochemical storage system applications for heat storage in building applications (Source: Kalaiselvam and Parameshwaran 2014)

Closed systems, on the other hand, have a different approach to the containment and cycling of reactants along with the stored energy. There is minimal to no contact between the reactants and the environment and the reaction usually occurs in a pressure controlled confinement (vacuum) (see Figure 3-19 right). This method is better suited to long term energy storage and can provide higher energy capacities for domestic applications and deal with higher temperatures that can be used in domestic hot water (Kalaiselvam and Parameshwaran 2014; Aristov 2015).

The cycle of charging and discharging in most closed sorption systems is assisted by heat pumps or heat exchangers and can be coupled with solar energy (PV or thermal collectors). The charging phase starts by mixing heated air (using a heat exchanger) with the stored sorption reactant, thus releasing water vapour and cool air. The released water vapour is then cooled in the condenser to extract heat and liquefy the water to be stored separately. The discharging cycle is initiated by moving the water vapour generated by heating the water at low temperature under a vacuum and transporting it to the sorption reactants in confinement to be absorbed or adsorbed. The heat energy is then released to the heat exchanger to be used to heat a space or to heat water (Kalaiselvam and Parameshwaran 2014).

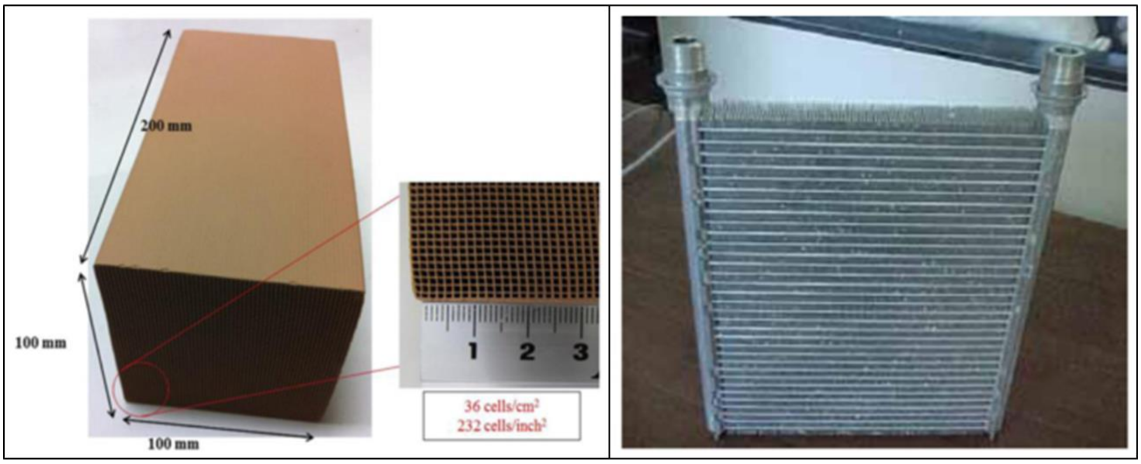


Figure 3-19: Open sorption storage system (left) and closed sorption system (right) (Source: Aristov 2015)

Several studies suggest that a closed system with separate reactors be considered for seasonal storage (see Figure 3-20). This would allow for a more controllable reaction with minimal heat loss to the environment (N'Tsoukpoe et al. 2009). Since the stored reactant is relatively larger in a long-term storage system, the extent of the adsorption and desorption of heat within the storage container results in a less efficient system. Furthermore, sensible heat loss from the reaction chamber to the surrounding environment will be higher. Therefore, an integrated storage would be more suitable for short-term or diurnal TES than a separate storage system.

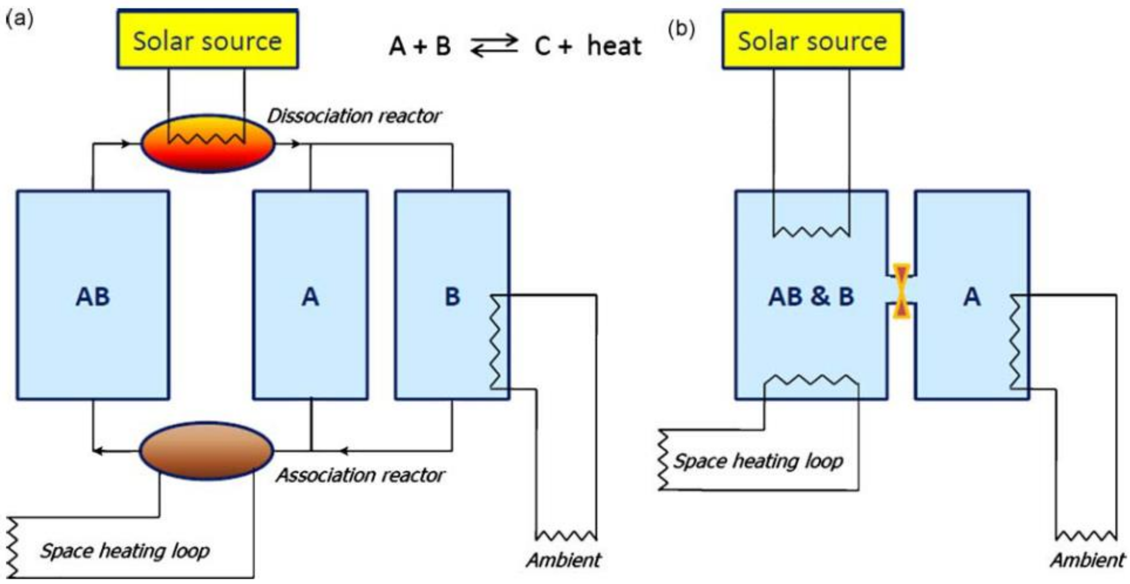


Figure 3-20: a) Separate reactors for seasonal storage; b) Single reactor for diurnal storage (Source: N'Tsoukpoe et al. 2009)

3.4.4 Thermochemical sorption case studies

Although the thermochemical sorption storage method been in development for the past two decades, very few applications in domestic buildings have been recorded in the literature. Several prototypes based on laboratory testing for the working principle or system design are cited. A brief overview of several case studies that relate to the topic of this research which were identified in the literature review is given in the following section.

The first case study concerns E-hub ECN. This system uses a thermochemical open sorption heat energy storage system intended for domestic applications. The system was constructed in a laboratory as a prototype to study the performance characteristics of an open sorption heat storage system under typical operational conditions. The storage medium used in this system is zeolite (type 13X) since this theoretically provided sufficient sorption energy (De Boer et al. 2014). The main advantages of using zeolites over salt hydrates in this prototype were identified in the testing of previous prototypes that used $MgCl_2$-H_2O as a storage medium. The research team concluded that, in general, zeolites are more mechanically and chemically stable than salt hydrates. Although salt hydrates have more energy density than zeolites, they lack long-term stability and safety. $MgCl_2$-H_2O was excluded in this prototype as it released HCl which is highly corrosive, hazardous, and irreversible, thus decreasing the general energy capacity of the storage system over time (ibid). The characteristics of this prototype are shown in Table 3-5.

Table 3-5: E-hub's open sorption prototype system properties

Property	Value
Storage container volume, dimensions	112dm^3, 70x40x40 cm (h x w x d)
Number of storage containers	2
Sorption material Shape and Weight	Zeolite 13X binderless, Chemiewerk Bad Koestritz, beads of 2.5-3.5 mm 150 kg
Air flow rate	Max 80 m^3/hr 200°C,
Maximum heat input:	200°C 2 kW

The E-hub prototype was constructed to be modular and compact to increase applicability and flexibility. It comprised two main units; the first housing the air heat exchangers and the second containing the zeolite reactant storage unit (see Figure 3-21). The research team concluded that this system could be feasibly used for domestic scale buildings given its energy capacity, long term storage capabilities, and the ability to provide thermal energy at adequate temperatures (De Boer et al. 2014).

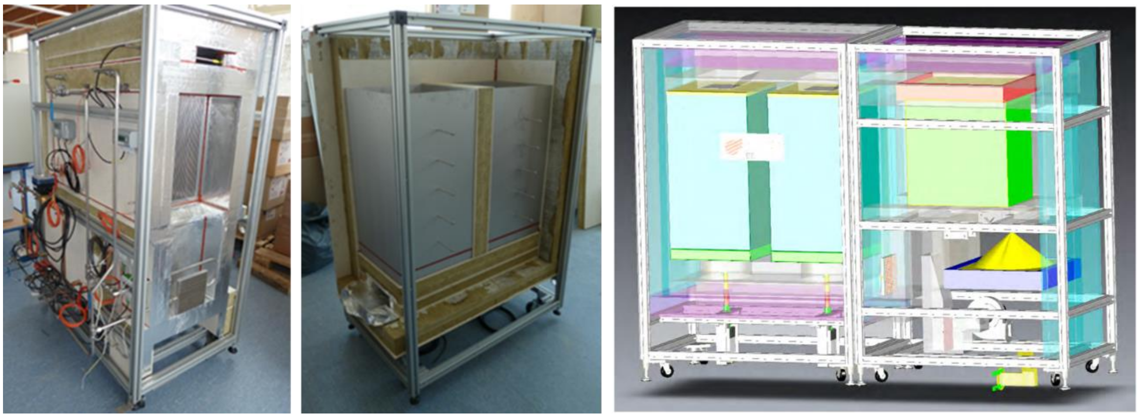


Figure 3-21: Open sorption storage system rom E-hub ECN (air handling unit (left), zeolite storage unit (centre), and the whole system in the design phase (right) (Source: de Boer et al. 2014)

The second case study concerns a development by CWS-NT (Chemische Wärmespeicherung-Niedertemperatur) and utilises zeolite and salt hydrate as a storage medium. The system was designed to heat the floors of domestic buildings. It integrates solar thermal panels to enhance the overall efficiency of the system while the thermal energy storage is connected to a heat exchanger (air-to-water and air-to-air) that draws heat from exhaust air and reactants to the buildings and turns it into space heat. Furthermore, the storage materials are stored separately within the storage unit while the reaction itself (charge or discharge) is conducted in a separate chamber. This step provides a more controllable heat extraction/storage from and into the storage tank without losing or reducing the energy capacity of the system as a whole (Kalaiselvam and Parameshwaran 2014). The literature review yielded a few details on the performance of this model under operational conditions. A schematic of the system components and working principle is provided in Figure 3-22.

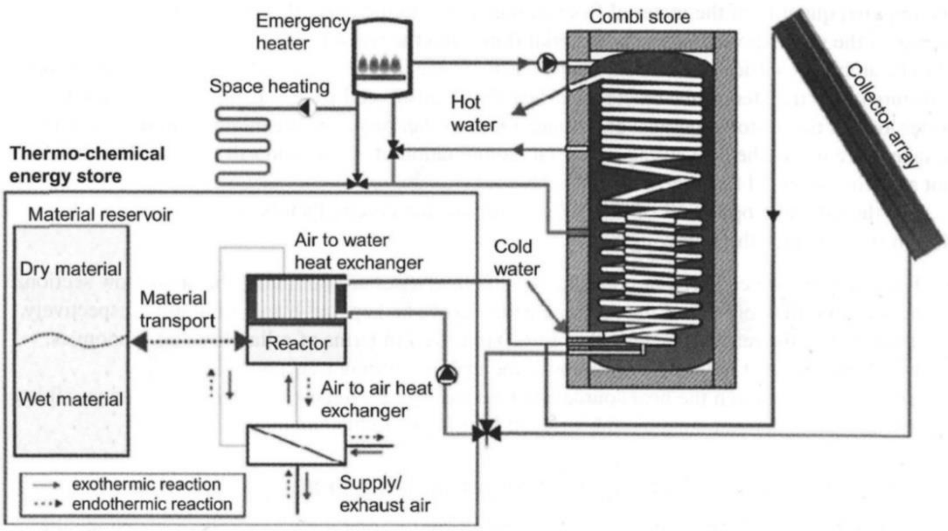


Figure 3-22: A schematic of the working design of CWS-NT thermal sorption model (Source: Kalaiselvam and Parameshwaran 2014)

The third case study concerns a thermal sorption closed system developed by the E-hub TNO centre. This model is considered to be a prototype alongside the prototype described in the first case study given above. Although this model also uses zeolites, it has a higher energy density and is coupled with solar collectors as an energy source. The design specifications are shown in Figure 3-23. Furthermore, this prototype has two different variations of storage capacity: 3 kWh and 16 kWh with 175 kg of zeolite. The main design goal for this system is long term energy storage for domestic buildings with minimum energy loss. To date this prototype has passed laboratory testing and is being tested under domestic building operational conditions (De Boer et al. 2014).

The design of this system is based on a closed storage system with a storage tank that operates under vacuum or very low pressure on a fixed bed storage medium. This operating method helps maximise the system's performance by reducing the energy required to evaporate water before introducing it to the zeolite storage container in order to release stored heat. The final results of laboratory testing surpassed the design criteria which encourages further development and testing of the system with a higher capacity and under more stressful conditions (De Boer et al. 2014).

Table 3-6: E-hub closed thermal sorption system performance compared to design specifications (Source: de Boer et al. 2014)

Criteria	Design	Experimental value
Heat storage capacity	3 kWh	3.6 kWh
Power output reactor	800 W	1570 W max 1040 W over 1.8 hours 640 W over 4.4 hours
Temperature evaporator	10 °C	Variable 5-15 °C
Temperature condenser	30 °C	Variable 5-30°C
Water temperature lift for space heating	20 °C	Peak 50,6 °C 36°C over 1.8 hours 20°C over 4.4 hours
Desorption temperature	90 °C	Variable 70-110°C

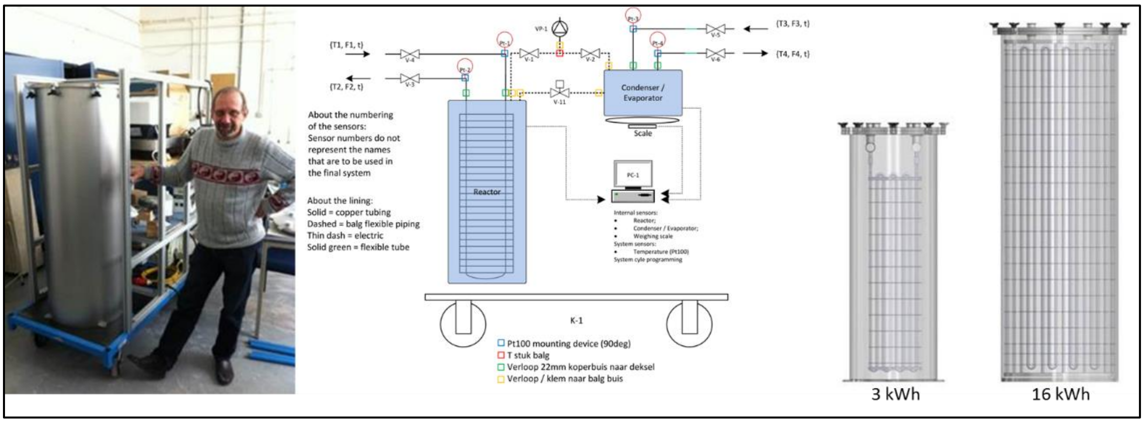


Figure 3-23: The E-hub's thermal sorption closed system (Source: de Boer et al. 2014)

The final case study concerns Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB's release of a new low maintenance and safe physicochemical storage system. According to Fraunhofer's publications, the thermal storage capacity of their zeolite system is three to four times the capacity of water which means a smaller storage size is needed. The principle of their reactor is based on the zeolite-water working pair (Figure 3-16 left). Fraunhofer claim that it is "loss-free" in terms of heat stored/used under normal operational loads. Furthermore, the new system invented by Fraunhofer has been tested on a small scale (1.5 and 15 litres) to prove the concept's success while a larger 750 litres mobile testing facility is currently under testing. The small-scale testing tanks proved the reusability of the storage system without any noticeable loss of energy or deterioration in terms of wear and tear from prolonged usage cycles. While Fraunhofer's system shows promise as a thermal storage system that can be used for different applications, especially in domestic buildings, the development's main target is to serve larger applications and non-domestic buildings (Fraunhofer 2012).

3.5 Thermal energy storage cycles

The thermal energy storage cycle is the time between the charging and discharging of the storage system, including the system-designed period of storage. This cycle can be either short-term (diurnal) or long-term (seasonal or STES) (Dincer and Rosen 2010; Kalaiselvam and Parameshwaran 2014). The two cycles respond to different thermal energy supply and demand depending on the application of the system. Furthermore, the cycle duration will determine the system's size, efficiency, and energy source input method.

1. *Short-term storage cycles*

This storage cycle is intended to satisfy load demands with few peak hours either based on diurnal energy swings or designed to meet electricity tariff rating requirements (ibid). The source of energy can be renewable or non-renewable but common practice is to combine this type of system design with solar energy (Dincer and Rosen 2010; Kalaiselvam and Parameshwaran 2014). In addition, sensible heat storage mediums can be either solid (usually concrete or rocks) or liquid (generally water) since these materials can meet the demand requirements of this system (ibid). The base temperature of this system depends on the temperature fluctuation between load peaks as well the volume of the storage medium when compared to the total demand and intended capacity (ibid).

2. Long-term storage cycles

Long-term storage cycles refer to seasonal storage or inter-seasonal storage cycles. This cycle is intended for longer storage periods (usually months) to be utilised in winter (for heat thermal storage) or summer (for cool thermal energy storage). The longer the storage period the more the system is affected by heat loss due to sensible heat loss and heat leakage into the surrounding environment (Kalaiselvam and Parameshwaran 2014). Thermal energy sources used in this storage cycle can range from solar and ground thermal sources to geothermal heat and air source heat pumps (ibid).

According to Dincer and Rosen (2010) sensible heat storage is the least efficient in long term or seasonal storage due to the insufficient amount of energy stored and the energy lost during storage. On the other hand, latent heat methods, such as PCMs, are more suitable for both types of storage cycles while thermochemical storage is best used for seasonal storage. The latter has a longer processing time for charging and discharging the energy from storage.

In order for the thermal energy storage system to meet the energy demand profile during peak hours, one of two strategies must be used. The first is full-storage, where the stored energy is used to shift the entire load peak, going into charging mode at other times. This method performs better in public buildings such as schools and offices since the loads are significantly reduced after 5pm, allowing the system to fully charge. The other strategy is partial-storage which relies on reducing the demand load peaks partially. Since this method is more economical than full-storage it has been used for the majority of TES applications (Dincer and Rosen 2010).

3.6 Thermal energy storage systems volume and efficiency

The International Renewable Energy Agency (IRENA) defines thermal storage efficiency as: *“the ratio of the energy provided to the user to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle.”(IEA-ETSAP and IRENA 2013 p.5)*

Several factors determine storage system efficiency including: heat loss, energy conversion, heat exchange, storage insulation and medium size and shape. Water, for example, has an efficiency rate for latent heat storage of 50% - 90%. PCMs have a higher rate of 75% - 90%, while chemical storage ranges from 75% to 100% (IEA-ETSAP and IRENA 2013).

While heat loss through the storage tank to the surrounding environment is common for sensible heat thermal storage systems, it can also affect other types of TES systems, such as PCMs and chemical storage. However, the rate of heat loss is bound to a regulated limit for use in domestic applications. In the UK, this regulation is monitored by the Hot Water Association which sets the limits of daily heat loss in storage tanks (Hot Water Association 2010). The amount of heat loss and the calculation method will be investigated in more detail in the chapter, which discusses case studies.

The issue of thermal energy capacity and the required volumetric size to store a certain amount of energy is significant, especially for small scale and domestic applications, since space availability is limited. In general, the storage volume responds to the energy density attribute of the storage medium. For example, water, when used as a thermal energy storage medium, would require a storage volume of 34 m^3 to store a 7.6 GJ or 1861 kWh compared to a chemical sorption reactant that has a higher energy density and thus would require far less volume to store the same amount of energy (about 8.7 m^3) (Arteconi et al. 2012). Figure 3-24 and Figure 3-25 provide a comparison between different storage mediums in terms of volumetric storage.

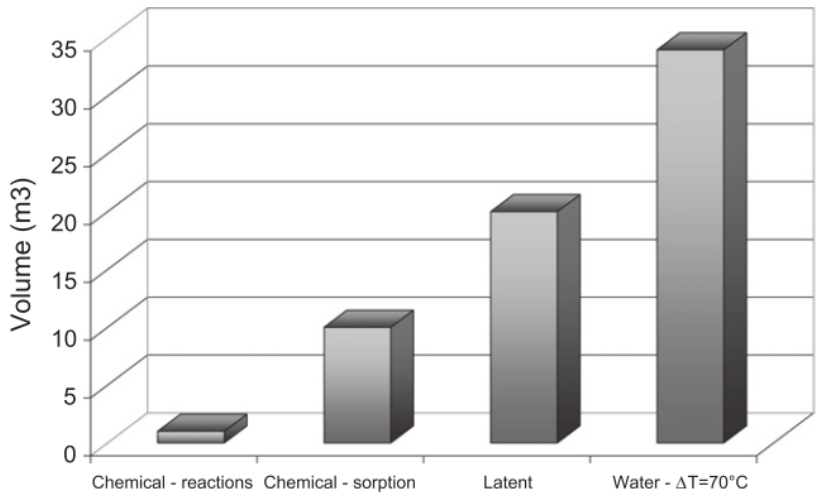


Figure 3-24: Storage volume required to store 6.7 GJ or 1861 kWh of energy in different thermal storage mediums (Source: Arteconi et al. 2012)

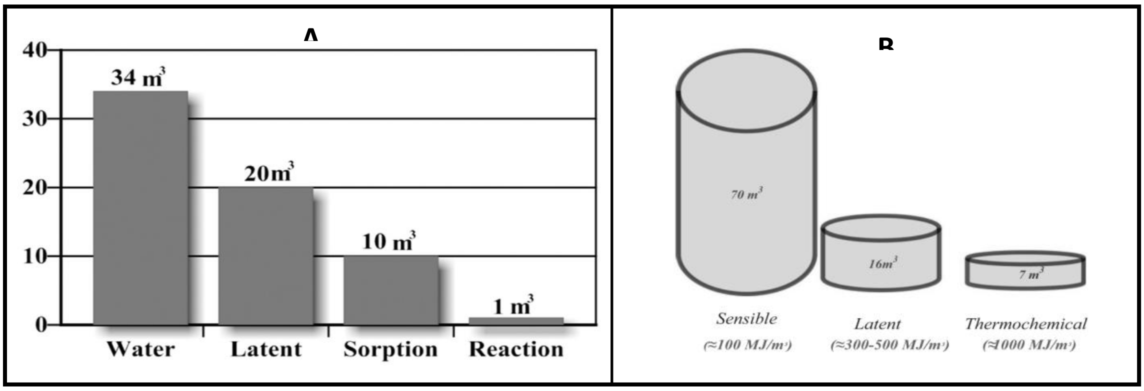


Figure 3-25: A) Volume of thermal energy storage system required to store 1850 kWh (Yu et al. 2013); B) Volume required to store 6480 MJ (1800 kWh) to meet the annual energy needs of a passive house (Source: Tatsidjodoung et al. 2013)

3.7 Thermal energy storage operation from renewables

On-site energy generation used in energy efficient buildings can be of four main types: solar energy, wind energy, ground source heat pump (GSHP), and air source heat pump (ASHP). These sources of renewable energy have been studied in terms of their capability to charge the thermal energy storage system. In their current state of development, there are several factors that limit the benefits of these on-site energy sources. The first factor is the thermal energy storage technology requirement of a specific temperature rise to start the charging reaction. Furthermore, thermochemical sorption and salt hydrates would require a range of temperatures starting from 95°C up to 200°C to start the charging reaction (desorption phase) (Chan and Russel 2011). Sensible heat and phase change materials will, to some degree, benefit from most of these on-site renewable energy sources. The second factor that limits the integration of on-site energy sources with thermal energy storage is the demand side requirement. When the thermal energy demand is utilised for space heating only, the temperatures required are in the range of 20°C to 35°C, which temperatures can be achieved by all of the on-site renewable energy systems. On the other hand, heat pumps and thermal solar panels are not able to deliver required temperature rises above 40°C (for DHW) in a stand-alone systems configuration (ibid). An auxiliary electrical system working with heat pumps or solar thermal panels would be required. Furthermore, solar PV panels on small scale applications can drive both of the thermal energy demand profiles (space heating and DHW) working with thermal energy storage systems. This system is capable of meeting the basic thermal energy demand in terms of amount of energy and temperature required, besides its capability to reach the charging temperatures of the thermochemical storage medium (Blanco et al. 2007; Dincer and Rosen 2010; Herrando et al. 2014).

There are several studies that experimented with combining a solar PV source with GSHP or ASHP worldwide, but no studies were carried out in the UK context. The lack of data regarding the operational benefits of on-site combined systems with thermal energy storage for domestic scale application limits the ability to predict the outcome via simulation (Mosallat et al. 2013). Table 3-7 lists some of the studies that experimented with thermal energy storage systems and the associated on-site energy source used. This table also shows the thermal energy storage type, thermal demand type, and location of the study.

Table 3-7: current studies on TES system charged with on-site energy sources

Thermal storage type	On-site energy source	Thermal demand	location	Literature
Thermochemical sorption - zeolite	Solar thermal collector	Space heating	Netherlands (laboratory)	(De Boer et al. 2014)
Thermochemical sorption - zeolite	Solar PV	Space heating DHW	Netherlands (laboratory)	(De Boer et al. 2014)
Sensible heat - stratified water	Solar thermal collector	Space heating	Spain	(Tulus et al. 2016)
Sensible heat - water	Solar PV	Space heating DHW	Italy	(Comodi et al. 2015)
Thermochemical sorption - silica gel	Solar thermal collector	Space heating	Laboratory	(Jähnig et al. 2006)
Phase change – paraffin	Solar PVT	Space heating DHW	Australia	(Fiorentini et al. 2015)
Sensible heat – stratified water	Solar PV Solar thermal ASHP	Space heating DHW	UK	(Welsh Government 2012)
Sensible heat – stratified water	Solar thermal GSHP ASHP Biomass	Space heating DHW	UK	(Energy Saving Trust 2012)
Thermochemical salt hydrate NaOH	Solar thermal	Space heating DHW	France	(Weber and Dorer 2008)

3.8 Solar energy and thermal energy storage integration

Although solar energy proposes to be a promising renewable energy source, it does have one major limitation which is its cyclic time-dependency. This intermittency of solar energy is due to diurnal cycles, seasonal solar emission variations, and local weather changes. Therefore, to ensure a continuous supply of energy with solar energy, it must be integrated with an energy storage system to balance out the supply and demand of a building's energy requirements (Dincer and Rosen 2010). Several factors should be taken under consideration while designing a thermal storage system with solar energy, such as the storage cycle and capacity. The storage cycle will determine the solar collector area, storage volume, and capital costs. The longer the storing cycle (e.g. seasonal), the more the required solar panels' area should be increased (Duffie and Beckman 2013). This will increase the storage volume, which will reduce the energy loss due to the volume to area ratio. One more advantage of increasing the storage cycle in solar energy systems is minimising the impact of weather on the system's energy output. A disadvantage of increasing storage capacity is the limitation of the system's applicability to small structures and buildings, such as small homes. On the other hand, a diurnal storage cycle has advantages such as the need for less capital investment and the fact that it requires smaller equipment and a smaller dedicated storage area. In terms of the performance of the two cycles, seasonal storage will contribute up to 100% of the building heating needs while the diurnal cycle will rarely exceed 60% of the total thermal demand (Dincer and Rosen 2010). The relationship between the potential solar energy from on-site energy generation and the demand is illustrated in Figure 3-26 based on a study conducted in Barcelona, Spain (Tulus et al. 2016). The solar energy available during the summer months creates a great potential for thermal energy storage systems to meet the thermal demand on a domestic scale.

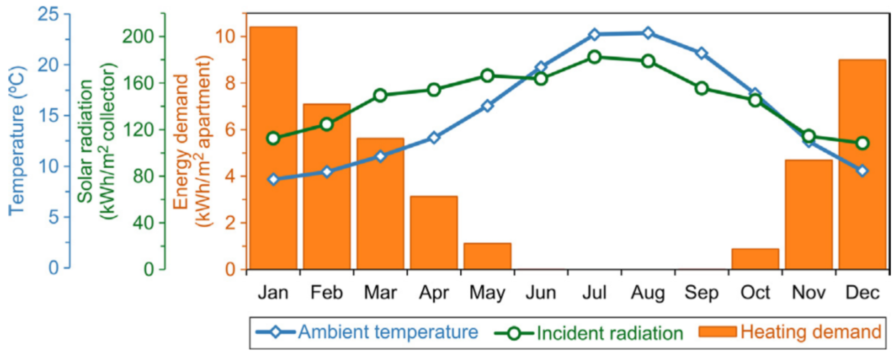


Figure 3-26: Solar radiation in Barcelona, Spain compared to heating demand from a domestic case study (Source: Tulus et al. 2016)

In several case studies presented in the literature, on-site solar energy offers sufficient energy to meet the domestic thermal energy demand. The case study presented in Tulus et al. (2016), for example, demonstrates how solar thermal collectors can meet the demand of domestic complex apartments by utilising a stratified water tank. Figure 3-27 shows the monthly thermal energy supply and demand from this domestic complex during the monitoring period. It also shows the system's capability of meeting the heating demand during the winter months without the requirement of an auxiliary heater, except in March when the thermal storage tank is almost depleted as solar energy produced is insufficient to meet the demand.

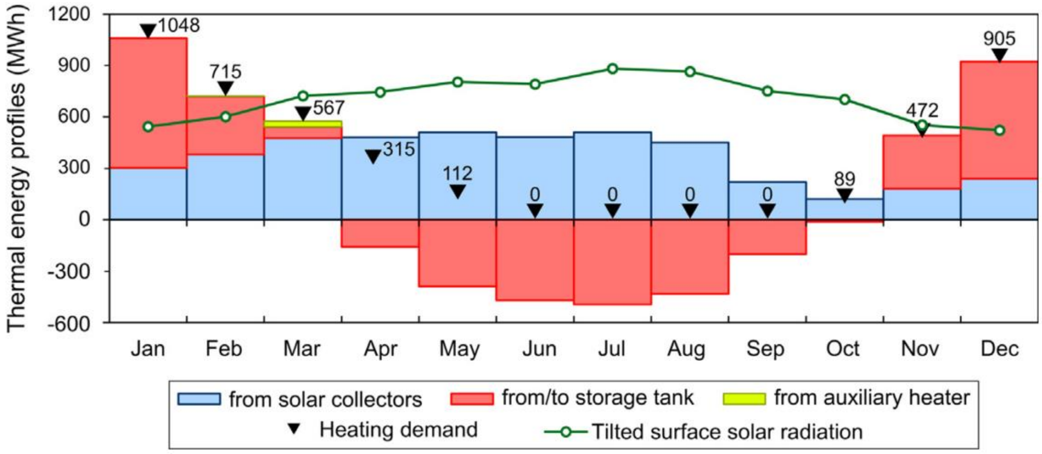


Figure 3-27: monthly thermal energy demand and supply from a domestic complex utilising solar collectors and thermal energy storage water tanks in Spain (Source: Tulus et al. 2016)

3.8.1 Passive solar thermal storage systems

The concept behind this system is rooted in thermosyphon mechanics where the change of density of the heat transferring fluid accurs due to the gradient heat change from the solar collectors which ciculates the fluid from and to the storage. The rate of heat transfer is dependent upon several factors, including:

- the thermal storage size and capacity:
- the storage medium specific heat capacity;
- heat transfer fluid thermal properties; and
- accumulated heat from the solar collectors.

The basic application of the thermosyphon method is illustrated in Figure 3-28. The storage tank is located on a higher elevation in relation to the solar panels. The heated fluid is introduced to the storage tank from the top and, through the thermal stratification effect, it cools down and then sinks back down to the bottom to be circulated once again or directly consumed by the building's energy demand. The solar collectors in this system can be replaced or combined with other solar technologies such as thermal panels, building envelope heat collectors and concentrated solar panels.

There are many advantages in implementing this system over an active solar system. The main advantage is the system's independence from other power sources. Furthermore, this system has very low maintenance requirements. On the other hand, the disadvantages of this system are its limitations and slowness. This system is more suited to sensible heat storage for domestic and smale scale buildings in general. The placement of the storage tank above the level of the solar collectors poses two main concerns: overcasting shadows on the solar collectors and loss of storage heat due to the ambient temperature or insufficient insulation (Kalaiselvam and Parameshwaran 2014).

3.8.2 Active solar thermal storage systems

This system employs an auxiliary mechanical system to transfer heat from the solar collectors to the energy storage medium with or without the assistance of a temperature control valve. The heat transfer fluid can be controlled in terms of volume and heat temperature with this method, allowing for faster heat transfer and larger thermal storage size. Furthermore, with the aid of a mechanical pump the fluid drag in pipes and inside the solar collectors is reduced. It also gives more flexibility in terms of locating the storage tank anywhere within the property. The disadvantages of this system mainly concern its dependency on an external power source to drive the mechanical pump thus lowering the system's efficiency.

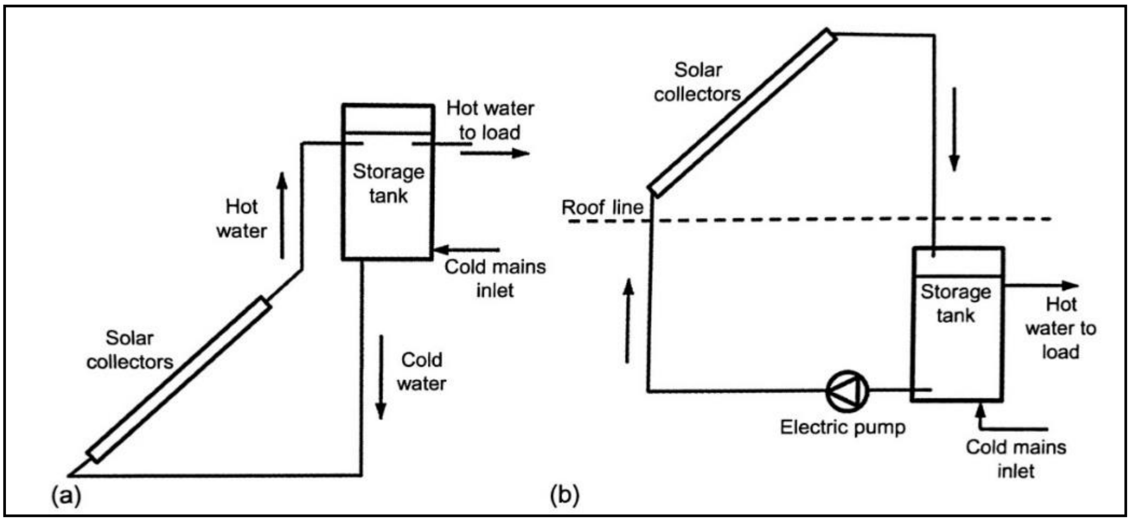


Figure 3-28: a) Passive solar thermal storage system; b) Active solar thermal storage system (Source: Kalaiselvam and Parameshwaran 2014)

3.9 Summary of findings

According to the literature, the full spectrum of thermal energy storage systems can be classified into three main types: sensible, latent, and thermochemical energy storage systems. Each of these storage systems has been studied extensively either in a laboratory environment or under operational conditions. Although these systems have different methods of storing and exchanging heat, their application in domestic buildings has been proven to reduce and shift the peak demand of heating/cooling energy demand. Furthermore, the size requirement of each type of thermal energy storage system varies significantly depending on the storage medium and the system design, where sensible heat storage methods demand more volume than latent and thermochemical systems. While thermochemical energy storage systems have a higher energy density and require the least storage volume, their design complexity and need for precise control make them the least desired systems by the domestic sector.

Several materials have been studied to be used as storage mediums for sensible heat storage systems, ranging from solid to liquid materials and water and concrete among the materials with the highest thermal energy capacity. The most noticeable advantages of this type of storage are the low construction cost, simplicity of installation and operation, and versatility of the mediums. In general, however, sensible heat storage can be beneficial only for short term storage purposes since it loses stored heat over time through leakage to the environment. A further investigation to the efficiency of sensible storage method can be done by analysing the exergy performance of the TES system. But since exergy analysis would require a full scale and detailed heating system design with integrated thermal energy storage that performance can be calculated under reference environment, this study will only focus on energy analysis of the thermal storage system only.

Latent heat storage methods utilise the heat of fusion accompanied by phase change of the storage medium. These systems work in a similar way to sensible heat storage methods except for their higher energy storage capacities and the higher temperatures that can be maintained within the storage mediums. Furthermore, a higher energy capacity (or energy density) of the phase changing material (PCM) allows for smaller storage volumes; therefore, the smaller the storage tank, the less energy is lost during storage due to the minimised contact with the surrounding environment. As for the types of storage mediums used, several materials, both organic and inorganic, have been studied extensively. Paraffin is considered to be the most desired among PCM materials as it has several advantages, including the fact that it is widely available, it has different variations that suit different application requirements, it is chemically and mechanically stable, it is inexpensive, it has a relatively higher thermal capacity and, finally it is environmentally safe to use for domestic applications. Although there are several potential inorganic PCM materials, which could be used in TES systems, most suffer from low thermal conductivity, are chemically or mechanically instable or are hazardous to use.

Finally, the thermochemical storage system offers higher energy capacities per volume compared to sensible and latent heat storage systems. Furthermore, this system can utilise either chemical or sorption reaction to store heat. Although chemical reaction can offer higher thermal capacity per volume than the sorption method, it lacks reaction stability and has safety issues associated with its operation in a TES system. On the other hand, sorption reaction is much simpler to install than the chemical reaction method and offers a safe and stable performance over a prolonged period. It utilises thermochemical sorption phenomena to store or release heat with endothermic or exothermic reactions. The amount of energy stored and released and the temperatures it operates under are suited to domestic applications (space heating and DHW).

In conclusion, the three types of thermal energy storage systems that have been covered in this chapter all have great potential for domestic application. While sensible and latent heat storage methods were extensively studied under operational conditions, the thermochemical sorption method has not been observed under domestic applications nor studied beyond laboratory prototypes. In general, thermal energy capacity and performance comparisons between the three types are made based on a theoretical basis and there is no evidence of performance comparison on a case study basis.

4 Methodology

The main aim of this chapter is to provide a clear guide to the appropriate methodology that can be used in calculating domestic buildings' energy performance in the UK. Furthermore, in this chapter of the study, several simulation tools will be investigated in order to determine the best-suited and most up-to-date tool for building energy prediction and analysis, which will serve the purpose of this study.

Chapter two of this study has provided an insight into the domestic thermal energy demand in the UK, variables that affects this demand, renewable energy sources, and the possible input of thermal energy storage in meeting domestic thermal energy demand. This chapter continue with brief introduction to current simulation approaches and process of creating energy performance simulation in domestic buildings. In the following sections of this chapter will review the published literature of different energy calculation methods and energy simulation tools prior to presenting the research methodology. The full framework of the research flow will be also indicated in the last section of this chapter. Therefore, the structure of this chapter will be as follows:

4.2 Introduction to energy performance calculation methodologies
4.3 Introduction to energy simulation tools
4.4 research methodology
4.5 conclusions

4.1 Introduction to energy performance calculation methodologies

Any energy performance calculation can be divided into three sections: input, calculation and results. In most cases, the higher the details of the input data are, the higher the levels of accuracy and complexity the calculation model will be (Swan and Ugursal 2009). Over the past two decades there have been several attempts to create a general methodology for calculating building energy performance. In the work of Swan and Ugursal (2009), a summary of residential building energy performance calculation methods was proposed by combining previous published work (see Figure 4-1). The authors have classified calculation methodologies into two types: top-down or bottom-up. The selected terminologies for these methods indicate the scale of the input data (ibid.). The top-down method treats the whole residential sector as one major input or an "energy sink" and depends on historical statistical data and economic theories to predict the long-term energy consumption changes in the entire residential sector (ibid.). Since this method does not count the end-use energy consumption, it can be used only in large-scale calculations. The bottom-up method starts with the data from the end-use, a single house, or a group of houses in order to represent a larger scale sample (e.g. city or nation). The sub-methods within this bottom-up method are statistical and engineering. The statistical method uses input data from historical consumption figures and a regression analysis to calculate the selected model energy performance. In contrast, the engineering method relies on equipment usage, power ratings, thermal performance and/or thermodynamic relationships (ibid.). While the engineering method is the only one that does not require historical data while accounting for the end-use energy consumption values, it is the only method that allows design modification and adjustments to be made to its logical and non-historical reliant method.

Swan and Ugursal (2009) also described the sub-methods of engineering and classified them as: distribution, archetype or sample. Distribution methods rely on the national or regional distribution of appliance ownership, use and end-use energy consumption. While the sources of this method are derived from national assessments and can contain historical values, the end-use consumption calculation level classifies it as a botton-up method (Swan and Ugursal 2009). The archetype method depends on classification of the housing sector in terms of its geometric properties, thermal characteristics and operating parameters. The details of the modelling and data inputted into this method can affect the accuracy of the output greatly. While the archetype depends on values from similar houses, the sample method uses the values of energy consumption from an actual monitored house (ibid.).

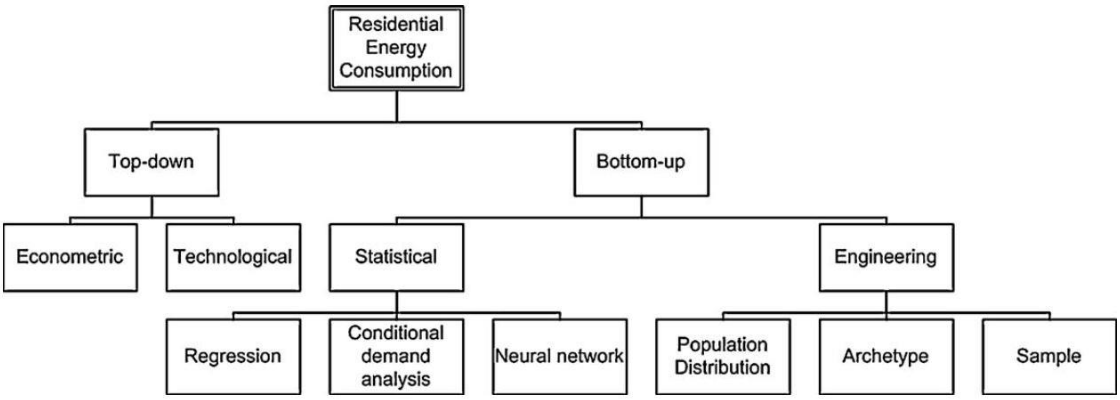


Figure 4-1: residential energy performance calculation methodologies (Swan and Ugursal 2009)

Since the scale and requirement of this study require small-scale and end-use consumption calculations, bottom-up methods are to be considered, specifically in relation to the engineering method and its lack of historical data requirement. In addition to the methodology classification of energy performance calculations, the modelling approach for engineering methods tools can be classified as zonal and computational fluid dynamics (CFD) (Mourshed et al. 2003). Figure 4-2 shows the types of the building energy simulation. Zonal is the method of dividing a simulated building into different zones and calculating each zone separately while assuming that each point of the simulated space has the same thermal properties and states. This method can be more conservative time and resource wise. Zonal simulation also has two types of simulation running methods: steady state and dynamic simulation. The steady state simulation method is based on a single simulation run during a chosen segment of time while a dynamic method is one that runs a simulation over a predetermined period of time. Most of the recent tools that use zonal simulation offer the option of running the simulation by using either one of the time-based methods (Mourshed et al. 2003).

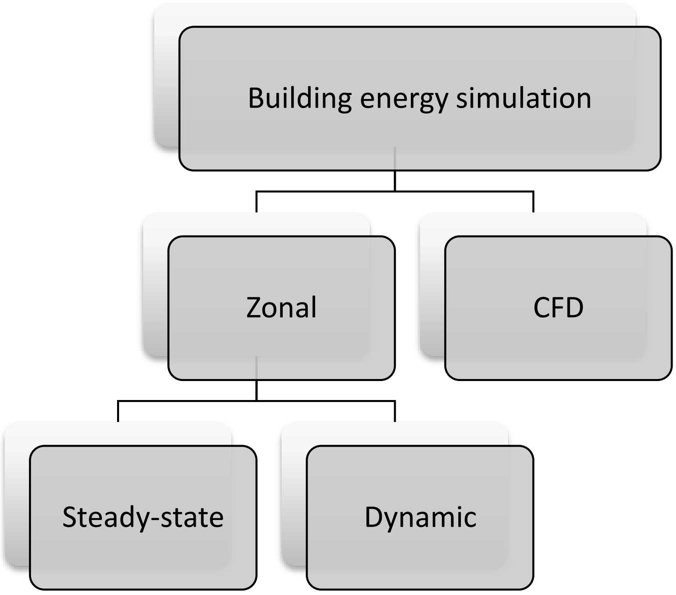


Figure 4-2: Building energy simulation types (Mourshed et al. 2003)

4.2 Introduction to energy simulation tools

Over the past several decades the whole building energy simulation (BES) method has gained wide popularity among designers because of the affordability, feasibility and time saving it can offer in predicting actual building energy performance (Coakley et al. 2014). Furthermore, several types of simulation software have been developed to provide building energy performance output from both analytical and numerical viewpoints while using different calculation methods to predict the outcome. Hence, this raises a main concern, which is to what extent the simulation software can actually predict the actual energy performance of a building. Since the 1980s several initiatives have been established to evaluate simulation tools and their performance under several input values (Judkoff and Neymark 1995). According to ASHRAE's 2009 handbook, there are three main methods of accuracy testing, which are empirical validation, analytical verification and comparative testing (ASHRAE 2009). The empirical validation method consists of comparing simulation results to actual monitored building data. The International Energy Agency (IEA) has created an empirical validation package which contains the description of three testing rooms with detailed monitored energy performance data for a selected ten days that can be used in comparison with the results of the simulated model (Lomas et al. 1994). The initial testing with this testing package for the tools available at the time (EnergyPlus, DOE-2 and BLAST) showed a significant variance between these simulation tools.

An analytical verification method depends on comparing simulation result data to previously known analytical solutions. Finally, the comparative testing method is conducted by comparing simulation results between different simulation tools or between different versions of the same tool. In 2004 ASHRAE published a testing method named Standard Method of Testing (SMOT), which includes both methods but each one focuses on a different aspect of the simulation process. ASHRAE describes the focus of a test set of the analytical verification method as being on the mechanical equipment's performance while the comparative method focuses on the building thermal envelope and fabric loads (ASHRAE 2004). The purpose of creating these two test sets are explained as follows: "This Standard Method of Test (SMOT) can be used for identifying and diagnosing predictive differences from whole building energy simulation software that may possibly be caused by algorithmic differences, modelling limitations, input differences, or coding errors" (ASHRAE 2004).

The Building Energy Simulation Test (BESTEST) was first proposed by IEA in 1995 to create a testing tool and diagnostic method for different BES tools (Judkoff and Neymark 1995). The test is conducted via several suits that contain analytical solutions, comparative testing and other tests in order to examine the simulation logic of the BES tools and easily compare the results (see Figure 4-3). This testing method has been widely accepted and several testing suits have been incorporated into the ASHRAE standard 140-2011: "Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs." The BESTEST validation method can be achieved through a sequence of three steps: analytical verification, empirical validation, and intermodal comparisons, as shown in Figure 4-3.

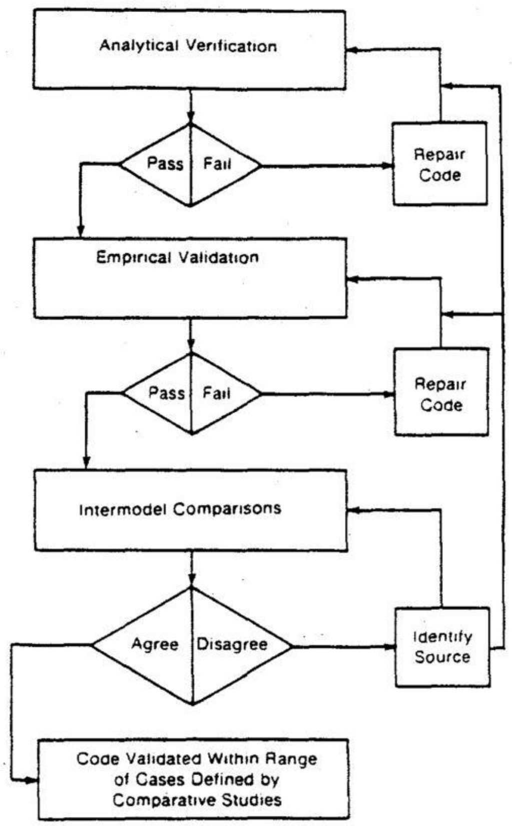


Figure 4-3: BESTEST validation method (Judkoff and Neymark 1995)

While BESTEST is considered to be the benchmark testing for several US agencies and other EU countries, the results of this testing method are not always consistent over time because of the continuous development of BES tools (Neymark et al. 2011). Furthermore, the test model's initial testing cases were not completely able to address the unconventional aspects of actual building modelling. For example, multi-zone buildings with several mechanical equipment specifications, multi-zone building shading, adaptable shading devices and ground-coupled heat transfer systems were not implemented in the initial testing cases. This point has been investigated in the work of Neymark and Judkoff (2009) and Neymark et al. (2011).

Additionally, there are several studies that have investigated the BES validation and model calibration techniques and methods that can minimise BES prediction errors. Furthermore, since the involvement of BES tools has bypassed the design phase to the post-construction phases the importance of identifying prediction issues has become more crucial than before. In Coakley et al. (2014) the authors summarise the modelling issues as being standards, expenses and integration. Standards issues do occur with the modeller due to inconsistent use of the methods or standards. Expenses issues are described as the modeller's lack of knowledge, time, expertise or what it costs to develop a working model. Finally, integration issues occur between different tools, pieces of software or during conversion between file types. The authors also describe other uncertainties that may occur when modelling such as specification, modelling, and numerical and scenario uncertainty. While specification uncertainty concerns the physical description of the building when there is an incomplete or inaccurate data, modelling uncertainty is more about transforming the physical model into a digital form. These uncertainties may occur either as a result of the user or the algorithm calculations for complex geometries. The numerical uncertainty will occur when the user performs an entry error of data. Finally, the last scenario of uncertainty occurs as a result of implementing inaccurate external conditions of a building related to factors such as climate or occupancy behaviour (Coakley et al. 2014). In the next section of this review, the selected BES tool for the purpose of this study will be introduced via published literature. The performance of this tool under the BESTEST method will also be investigated in order to determine its accuracy in delivering the simulation results.

4.2.1 HTB2 introduction

The Welsh School of Architecture (WSA) at Cardiff University has developed a zonal tool that offers both types of building simulation methods (steady state and dynamic). This tool, known as HTB2, is a freeware PC application that is intended as an investigative research tool (Alexander 2008). It is based on the FORTRAN-77 programming language and aims to decrease the dependency on computer components and increase mobility. It uses a text input method and is limited to built-in databases with the ability to add more or adjust current properties. The WSA has also developed a plug-in for Trimble SketchUp that runs with an HTB2 engine known as Virvil. Both tools investigate the thermal performance of buildings, provide a building energy consumption profile and monitor building systems while allowing for further developments. HTB2 also offers end-users the ability to customise and add features by using somewhat basic programming knowledge. It also provides an elementary dataset of materials and construction elements that can be used in the model or modified accordingly. The HTB2 simulation engine has the ability to calculate several renewable energy sources as potential for the given designs, i.e. solar energy. Other abilities include urban scale modelling, solar reflection and refraction, and shading masks for buildings' openings and surfaces. The ability to add other features such as thermal storage, wind power etc. will require further programming (Alexander 2008).

The basic methodology in which the HTB2 engine works is no different than the general simulation process explained previously. It follows the main steps while the model preparation and simulation deployment proceeds as shown in Figure 4-4. Alexander states that "HTB2 is intended primarily as an investigative research tool, rather than a simple design model" (Alexander 2008). Although there is an option of using a graphical interface to input the building layout and construction file, it depends solely on the text input for the rest of the data required to run the simulation. This can be achieved via any text editor available. The output of the simulation would be in the format of comma-separated files, which can be viewed by multiple types of spreadsheet software. The HTB2 bundle provides a data viewer for its data output, which also has the ability to generate graphs for selected fields such as energy consumption, solar radiation etc.

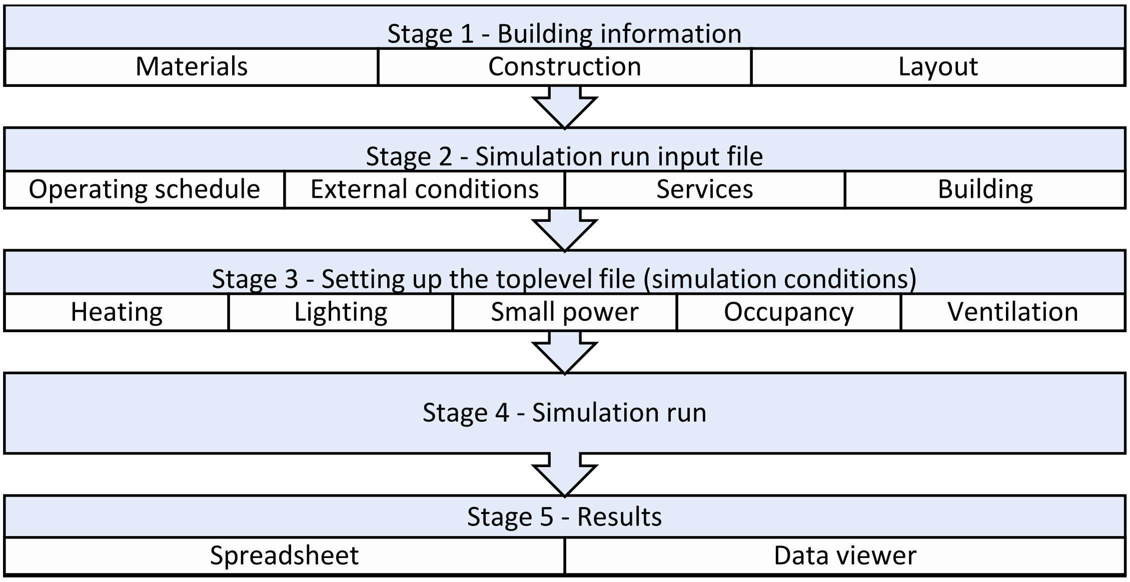


Figure 4-4: HTB2 simulation process (Alexander 2008)

Although HTB2 shares the main methodology of model processing with many other tools, it still lacks some features shared by commercial type tools such as the fully interactive graphical interface and fully built-in libraries. In addition, HTB2 energy prediction and performance was on par with other tools, according to Neymark et al. (2011). The authors have conducted a BESTEST method on several BES tools on a multi-zone with an air flow case study to compare the performance of these tools. The performance results were also consistent with findings (Alexander 2003) where the study was conducted by applying four testing methods, which are: open inspection, empirical, analytical and inter-model. The author has concluded that HTB2 has performed better than the other tools tested by predicting close figures such as those measured from the case study (ibid.). Figure 4-5 shows the testing results of HTB2 in Alexander (2003) compared to other simulation tools. In contrast, HTB2 performance as measured by Lomas et al. (1997) was not as close as what was found in the research conducted by Neymark et al. (2011) and Alexander (2003). While it did underperform the other tools in terms of calculating cooling loads and energy saving, it did perform consistently and more accurately in cold climates.

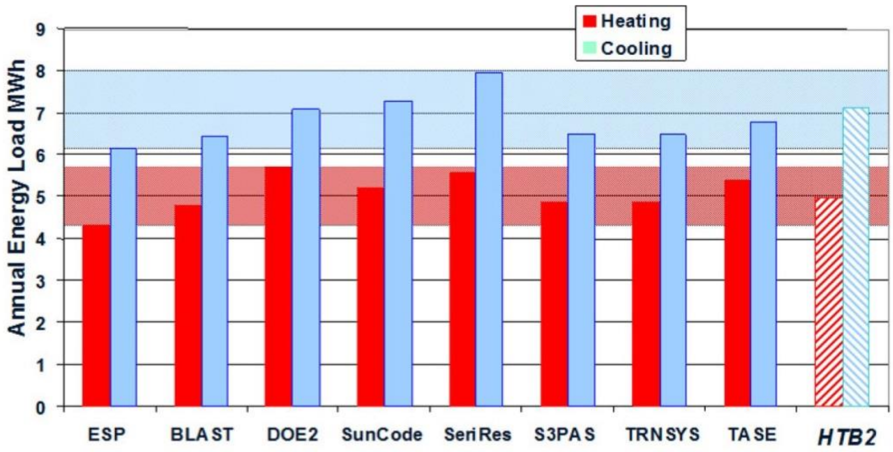


Figure 4-5: BESTEST case results for variant of simulation tools (Alexander 2003)

4.2.2 Simulation input and output data

All simulation tools use one or more methods of inputting the data that is required for the building energy simulation. These methods consist of text editing, manual input, visual modelling, database importing and converting data from other software. The required data for each simulation run includes multiple entries such as location data, building specifications, equipment included and occupancy. During the simulation deployment phase, the simulation software can be set to include all or ignore one or more of these entries (Augenbroe 2002). As for HTB2, the main input method is text editing in an ASCII file format, while the graphical input is limited to the translation of building schematics. This input method also poses potential challenges in describing complicated building forms and geometries. The lack of 3D editing and visual representation of the modelled building may also lead to inputting mistakes.

The HTB2 manual describes the file structure of HTB2 simulation runs, which consists of three levels: the first (top level), where the simulation run parameters are defined; the second, which defines the sub-parameters of the simulation run (e.g. metrological data, location, heating systems parameters etc.). Finally, the third level can be defined as the problem definition and the geometry of the simulation model (see Figure 4-6) (Alexander 2008).

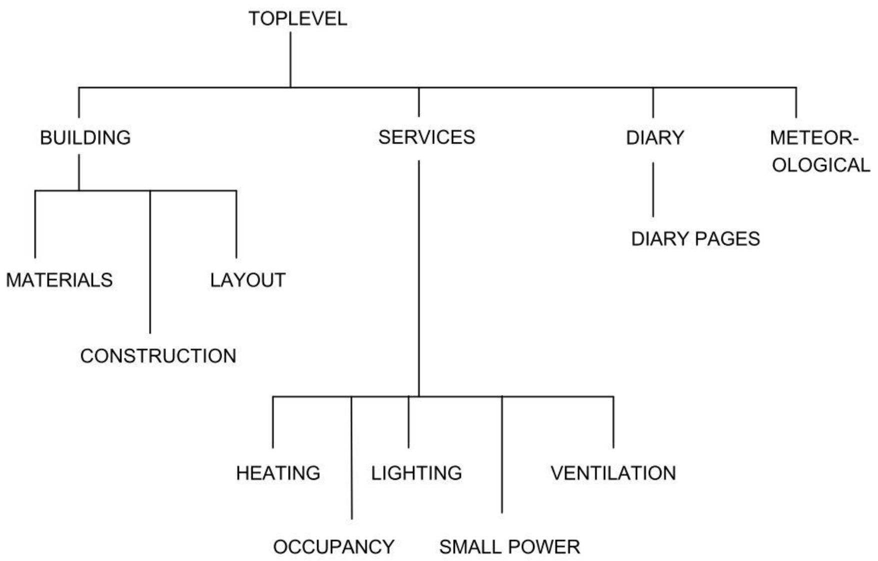


Figure 4-6: HTB2 file structure (Alexander 2008)

The following section will introduce a detailed definition of each entry and the common standards based on previous researches and reports.

4.2.2.1 Location data

Location data includes all building location related information needed for the simulation run. This information consists of: geographical location, altitude, orientation, meteorological data, surrounding environment, solar radiation and other aspects. Although most of this information is usually reflected in the initial design, the simulated model can provide a more reliable design input (Augenbroe 2002).

The only information that can be obtained from an external source would be meteorological data. This data is extracted from an existing database or generated artificially from a pre-established model using special software. Existing datasets are provided by weather stations located near the building site. Mostly, the data generated is in the form of annual, daily and hourly weather statistics and summaries (Adelard et al. 2000). The UK official weather service is the Met Office, which has hundreds of stations distributed nationally that provide weather datasets and forecasts. The standard method the Met Office uses to generate weather datasets exists in the form of Extensible Markup Language (XML) and JavaScript Object Notation (JSON). Both types are in compliance with the EU's current climate weather standards (MET Office 2014).

4.2.2.2 Building information

Building simulation tools employ different methods in which the software will recognise the boundaries and restraints of the given design. By using a zonal building simulation tool, which depends on calculating each zone of the simulated building on its own, it is essential to identify the building zones first (e.g. rooms, living space, kitchen etc.). The definition of the zone starts with the area and volume, which then progresses into defining openings, construction and then the adjacent zones. On the other hand, CFD tools recognise buildings as a complete example of geometry with a pre-defined shape that includes every detail of the simulation before converting it into a 3D grid (Mourshed et al. 2003). As this research focuses on the zonal method of simulation, the following part will discuss the simulation requirements of this type only.

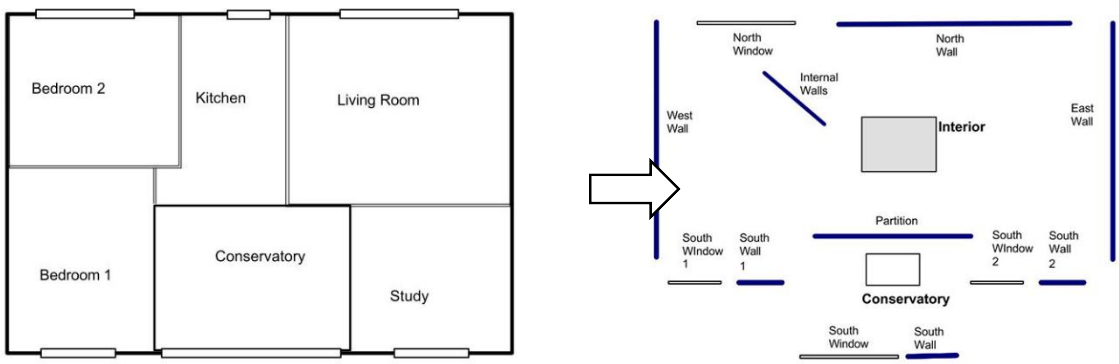


Figure 4-7: modelling a simple floor plan into the HTB2 (Alexander 2008)

According to Alexander (2008), the HTB2 will view the building as "a network of thermodynamic connections". Each room or zone defined in the software will be identified as a volume of air with a known surface area and orientation (see Figure 4-7). Furthermore, it will need to link adjacent zones together in order to perform a thermal simulation correctly (see Figure 4-8). Each surface of each zone will have its separate properties in terms of relation to the main zone, area, tilt and construction. Glazing and openings are also defined in each zone in relation to their unique properties including type, construction and transparency, which are all defined in the main construction file of the building. One more piece of information needs to be implemented in relation to the glazing, which is the solar patching that determines the radiation effect that passes through the glazing surface on other internal surfaces. Furthermore, the HTB2 also has extra features that can be implemented by the user such as surface colour, shading and reflection. These features are set to default values unless they are modified (Alexander 2008).

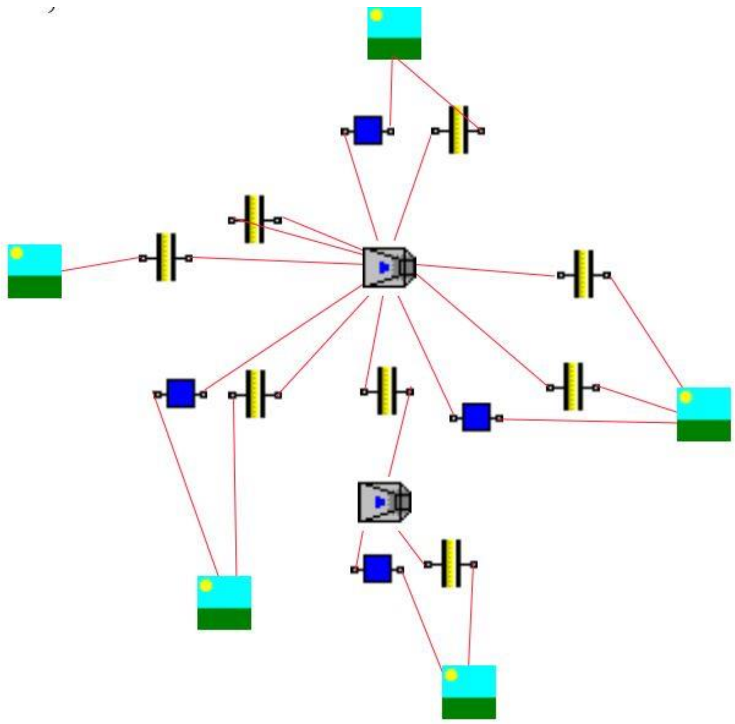


Figure 4-8: the simple building structure as represented by the HTB2 (Alexander 2008)

4.2.2.3 Equipment

Building systems and equipment are the user operational dependent part of the building simulation. They include heating, cooling, lighting, DHW, small power, cooking, brown and wet appliances. The values that represent each type are in the form of wattage of consumption and heat emission. The source of the power consumption values and heat emissions come from the manufacturers' specifications. They also rely on the current and local regulations that limit energy consumption or rising efficiency. Several studies on building energy simulation use different standards regarding the values of these systems. For example, ASHRAE have several standards for US building systems and equipment while the UK has CIBSE standards for cooling and heating demands. Other appliances have general energy consumption standards that can be referred to, such as the International Energy Agency (IEA) guide or case studies on local buildings' average energy consumption.

Equipment and building systems should also employ operational scheduling that allows for more precise energy simulation as this controls the time of operation and running capacity. This schedule can be based on daily or seasonal bases. HTB2 software has the ability to control this aspect by editing the diary file on the third stage of the simulation process (Alexander 2008). Furthermore, it can allow for its operation under a certain condition (i.e. heating starts when temperature drops below 15°C).

4.2.2.4 Occupancy

Building occupancy has a major role in affecting simulation results since inhabitants' behaviour is the main energy consumption factor (Janda 2011). To be able to simulate the energy consumption accurately, behavioural profiling of the residents will be essential to the study. Such a profile would be based on local case studies and surveys. The UK government has issued several energy consumption reports that mark several aspects of the residents' habits and income level but further investigation is required if we are to determine daily lifestyle patterns (Waltz 2000).

Simulation software (e.g. HTB2) will require an occupancy profile of the simulated building. This profile includes the number of people living in each zone, their presence time and their activity level. The latter one is of importance since it marks the metabolic level or the heat emitted by the inhabitants (in wattage) during the time spent in that state of activity. HTB2 uses a scale from 1 to 3 to determine the metabolic state of the space inhabitant (where 1 is sleep and 3 is very active) (Alexander 2008).

4.3 Research methodology

In the following section, the research methodology will be presented in detail in order to meet the objectives and goals. The selected main approach will be described, as will the framework plan for the research. Finally, the research methodology's limitations will be listed and defined.

The study described in this research was carried out in two stages: a building energy simulation, and TES modelling. While the building energy simulation stage generated hourly results for the zero-carbon building, these results were then used as input for the second stage when calculating and modelling the performance of the TES systems. The process by which both stages are sequenced can be illustrated in Figure 4-9. These two stages are then incorporated into the research's main framework, which is described in section 4.3.4.

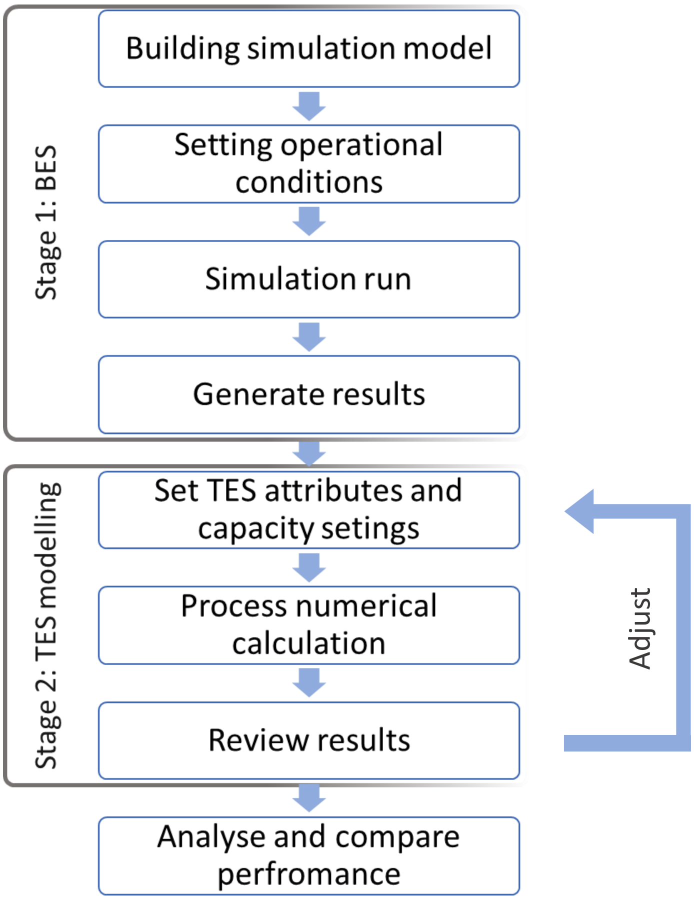


Figure 4-9: research's two stages process

4.3.1 Building energy simulation

Since this research requires the implementation of building energy calculations in order to answer the research questions and meet its objectives, before constructing a detailed outline for the research methodology a main approach to the building energy calculation methods must be determined first. Although the methods classification is based on the published work of Swan and Ugursal (2009), the method's logic is considered valid for this research and also for similar types of studies on building energy calculations. The bottom-up approach in general and the engineering archetype specifically will be used as a main method to help achieve the required results for this research.

The main benefit of adapting the archetype method, rather than the sample or population distribution methods, is based on the lack of historical data requirements for this method. Furthermore, it depends on the classification of building attributes such as geometrical type, thermal properties and operation parameters, which will be presented in detail in the next chapter.

The selection of a specific BES tool among the multiple tools that are available to serve the purpose of this research depends on comparisons in the reviewed articles and the performance figures for the major BES tools under BESTEST benchmark testing from ASHREA standard 140-2011. Furthermore, the tool support available at the Welsh School of Architecture (the tool developer) has made HTB2 the selected BES tool in this methodology. And since HTB2 is considered to be one of the bottom-up engineering methods it brings all the advantages and disadvantages of this method. Some of the main advantages presented to this research are as follows:

1. It can develop a better understanding of the thermal energy performance of domestic zero-carbon buildings. As the current building standards count renewable energy sources input to reduce the building’s carbon footprint, the intermittency of these renewable energy sources presents a challenge to building designers and developers in meeting a zero-carbon target. And that’s where the BES tool results will predict energy surplus and grid demand over several time periods.
2. It will help to determine whether the Passivhaus building standards will meet the zero-carbon state for domestic buildings in the UK. By testing the energy consumption limits of the Passivhaus on zero-carbon buildings rather than the null carbon emission for the selected case study, this tool will help to predict the outcome thermal energy performance of each building attribute.
3. HTB2 can consider a range of systems that been included in this study in the simulation phase. For example, it can calculate energy demand by the electrical heating system, energy return from the MVHR system, and calculate the potential electrical energy generation from the solar PV panels mounted on a specific location on the building depending on the solar exposure and the angle of inclination. Although the operation of these systems is simplified in this study, this simplification would not alter the simulation process nor method.
4. There is a possible input of a thermal energy storage system in reducing domestic energy consumption in zero-carbon buildings. Furthermore, the

outcome of simulation runs over several periods of time (diurnal, seasonal and annual) and will help to measure the thermal energy supply and demand. These figures will determine the potential contribution of thermal energy storage systems over different time periods.

In summary, the selected bottom-up method alongside the selected BES tool will satisfy the requirements of this research and help to achieve its aim. Furthermore, the overall approach will also provide a suitable method for similar researches so they can easily predict the potential contribution of thermal storage to energy efficient buildings.

4.3.2 Thermal energy storage modelling

Thermal energy storage systems implementation into the simulation would be calculated numerically based on the building energy simulation results. The outcome of the simulation runs by HTB2 will determine the building performance and internal heat loads which will be counted for in the thermal energy storage (TES) calculations. Furthermore, solar energy from the building's roof will be included as an input source of TES beside mechanical ventilation heat recovery (MVHR).

The TES systems that have been investigated in this research are mainly sensible, phase changing materials (PCM), and thermochemical storage systems. The exclusion of chemical decomposition from the scope of this study is due to the related factors associated with this type of storage (space requirement, safety, and maintenance) and their impact on domestic scale buildings (Dincer and Rosen 2010; Chan and Russel 2011; Kalaiselvam and Parameshwaran 2014).

The general method of calculating TES size for the selected case study is based on the total capacity set by each material in relation to volume of storage. While there are several other factors that affect the performance of the energy storage system, such as heat loss and thermal expansion, these factors are accounted for in the final calculation phase, which is made up of the following four steps:

1- Material specifications and thermal properties input
2- Thermal capacity calculations for each material
3- Implement TES systems into the building simulation
4- Measure energy performance and run comparative analysis between different TES systems

In addition, is expressed as the following formula:

(thermal energy source) – (thermal energy demand) ≥ (TES heat capacity)

Which can be expressed as:

(solar PV energy + MVHR) – (space heating + DHW) ≥ [(TES material heat capacity x volume) – Heat loss]

While the energy demand represented in space heating and DHW is classified as a thermal energy type as well as the returned heat from the MVHR system, the energy produced from the solar panels are in the form of electrical energy which can be converted into a thermal energy via convective heating system into the ventilation. The details of the heating system design are not relevant to this study.

Furthermore, the selection of storage mediums from each system type (sensible, PCM, and thermochemical) will be discussed in further details in the next chapter along with the calculation method used for each system type.

4.3.3 Software development for thermal energy modelling

To create repetitive calculations for the several thermal storage systems included in this research, a software tool will be developed. This software will use the HTB2's simulation results, which include thermal energy demand figures concerning on-site solar energy, and MVHR energy. Then these results will be used in combination with TES system settings (such as thermal energy capacity and volume) to process the calculation phase of the research and predict the performance of the different TES systems. The main methodology applied to the software development process employed in this research is adapted from Royce's Waterfall method (Royce 1970). The method follows linear development phases as illustrated in Figure 4-10. The process of developing the thermal energy storage modelling software for this research will be conducted as follows: 1) setting system requirements, 2) setting software requirements, 3) program design, 4) coding, 5) testing, and finally 6) operating.

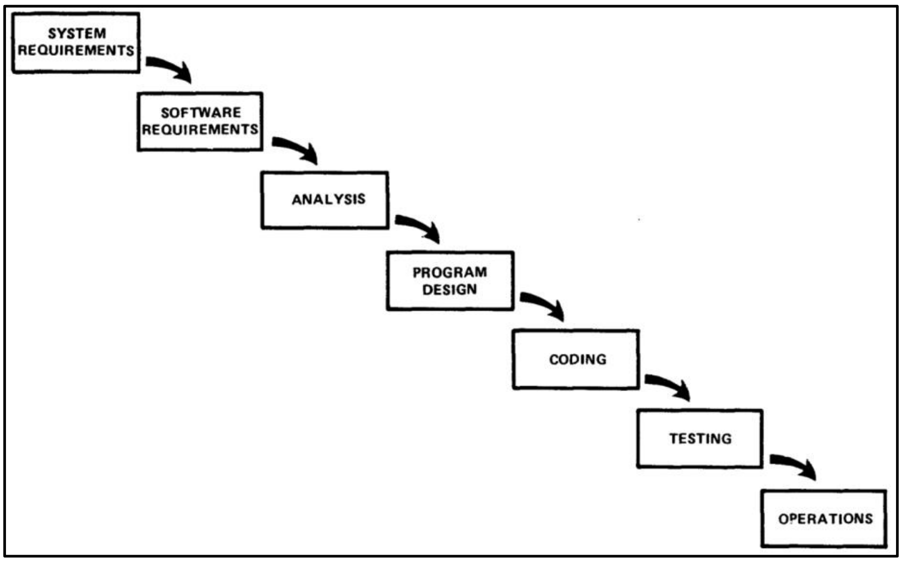


Figure 4-10: Royce's Waterfall method of software development (Royce 1970)

The first step in the software development process is to set the system requirements (or hardware working conditions) for the proposed software. The system requirements decided upon for this research tool are based on a 64-bit PC architecture with no cross-platform compatibility. The second step in the development process is to establish the software requirements. This includes determining operating system compatibility, preferred programming language, and included coding libraries. In this research, the software will be written in C# language with database integration operating under the MS Windows environment (Windows 7 or later). The coding compiler used is Microsoft Visual Studio 2015. This compiler includes the requisite C# language editor and the essential coding libraries. This programming language was developed by Microsoft from language C to simplify the programming of Windows based applications. C# allows advanced integration between built-in databases and other applications, such as spread sheets and database mangers. This facilitates the output of the developed software, making it possible to export results readily to other applications, where the data can be analysed and plotted. The utilising of C# language in this research will also make it possible to channel the PC's resources to assist with mass calculations. Furthermore, database integrated libraries permit the software to access the HTB2 results file, and read predetermined fields from it. It also makes it possible to generate an external file that calculation results can be added to.

The program design step consists of identifying key input and output variables. These input and output variables are generated from the research questions and objectives. The first set of software inputs include hourly thermal energy demand figures, on-site solar energy production, and MVHR, which are all generated by the building's energy simulation (HTB2). The second set of inputs are building attributes, which include number of occupants, area of solar panels, and the energy return rate for the MVHR system. The third and final set of inputs are the TES system properties. These properties include thermal energy capacity and the material types utilized by the different TES systems included in the calculation run. After all the inputted data is complete, a processing phase is initiated to generate results. The entire process is depicted in Figure 4-11.

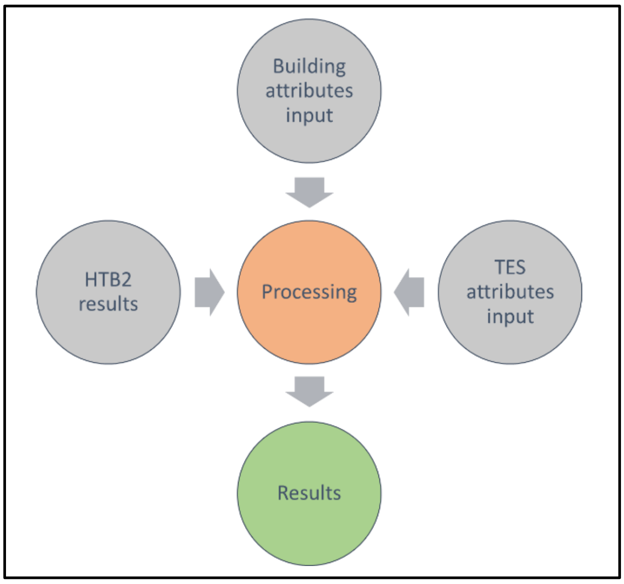


Figure 4-11: TES modelling software processing inputs and output

The results generated by this software are identified as the output. These results are summarised and presented at the end of the calculation run. An output file is then created to detail the hourly performance of each TES system included in the calculation run.

The program design phase also includes the act of designing the components of the graphical user interface (GUI). Since the software operates in the MS Windows environment, C# language interface design tools will be used. The GUI for the developed software will be designed according to input/output from the modelling process. Figure 4-12 shows the basic layout of the interface chosen for this software. While the results presented on the GUI describe the final energy consumption and generation figures only, the hourly data for the TES modelling is exported to a spreadsheet file, which can be accessed by any spreadsheet processing engine, to help analyse and extract specific data sets.

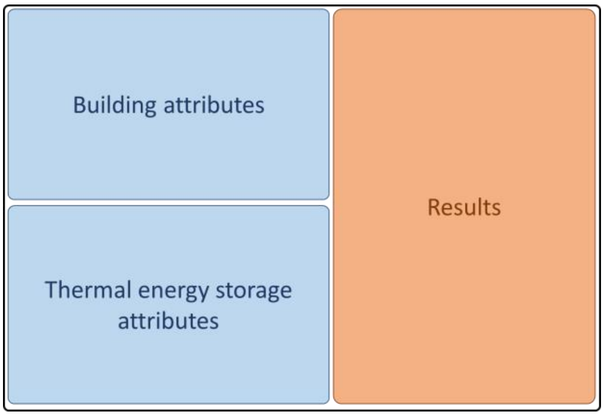


Figure 4-12: Basic layout of the graphical user interface of the TES modelling software

4.3.4 Proposed framework

Since the main aim of this research is to examine the potential input of thermal energy storage in conserving energy in zero-carbon buildings, the research methodology must be designed to explore thermal energy storage systems performance under domestic thermal energy demand profile over an annual cycle. Therefore, the proposed research methodology will be focusing on building energy simulation as the data output of this simulation is considered as an initial basis for calculating thermal storage performance.

The proposed methodology consists of four phases that mark a significant portion of the research progress. The first phase consists of a literature review and then building a database for simulation and calculation, which can be conducted later. The goal of this phase is to establish a solid foundation and build a proper case study for building energy simulation. Starting with domestic thermal energy demand profiles in the UK, this will extend to renewable energy sources input based on location data. Then it will establish a proper methodology and approach for building energy simulation with a selected BES tool as well. Finally, a database for thermal energy storage systems for domestic buildings will be built.

The second phase is the building energy simulation phase, which is divided into two parts: setting the conditions of the simulation process, and building and running the simulation model. Setting the conditions of the simulation does include several aspects of the simulation run and holds the main and fixed (unchangeable) attributes of the simulation process. For example, location data and building layout are among the main objectives of this stage. On the other hand, building the simulation model allows us to add more detailed information into it in order to determine the simulation's model construction, fabric, occupation profiles, insulation and internal energy demand profiles. Both parts of this phase are based on the first phase database for the tested case study.

The third phase involves thermal energy storage input and an efficiency analysis. The preliminary part starts by calculating the energy trends from phase two. These energy trends are the output of the building energy simulation and by examining the supply and demand of thermal energy over several time intervals these can be analysed to predict possible energy transfer from high peaks and how they meet or reduce low peaks of demand. The second stage covers different thermal energy storage systems. By examining the different types and their properties, such as storage capacity, storage cycle, volume and energy loss over time, this step can determine each system's potential and input level. The development of software tool that gather all input data from this phase then transfer to the processing stage to generate the thermal energy storage systems performance is established within this phase. In addition, the development of this software tool will assess the analysis of the output data in the next phase by producing the output in a numeral and graphical forms. Finally, this software will serve as a general tool that may assess researchers and system designers in determining the suitable type of thermal energy storage system for domestic applications in the future.

Finally, the fourth phase contains the analysis and optimisation of the previous phases. The analysis part starts by establishing validation for the resultant simulation with other case studies reviewed in phase one. Next is to review both thermal energy supplies from renewable sources and to what extent a thermal energy storage system can impact energy consumption. From the previous analysis, the outcome will determine if the model needs to be optimised to achieve more reliable results or draw conclusions. At the end of this phase, the final recommendations are concluded by identifying the best working system and posting any further recommendations for future development or research. Figure 4-13 summarise the research methodology framework and the phases within the framework.

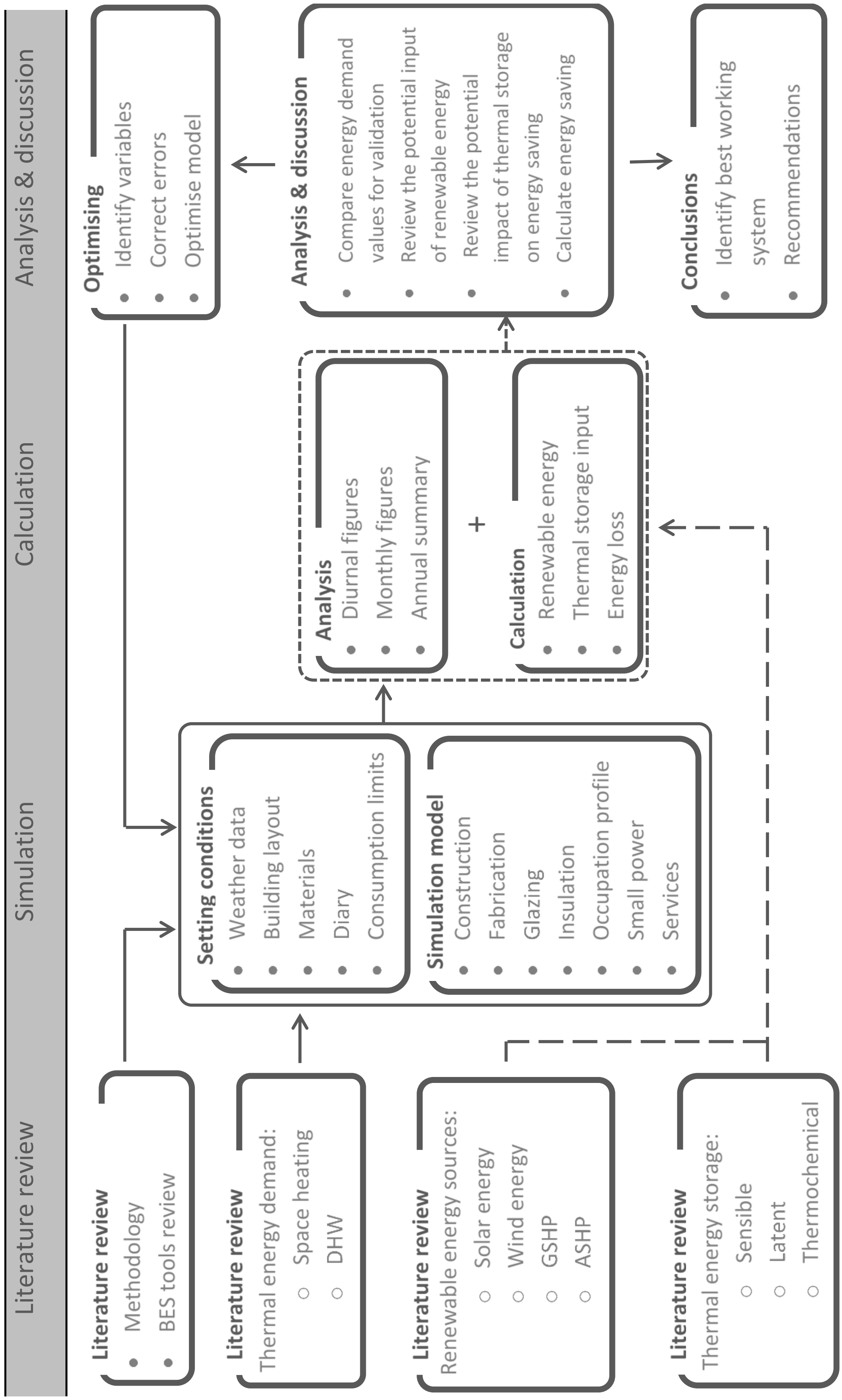


Figure 4-13: Research methodology framework

4.3.5 Methodology limitation

The proposed methodology in this research has a few limitations that should be addressed in order to acknowledge its capability. As these limitations are associated with the chosen simulation method and thermal storage calculation, these limitations are also applicable to every other study of a similar type as well.

The first limitation is posed by the employment of the archetype methodology. While this method has many advantages that help to achieve the aim of this research it also has some disadvantages that restrict the research range. The lack of comparable historical data on the case study's simulation of zero-carbon status as a validation system is one of the disadvantages considered here. For that reason, implementing the use of a pre-established energy consumption limit set by the Passivhaus standards has been proven to achieve the desired zero-carbon status. These standards are tested and have proven to be a valid method in the reviewed literature (Passivhaus Trust 2011; Williams 2012).

Secondly, the use of HTB2 as the main tool to simulate building energy in this research has also posed several limitations as well. The lack of 3D representation of the modelled building has restricted the building description for the tool user. The details and complexity of the geometry are translated into HTB2 as a text file while linking the component through an interface with very few capabilities. This method of translating the model affects the learning curve of the user and may cause several geometrical errors that have to be validated by an expert level user. Furthermore, the HTB2 thermal calculation method used for zones within the modelled building is set as uniform in temperature while the radiation and conduction are calculated independently. As a result, HTB2 does not simulate the operation of the heating systems but rather predicts the energy that should be provided to the zone in order to achieve the temperature set by the user (Lomas et al. 1997).

Thirdly, the lack of actual monitored case studies of chemical thermal storage in domestic buildings in the UK is a major limitation to this study. Several studies refrain from recommending the implantation of chemical storage in domestic buildings for multiple reasons such as size and cost. The reviewed literature on case studies relies on theoretical data obtained by knowing and calculating the thermal properties of the used chemical (Sukhatme and Nayak 2008; Dincer and Rosen 2010). Although there are several large applications of the chemical thermal storage systems, such as urban scale or non-domestic application, the calculated performance of these systems does not differ from the on-site monitored data. As such, to serve the aim of this research, the theoretical calculation method will be adopted and used to calculate the input of chemical thermal energy systems.

Finally, the use of a design year weather set by CIBSE during the simulation of building energy performance will restrict the far future prediction of energy demand and thermal storage performance. Since climate change is an on-going change and an issue that may affect the energy demands of the domestic sector in the UK, the design year selected for simulation runs will only reflect the actual data of that year and similar years. Furthermore, overheating of the UK's domestic buildings has been an issue discussed by several studies recently, especially in terms of zero-carbon and passive houses (Ampatzi and Knight 2007; Peacock et al. 2010). To serve the purpose of this research, the use of the design year will be used along with a CIBSE guide for overheating limits while the overheating figures are reduced to a minimum.

4.4 Conclusion

The previous review of the research methodology can be concluded into three main points, which are:

1- **The bottom-up engineering method is the best suited approach to predict domestic thermal energy demand for zero-carbon buildings**

The two main methods of building energy performance calculation are top-down and bottom-up, which can be used to achieve different targets with different sources of data. What determines the best approach for any research is one or more of: scale, source of data, available tools and desired outcome format. The top-down method relies on statistical historical data and economic indicators in order to calculate the long-term energy performance of an entire residential sector. This method is intended for large-scale applications only such as a city.

The bottom-up method is devised to calculate the energy performance of different scale applications starting from their end-use. It uses one of two main sub methods, which are statistical and engineering. The statistical method is based on the historical consumption data of a building type and how it is then applied to larger-scale applications. In contrast, the engineering method uses the performance of equipment, building type, occupancy profile, and location data to feed it into a simulation tool and then predict energy performance within a selected time frame. While the engineering method has several types underneath it, an archetype is chosen for this research. Since it has total independence from the requirements of historical, sample comparison or consumption distribution data, this method is most suited for the purpose of this research. This method also has been used and tested for similar researches successfully and will help to serve the aim of this research as well.

2- **The selection of HTB2 as a building energy simulation tool will satisfy the requirements of this research**

Since building energy simulation plays an important role in achieving the aim and objectives of this research, it is essential to inquire about and select the right tool that predicts energy performance accurately and consistently. Furthermore, since the available tools are numerous, a benchmark testing and performance comparison must be conducted to assess the selection of the right tool. ASHREA standard 140 and BESTEST have provided useful testing cases and comparisons between several tools. This method of testing BES tools has been used in several studies to determine the best performing tool available to date. HTB2 was presented in several studies that use comparison testing, which indicated that HTB2 could accurately predict outcomes due to its processing engine evaluating the thermal energy performance of buildings (Lomas et al. 1997; Alexander 2003; Neymark et al. 2011). As a result, the use of HTB2 will help predict the thermal energy performance of zero-carbon buildings used in this study.

3- **A thermal energy storage modelling approach, based on thermal storage capacity measurements will be used to determine the TES performance in this study.**

The numerical calculations for the thermal energy storage systems included in this study are based on thermal energy supply from on-site renewable resources and demand from space heating and domestic hot water systems. The overall thermal energy storage systems’ capacity is calculated and compared to determine the performance variables across different TES technologies operating under zero-carbon housing demand.

4- The constructed research methodology of the four phases scheme will provide suitable results to achieve the research aim and objectives

In order to assess the thermal energy storage potential input in residential zero-carbon buildings, a four phases scheme methodology is proposed. The first phase can be defined as the research foundation as it builds a database about the four main topics of the research itself. These topics are: domestic thermal energy demand in the UK, thermal energy storage technologies and properties, on-site renewable energy sources and, finally, building energy simulation methods and tools. As a result, the gathered data on all of these topics can be used as an input to the next two phases. Phase two will focus on domestic building energy simulation. This phase does consist of setting out the main conditions of the simulation runs and model building and simulation. The third phase will process the simulation output data and calculate the possible input of the thermal storage and renewable energy sources in order to help reduce thermal energy demand or shift the supply to meet the demand within the selected time cycles. The final phase is the analysis and optimisation phase, whereby the results of phases two and three are analysed and then evaluated for further optimisation or are concluded in the final research findings.

5 Case study

A successful simulation and calculation of thermal storage in zero-carbon houses requires the creation of a successful representation of a zero-carbon building with TES system as a case study. While zero-carbon buildings rely on several technologies to achieve carbon neutrality, the definition of 'zero-carbon' itself varies globally. In this study, Passivhaus standards will be used as the main method to achieve zero-carbon state.

This chapter will describe the zero-carbon building chosen for the case study of this research. The physical description and energy profile of the chosen design will be supported by several reviews of successful and already built case studies. The aim of adapting the configuration of previous case studies is to successfully simulate a zero-carbon building in order to fulfil the research objectives. Furthermore, the chosen design attributes will be simulated to test the case study viability for this research. The simulation results then will be compared to the Passive House minimum standards.

This chapter will discuss several issues in regards to the case study, the first of which is the weather and location data for the simulation run. The second issue is the energy consumption profile and occupants' behaviour. Lastly, there are certain simulation uncertainties, from modelling to the simulation run parameters.

Finally, this chapter will review the thermal energy storage technologies and methods used in this study. Which include the storage mediums, thermal energy capacity calculation method, and operations method.

5.1 Case study: physical attributes of the building

In this section, several topics will be discussed in detail to determine the most appropriate simulation case study approach in terms of physical attributes; these topics include the simulated building design, fabric, location, orientation, and operational loads. Within each topic there will be a brief review of the relevant existing literature.

5.1.1 Location data

Since the aim of this research is to provide an understanding of thermal storage in zero-carbon houses in the UK, the location data will be limited to the mainland of the United Kingdom, utilising the local weather profile. Cardiff city was the selected in this study as the main location.

Weather data files have been provided by the Chartered Institution of Building Services Engineers (CIBSE). These weather data files are identified as Test Reference Year (TRY) data files. The weather data included in these files consists of hourly averages that have been calculated for the past ten years, for the purpose of building performance simulations. While these files are provided in the format of EPW (Energy Plus Weather files), they must first be converted to a compatible format that HTB2 can utilise. A weather file conversion tool is included in the HTB2 software bundle, which will carry out the necessary conversion process. As for future weather data, CIBSE also provides an hourly weather series that is based on current Design Summer Years (DSY) and Test Reference Years (TRY) for several UK cities. For the purposes of this research, TRY files were selected for the city of Cardiff. Although CIBSE provides weather data for future projection years with variance of average temperature levels (high, medium high, medium low, and low average temperature years), current Test Reference Year will be used for this study.

5.1.2 Passivhaus standards

The current UK requirements for energy efficient buildings are set to meet zero-carbon emission standards. While this standard does try to govern carbon emissions based on annual building performance, it does not set clear standards regarding building design or element-specific performance (Passivhaus Trust 2011). Furthermore, since the regulation for zero-carbon buildings emphasizes on overall building performance and does not set a minimum thermal performance for the building fabric components, an alternative set of regulations will be implemented in this research. The selected set of regulations must perform either equally to or better than the zero-carbon buildings standards.

One of the best performing sets of building energy regulations is the Passivhaus standards (McLeod et al. 2012). Furthermore, it is one of the primary energy plans initiated and optimised in the EU to govern housing energy consumption levels, thus reducing the carbon emissions of the whole sector. The Passivhaus standards require buildings to meet strict design criteria and performance levels in order to be classified as a Passivhaus accredited building. These standards focus on several issues regarding the thermal performance of the building such as: the air tightness of the building, limiting thermal bridges, level of insulation, and mechanical ventilation heat recovery systems

(Heffernan 2013). Although the Passivhaus regulations have already been reviewed in the literature review (section 2.3.4), the fabric requirements and different components designs will be investigated in more depth in this section of the research.

5.1.3 Building design

The design of the simulation model and element manipulation has a major impact on the energy performance of the model. Furthermore, design decisions will also impact on thermal performance, heating and cooling demands. These design factors can take the form of building orientation, façade design, openings ratios, internal spaces plan, and building type. Each of these factors can influence the results greatly, yet maintaining a practical model is required if the research is to yield any useful results. Therefore, several survey reports of the current housing stock are used to help ensure the design factors are practical and relate to actual market practice.

5.1.3.1 Literature review

Building type and size are some of the main issues that needed to be resolved before initiating the modelling process. Table 5-1 shows the housing stock, in terms of type and area, with data taken from the English Housing Survey (Department for Communities and Local Government 2010b) which is applicable to Cardiff (selected location of this study) and Wales in general (Pan and Garmston 2012). The figures in Table 5-1 relate to the most common building types within the UK since the early 1900s. These figures are also consistent with a RIBA published report on the size and types of newly built housing in the UK (RIBA 2011). Both sources present the most common housing types, which are as follows: semi-detached, detached, and terraced houses. While semi-detached houses are the most commonly developed housing type in the UK, there is not much difference between the other two types (terraced and detached houses). The reviewed surveys also illustrate the developments of other housing types, such as flats and bungalows, although these represent a low percentage of total housing developments.

Table 5-1: UK's housing stock (Department for Communities and Local Government 2010b)

Dwelling type	Owner occupied	Privately rented	Local authority	Housing association	Total
Small terraced house	8.1	16.6	9.7	11.1	9.8
Medium/large terraced house	19.1	18.6	16.8	19.1	18.8
Semi-detached house	30.1	16.9	18.4	18.0	26.0
Detached house	23.8	8.1	0.3	0.9	17.4
Bungalow	10.3	4.0	8.8	12.1	9.4
Converted flat	1.9	13.0	1.9	3.9	3.7
Purpose-built flat, low rise	6.2	21.4	36.5	32.1	13.4
Purpose-built flat, high rise	0.5	1.5	7.7	2.9	1.5

Although the figures above relate to all housing stock built over the past 100 years, recent reports from RIBA and BRE show that detached houses are the most commonly built type of housing post-1990 (see Figure 5-1). Furthermore, the RIBA report also notes that although that building types have been shifting from semidetached to detached since the 1980s, the building sizes have remained similar, or very close, to those of pre-1980s (Roys 2008).

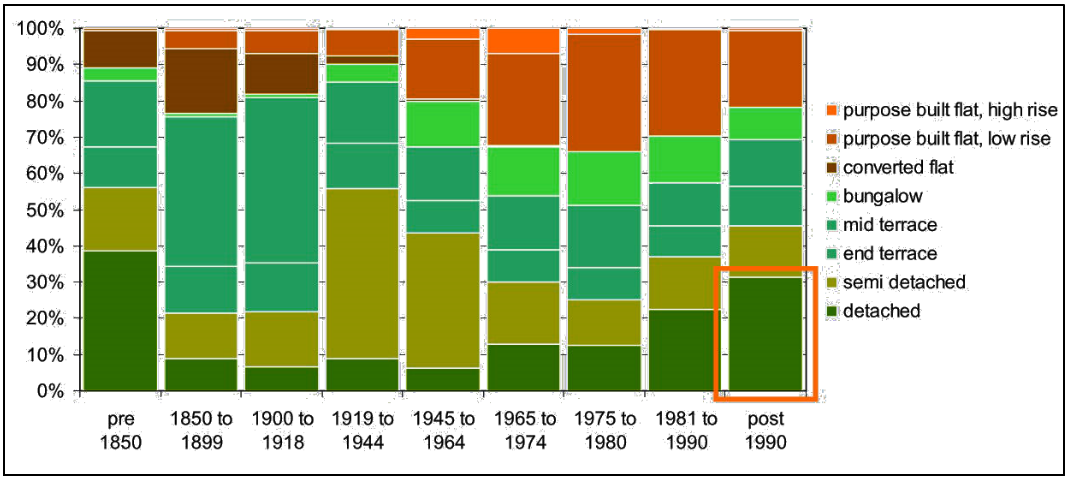


Figure 5-1: UK's current building types (Roys 2008)

In terms of housing, size and area have both been covered in several reports and surveys which will be reviewed in this research. For instance, the English Housing Survey (2008) presents the number of floors per housing type, as shown in Figure 5-3. It can be observed that most housing stock is made up of two-floor buildings (Department for Communities and Local Government 2010b). This also reflects the total area of the houses, particularly notable is the area of semidetached houses, which ranges from between 70m^2 to 90m^2, whereas for detached houses this increases to reach up to 110m^2 (Department for Communities and Local Government 2010b). These figures reflect current English housing stock, and apply to the whole of the British Isles, according to the RIBA report (Roys 2008).

With regards to the number of bedrooms per housing type, this figure has not changed since 1919 (Roys 2008). Furthermore, in terms of area size, there have been minor changes to bedrooms and living rooms over the same period of time, as is illustrated in Figure 5-2 (Roys 2008). Although the Greater London Authority have issued space standards, including an area guide for builders according to the number of floors and bedrooms, a RIBA report shows that 92% of surveyed houses fell short of meeting that standard by an average of $8m^2$ per house (RIBA 2011).

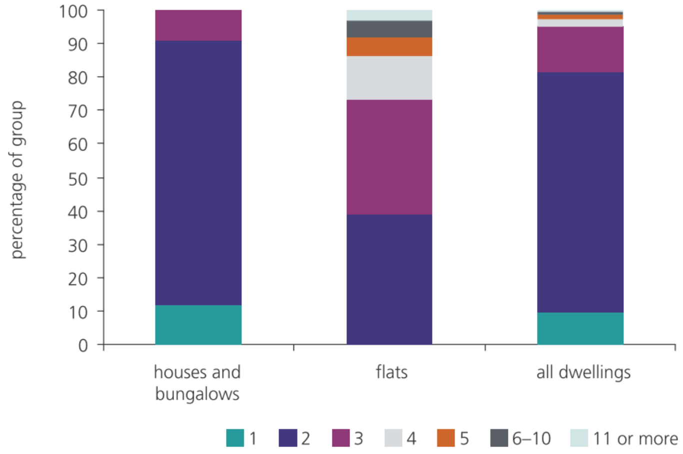


Figure 5-2: number of bedrooms per dwelling in the UK (Department for Communities and Local Government 2010b)

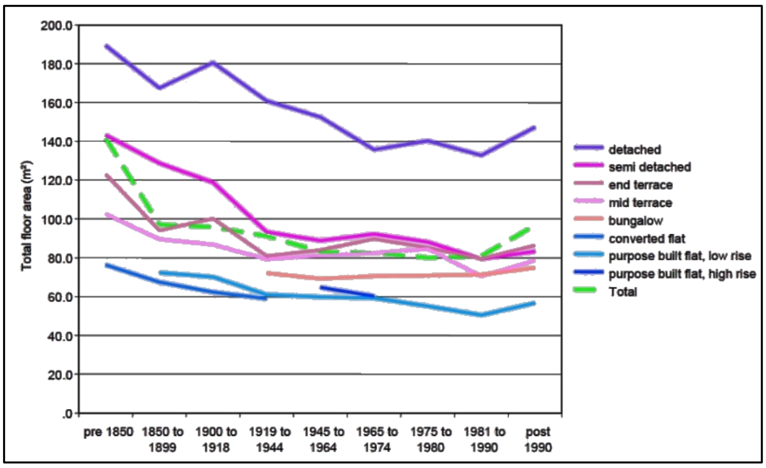


Figure 5-3: dwelling floor area over time (Roys 2008)

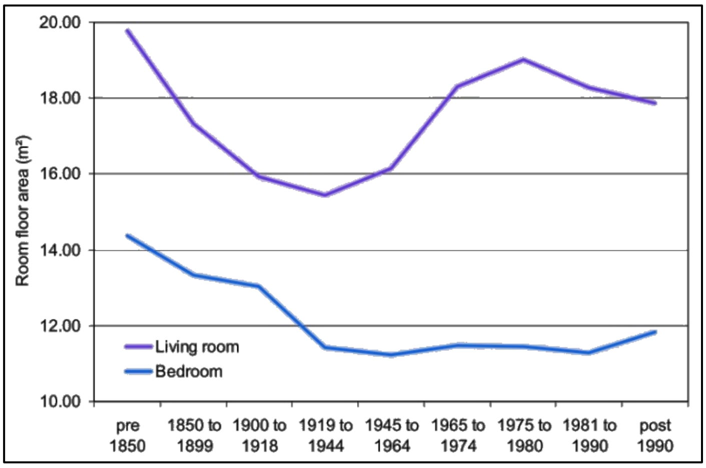


Figure 5-4: room floor area comparisons over time (RIBA 2011)

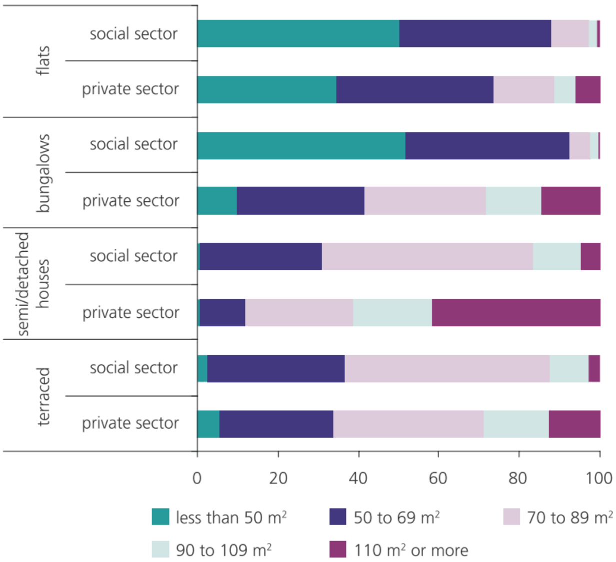


Figure 5-5: dwelling area according to type (Department for Communities and Local Government 2010b)

Table 5-2: essential gross internal area as set by RIBA (RIBA 2011)

Dwelling type	Number of bedrooms	Person-bed spaces	Essential gross internal area (m^2)
Flats	-	1	37
	1	2	50
	2	3	51
	2	4	70
	3	4	74
	3	5	86
	3	6	95
	4	5	90
	4	6	99
Two-storey houses	2	4	83
	3	4	87
	3	5	96
	4	5	100
	4	6	107
Three-storey houses	3	3	102
	4	4	106
	4	4	113

In order to determine the design of the simulation model, a detailed examination of the plans commonly used in the UK is required. RIBA present several plans that have been developed in the past decade, based on local authority records, published works and surveyed housing developers. These plans cover different types of housing, excluding the Affordable housing types only (RIBA 2011). For the purposes of this research, these plans will be examined and adapted into the simulation model (Figure 5-6).

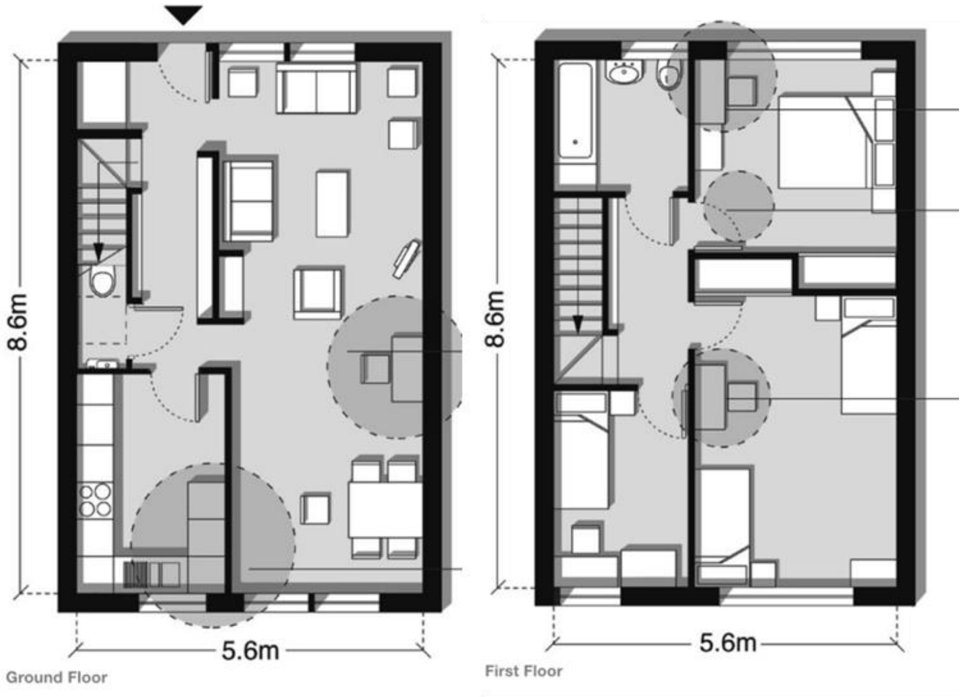


Figure 5-6: floor plans published in RIBA's survey report (RIBA 2011)

5.1.3.2 Simulation model design

Based on the previous literature review of current housing stock of the UK, several design factors have been determined as essential to consider in order to achieve the aim and objectives of this research. These design factors are as flows:

1- **Building type:** according to the reviewed literature, since 1990 detached houses have been the most commonly developed housing type (Department for Communities and Local Government 2010b; RIBA 2011). Although semi-detached houses represent the majority of the current UK housing stock (Roys 2008), for the purposes of this research a detached house will be used as the housing type for the simulation model. This selection is influenced by the fact that the present research is investigating newly built housing building rather than a retrofitting of an older development. Furthermore, selecting a detached house will simplify the simulation by reducing the thermal and environmental factors affecting the performance of the simulation model.

2- **Building size:** the building size is determined by two factors: number of storeys and the total usable area. The reviewed literature presents a good base for both factors. For the simulation model the building area will be within the UK's average space for three bedrooms' houses (about 100m^2), within two-storey buildings. These factors will greatly influence the final building model plans and design.

3- **Floor plans:** by adapting plans from a RIBA (2011) survey report, the following floor plans have been used and adjusted for the simulation modelling (Figure 5-7). The adjustments made to increase total surface area of the roof to be utilised by solar PV panels later in the simulation. The floor plans for this building model include a living area, dining room, kitchen, three bedrooms, two toilets, and two small storage and HVAC cabinets. This design will satisfy the research requirements and objectives. Furthermore, this design can be used for a detached house or a semi-detached house with some modifications.

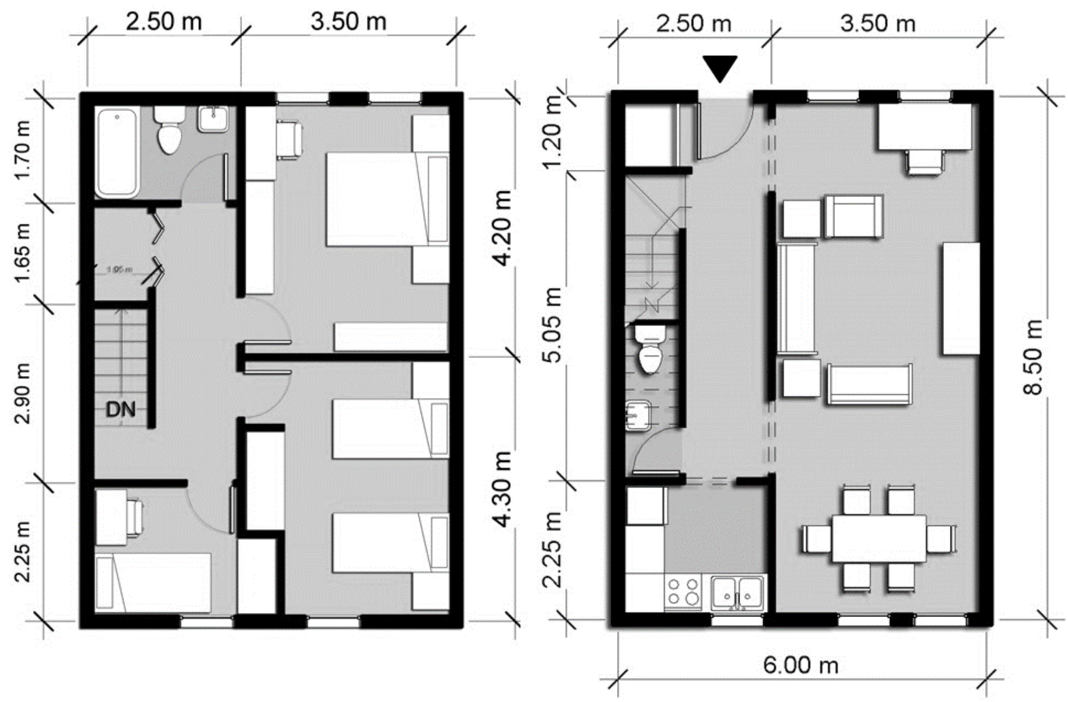


Figure 5-7: floor plans adapted from RIBA's survey

4- **Simulated zones:** by dividing the simulation model into different zones, the energy performance of each zone can be calculated separately, which leads to more accurate results. This research model will be divided into three main zones: the living area, bedrooms, and loft zones. Since each zone is operated differently, each zone will have its own schedule of operation regarding heating, ventilation, and occupancy. Further details of each operational aspect of these zones will be examined later in this chapter.

5.1.4 Building fabric

Building fabric is the main component in regulating an internal environment. Furthermore, despite the cradle to grave carbon emissions of the building fabric, the life time performance of the materials used and technologies implemented in the fabric will govern the total carbon emissions of the whole building. Proper design and selection of fabric materials will reduce dependency on supportive systems such as HVAC and lead to significant energy consumption reduction. The main components of the building fabric used in the case study are: roof, floor slabs, walls, and openings (windows and doors). Each of these components will be addressed within this section to establish the required performance of the zero-carbon building simulation.

5.1.4.1 Roof

The roof construction method is of significant importance in determining the building energy performance simulated in this research. This importance is because of its impact on the amount of energy the building receives annually, which can be transmitted directly to the building in the form of thermal energy or absorbed by the solar panels mounted on the roof. Therefore, the area, pitch angle and slope direction of the roof will determine the amount of solar energy that is received.

While Passivhaus standards do stipulate minimum thermal properties for roofs, no design guides are provided in reference to the sloping angle or direction of the roof. The published Passivhaus guidelines set the U-values of roofs to be between 0.10 W/m^2K to 0.15 W/m^2 K. Furthermore, the guidelines focus on eliminating thermal bridges and maintaining high level of air tightness in the building fabric more than the construction method of each element. Roofing methods are covered in the guide in terms of insulation location only. The guide introduces the cold roof, flat roof, and cathedral roof methods. The cold roof method is where the insulation is located on the internal side of the attic floor, while the roof itself contains no or minimal insulation. On the other hand, the cathedral roof contains full insulation in the envelope. While both methods (cold and cathedral roof) can be constructed from timber frame or steel structure, air tightness and insulation is the key factor in determining the performance of the roof (Passivhaus Trust 2015).

For the purposes of this research the Passivhaus standards will be used to set the U-value of roof construction. The selected type is a cathedral roof with a pitch angle to influences the energy performance of the solar panels mounted on the roof; the previous examination of the optimum angle of solar panels in the literature review chapter suggests an optimum angle of 38° degrees, facing south, and maximizing the roof area to include as many solar panels facing south as possible. The final design is presented in Figure 5-8. The south-facing roof measures 8.5m long by 5m wide, while the north-facing roof is 3m wide and 8.5m long. Figure 5-9 shows the roof type (cathedral type) and detailed construction of the roof, including layers of insulation, the thickness and U-values of each layer.

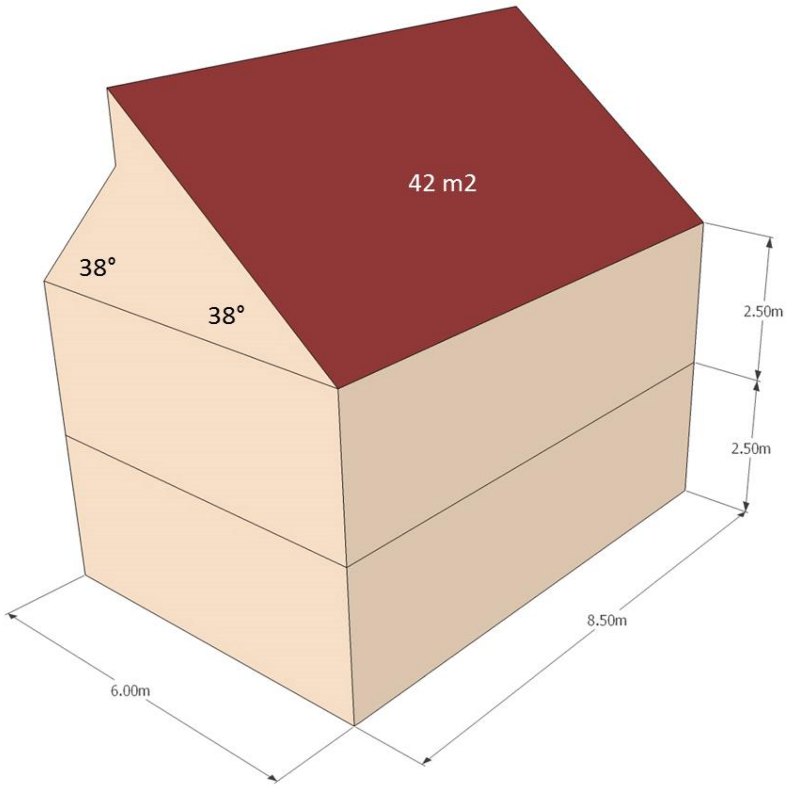


Figure 5-8: simulation building model showing dimensions and utilised roof area

The construction of the roof and material selection was based on Passivhaus Trust recommendations and samples published in their guide and on their website. The construction method used in the simulation model is a timber frame structure with polystyrene insulation and metallic roof panels on top. Whilst other materials could achieve the same total U-values recommended by the guide, they would not enable the building to be air tight, or facilitate thermal bridging, and would require different construction methods. For example, metallic roof panels would be a good replacement for roofing slates with similar thermal performance, yet construction methods would differ due to the weight involved. Furthermore, these metallic panels have a low thermal mass, which means less heat is contained within the roof. Additionally, these panels are coupled with an 80mm polystyrene insulation layer that extends 250mm beyond the wall-roof joint to provide extra thermal insulation and shade. Moreover, the continuation of the wall insulation (water proofing and thermal insulation) into the roof cavity will provide limited thermal bridging whilst also maintaining greater air tightness and water proofing properties.

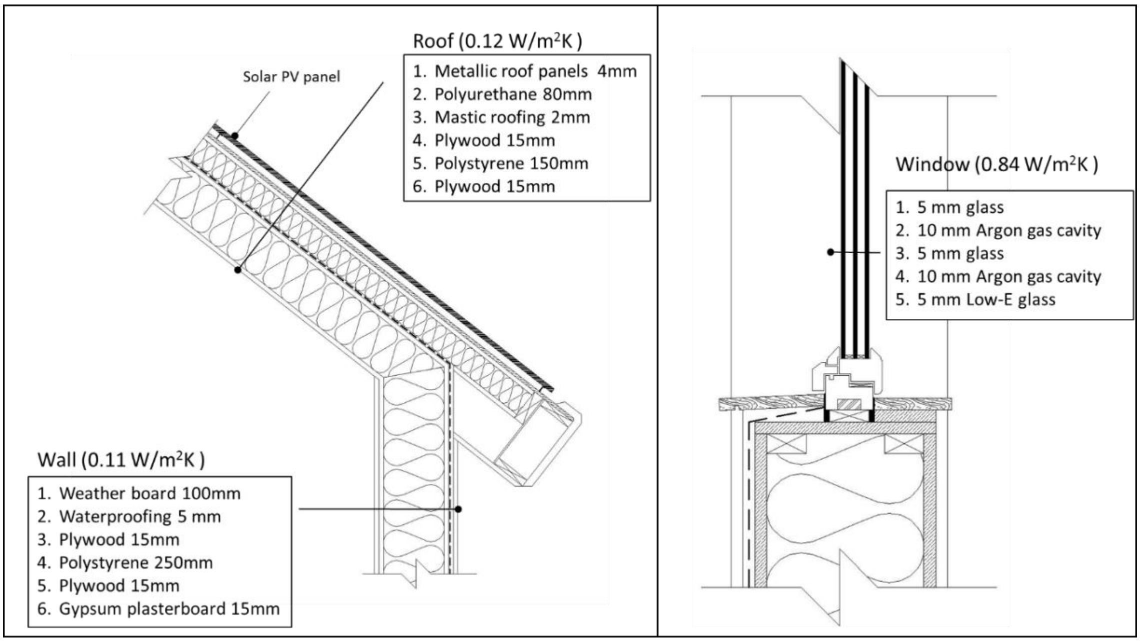


Figure 5-9: insulation of the simulation model's walls and roof (left), and window construction layers (right)

5.1.4.2 Walls

Since the Passivhaus standards and design guidelines serve as the main reference point for the design of the simulation model, wall construction methods and thermal properties are not an exception. The Passivhaus guide states that the U-values of walls are to be between 0.10 W/m^{2}K to 0.15 W/m^{2}K, with minimal thermal bridges. Although the preferred wall thickness stipulated in the guide is dependent on the amount of insulation used, but it recommends a wall thickness of between 300mm and 500mm. Furthermore, the guide introduces several wall construction methods alongside different suggested insulation techniques and case studies. These construction methods are as follows: timber construction, component materials with timber frames, masonry cavity, solid masonry with external insulation, and structural insulated panels (Passivhaus Trust 2015).

Timber construction and timber frames are considered to be one of the fastest methods of erecting a building. However, these methods have been criticised by Passivhaus as they are deemed to rarely achieve the required U-value, although they do provide significant thermal bridging due to the structural requirement for vertical studs. Furthermore, the moisture builds up in the structural wooden frames during winter and its release in the summer will lower the performance of a building constructed using this method (Passivhaus Trust 2015).

Masonry cavity has several advantages that make it suitable for the UK housing market. These advantages stem from the local availability of materials and the familiar construction methods in the local environment. In addition, the physical and thermal properties of the masonry, such as soundproofing and thermal storage, make it more appealing to developers of high-energy performance buildings. On the other hand, this building method presents several quality and performance difficulties. For example, the porous nature of masonry and mortar challenges the air tightness of the whole structure, while allowing humidity leaks into the structure. This requires several treatments of the inner layers to raise the performance levels of this building method. Furthermore, the rough surface of the masonry wall will require the usage of soft fibrous insulation, such as mineral wool, to prevent air passages within the wall cavity. The Passivhaus Trust (2015a) states that this type of construction will pose an extra difficulty in quality checking the insulation continuation and air tightness.

Solid masonry with external insulation provides several new advantages to the masonry building method while maintaining the benefits of the masonry itself. This is due to the separation of the structure and the insulation, which eliminates thermal bridging. It also enables easy checking of the thermal insulation quality and air tightness. The Passivhaus guide states that this method is one of the easiest ways to achieve its standards and the U-value targets using a variety of rigid and soft insulation. Even though this method is considered the most flexible, it does have several disadvantages; for example, it exposes the insulation to external damage from external building works or heavy cladding. Furthermore, the method is considered new to the UK housing development market, which means that contractors have a lack of relevant experience and building costs are high (Passivhaus Trust 2015).

Finally, the structural insulated panels (SIPS) method of wall construction has been praised in recent decades for the array of benefits it offers. This construction method uses off-site prefabricated walls that can be assembled easily in a relatively short time. Furthermore, this method also has a low embodied energy property that offer even more reduction in the buildings overall carbon footprint. The structural components of these walls can be described as insulation sandwiched between two layers of 15mm boards. These panels are then joined together on-site to form the building walls. The ability to manufacture these walls at an off-site location means higher quality checking can take place, particularly for the wall to door and window joints. Despite all of the advantages of this method, Passivhaus (2015) advises further adjustments to this method in Passivhaus accredited buildings to minimize thermal bridging.

For the purposes of this research, the SIPS method is the best option for wall construction, due to the thermal properties that this method offers. According to the Passivhaus guidelines, these walls should achieve a minimum U-value of 0.15W/m^{2}K. Therefore, the proposed construction for the simulation model is as follows: 1- weather board, 2- waterproofing material, 3- plywood board, 4- polystyrene insulation, 5- plywood board, and 6- gypsum plasterboard. The total thickness of this wall will be 350mm with a U-value of 0.11W/m^{2}K. Figure 5-9 shows the external wall construction layers along with the corresponding U-values.

5.1.4.3 Floor slabs

Different floor types will be examined to determine the best choice for the simulation model. There are two main types of flooring commonly used in housing in the UK: suspended and solid floors. Although the Passivhaus guide does not recommend suspended floors, due to structural properties that force thermal bridging, the guide leaves suspended floors as an option to accommodate local laws and insulated envelopes above basements. On the other hand, solid floors are preferred, due to their easy and low cost construction, as stated in the Passivhaus guidelines (Passivhaus Trust 2015).

Since the simulation model is considered a light structure, the walls and building envelope do not require support from foundations. The building envelope will be supported by the on-ground solid floor; this floor will be insulated on top of and connected to the envelope insulation to ensure the continuity of thermal insulation and air tightness. The use of polystyrene thermal insulation is recommended by several building guides, owing to its rigidity and ability to withstand construction damage (Shorrock et al. 2005; BRE 2006; Wolfgang 2013; Passivhaus Trust 2015). Furthermore, the total thickness of the floor, including the waterproofing and thermal insulation, will not exceed 430mm with a U-value of 0.15 W/m^{2}K. Although the ideal location of the waterproofing insulation or bitumen felt is debatable, the thermal effect of its location is insignificant to the simulation results.

5.1.4.4 Windows and doors

As this element of the simulation model is dictated by the limited input of the simulation software, a selection of input data will be investigated, including: openings area per facade, windows type, glass type, number of layers, and amount of solar radiation that is transmitted and absorbed. It should be mentioned that several aspects of the modelling are ignored due to software limitations, such as the opening frame and construction. These limitations will prevent the simulation software from counting the thermal energy that leaks into or out of the simulation model through the windows and doors frames (Alexander 2008). Furthermore, the definition of external doors is also limited, since the simulation software does not recognise this opening as a different type of opening to windows. As well as taking these factors into consideration, Passivhaus standards must also be applied. Their guide sets the minimal U-value of any opening in the external envelope at 0.85 W/m^{2}K (BRE 2006; Passivhaus Trust 2015). This low figure requires high performance windows and doors, which includes a need for thermal insulation, multi-layers, and low-e glass to be implemented into the design.

In regards to the research model, the selected external window type is the triple-layered glass window. The inner layer of glass will be low-emission glass of 5mm of thickness. In between these layers of glass is an insulated cavity of isolated argon gas at 10 mm thickness (see Figure 5-9). These properties will give the window a U-value of 0.84 W/m^{2}K. The solar radiation emitted through the glass is measured in the simulation software according to a series of values of solar radiation transmission and absorption levels over different angles predefined in the HTB2 tool (see Table 5-3). These figures are taken from technical papers and case studies of high performance buildings simulated or built in the UK (Barratt Developments PLC 2007a; Roberts 2008; Ridley et al. 2013). As for the window area of the model, the average area for openings in UK housing is set by BRE and the Passivhaus Trust and must not exceed 25% of the external wall area (BRE 2006; BRE Global 2015; Passivhaus Trust 2015). Therefore, by adhering to this value, the simulation model will have a total area of 29m^2 in relation to the 116m^2 available façade; that is 8.5m^2 of openings for each of the northern and southern façades and a further 6m^2 for eastern and southern façades.

Table 5-3: solar radiation transmission and absorption set in simulation model

Angle	Net	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Transmission	0.19	0.25	0.25	0.25	0.25	0.25	0.25	0.2	0.15	0.09	0.0
Absorption	0.23	0.25	0.24	0.23	0.22	0.2	0.17	0.14	0.11	0.08	0.0

5.1.5 HVAC systems

The HVAC system plays an important role in determining the energy efficiency of the whole energy simulation model. The exact settings of heating, cooling, and mechanical heat recovery should meet the requirements of net zero-carbon house standards. According to the strategies for new homes published by Zero Carbon Hub, the proposed limit for heating and cooling demands should be set in accordance with the Fabric Energy Efficiency Standard (FEES). In regards to detached and semi-detached houses, the maximum energy consumption figures set by FEES should be below 46 kWh/m^2/year (Jefferson et al. 2013). This is higher than the Passivhaus requirement of 15 kWh/m^2/year for heating demand and 15 kWh/m^2/year for cooling demand (BRE 2006; Sei 2007). Although cooling demands in the UK should be minimal, several studies have highlighted that overheating in high performance buildings is predictable (Roberts 2008; Peacock et al. 2010; Ridley et al. 2014). Therefore, an expected rise in temperature in the summer months will require HVAC cooling. CIBSE Guide A gives a clear definition of overheating in dwellings and can be used as a reference point for this study. The guide sets the temperature limit for the living area at 28°C, which should not be exceeded for more than 1% of the annual occupancy time. However, bedrooms have a lower temperature limit of 26°C for a maximum occupancy time of 1% annually (Roberts 2008). The Passivhaus guidelines stipulate an overheating temperature of over 25°C for more than 10% of occupancy time annually (Sei 2007).

While heating and cooling demands do indicate the thermal performance of houses, thermal leaking through ventilation does influence these figures. This is where mechanical heat recovery ventilation systems (MHRV) have to be implemented to recover most of the space thermal energy. The efficiency of MHRV is measured in accordance to the percentage of heat recovered from ventilation. The Passivhaus guidelines require the MHRV system to recover heat at a rate of 75% or more (Sei 2007). The ventilation of dwellings is managed mechanically, which means there will be auxiliary fans and no passive or natural ventilation. By contrast, zero-carbon houses have no minimum requirement for MHRV systems. As for ventilation flow rates, Passivhaus suggests 30m^3 of air per person per hour in any dwelling type; the amount of extraction points is design dependent.

The HTB2 simulation tool definition for meeting heating and cooling demand is provided in its heating text file. Simulation runs can use the data in the text file to operate both heating and cooling equipment, while maintaining a pre-set range of temperatures. The simulation model of this research is set to maintain a temperature between 20°C and 28°C, which is within the guidelines suggested by CIBSE. Below this level, the space will require heating from a 5000W convective electrical heater, and above it a cooling via ventilation will occur. While an active cooling system may be required during the simulation run, the focus of this research will be on heating demand only. Furthermore, the operation times of the HVAC system in the simulation runs will be governed by the occupancy of the space, which will be explained in further detail later in the research (see Table 5-4). Moreover, the MHRV system setup under HTB2 is not feasible, so post-simulation manual calculation to determine actual energy performance may be required. These calculations will be based on the Passivhaus guide of 75% MHRV efficiency rate out of HTB2's ventilation heat gain produced after each simulation run. The heat delivery method into the space that combines both space heating and the heat return from the MVHR system is carried by convective heating system into the ventilation system that responsible for maintaining the set space temperatures. While this system is not simulated under HTB2, the energy conversion from electrical to thermal performed by the electrical heater assumed to have an efficiency rate of 100% which means there is no heat loss and the figures of energy demand for space heating by HTB2 simulation can be used directly as an input for the TES modelling. Furthermore, heat return from MVHR system will be through the heated ventilation system managed by active heat exchanging method.

5.1.6 DHW

The supply of domestic hot water is strictly regulated by local building authorities. These regulations are intended to maintain sanitation and safety for the end users, including scalding prevention, pressure release valves, microbial elimination, and energy regulation. Most of these elements relate heavily to temperature regulation inside and outside of the water heater. While all of these regulations are relevant, this research will focus particularly on temperature setting for thermal storage purposes and consumption rates.

The Passivhaus guide provides a good starting point, but it is not sufficiently thorough, since it focuses on the building fabric more than its services. The guide suggests an energy limit of 120kW/m^2/year as a benchmark not to be exceeded in the building design, including domestic hot water (DHW). Further on in the guide, the location of the water heater within the building plays an important role in minimising draw-offs and heat loss (Passivhaus Trust 2015).

Temperature regulation can be managed using several methods: limiting the heating element, storage temperature, and valve mixers. The CIBSE Guide F suggests reducing the temperatures of water heating systems to increase energy efficiency. The guide also limits the water storage temperature to a minimum of 60°C to prevent legionella multiplication. The end temperature, according to the same guide, is set at 50°C, which may require a mixing valve (CIBSE 2004). BRE (2003) states that a 50°C water temperature will induce skin scalding in one minute. The suggested temperature for showers is 48°C, which lowers the risk of scalding and extends the time of scalding to 35 minutes of exposure (BRE 2003). Higher temperatures are also feasible, but in separate storage tanks for thermal storage purposes only. It can be mixed with DHW, but under 50°C for end utilisation. The maximum temperature that water can be stored at is below boiling temperature, which is 95°C – 90°C (CIBSE 2004; Hot Water Association 2010). The DHW demand in volumetric units per occupant per day can be estimated using the BREDEM formula:

Hot water demand (litres/day) = 46 + 26 N *where N is the number of occupants*

The assumed DHW arrived at with this formula is very close to the surveyed data from the Energy Saving Trust (2008) study of 120 domestic buildings in the UK. While this figure is important to estimate the initial energy demand for hot water, it lacks the hourly demand levels, a figure that is required by this study to calculate energy demand versus supply. However, these hourly figures can be drawn from the Energy Saving Trust (2008) survey, which presents hourly hot water demand in litres and energy (MJ) per household (Figure 5-10).

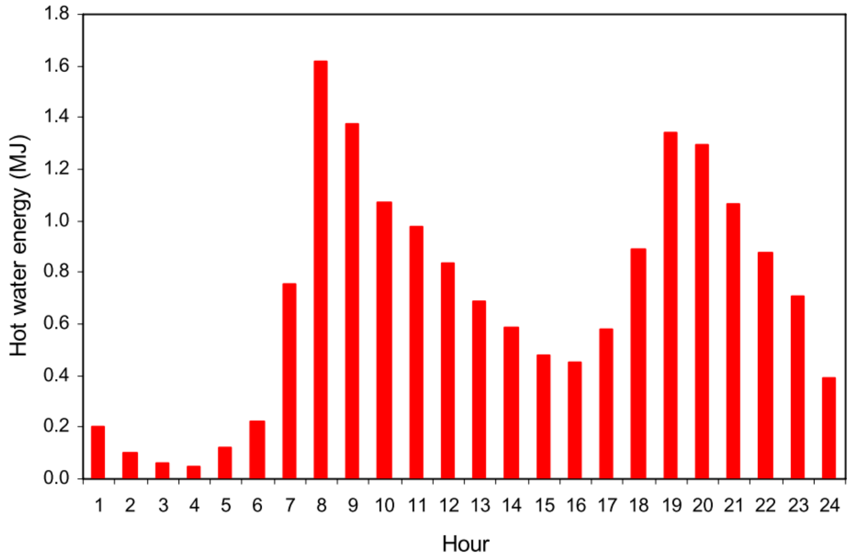


Figure 5-10: average hourly energy consumption for DHW in 150 survey sample in the UK (Energy Saving Trust 2008)

Next, the HTB2 input for hot water is required to calculate heat emissions by the water heater in the simulated zone. While the simulation runs will not include DHW total demand and energy consumption levels, they will provide the total internal gains from occupants and building services, including the water heater. The hourly and daily demand figures will be introduced via manual calculation in next stage of this research in order to measure the building performance and TES efficiency. By applying the BREDEM formula in the simulation model, four occupants will demand approximately 150L/day of hot water. This figure also complies with the Energy Saving Trust (2008) survey results for similar sized dwellings. The significance of using the survey results will also reduce the internal scenario uncertainties from the simulation model via validation. Several combinations and hot water storage systems will be examined later, in the TES system design chapter. Furthermore, the set temperature of 60°C stipulated by the CIBSE Guide F will be used as the minimum for water heating and storage for DHW, while higher temperatures may be explored for TES system possibilities.

5.2 Energy demand parameters

Energy demand parameters determine the operational performance of the simulation model. HTB2 input files allow for several aspects to be determined, such as occupancy, operation schedule, small power, lighting, and HVAC systems. Each of these inputs will be examined with reference to existing literature and model design in the following section.

5.2.1 Occupancy

While design parameters, building fabric, and location may have the most significant impact on domestic building energy performance, occupants' behaviour and habits also influence the total energy demand. An estimation of 10% to 30% change in consumption levels can be attributed to different behaviours and patterns of occupancy (Yohanis et al. 2008). Different factors are linked to energy consumption variation, such as number of occupants, age, working habits, lifestyle, income, and awareness (Yohanis et al. 2008; Oldewurtel et al. 2013; Feng et al. 2015). The difficulty in simulating occupancy-related energy demands is due to its stochastic nature. Several studies have been conducted that attempt to generate a simulation model that is able to predict occupancy variation by implementing programming algorithms or statistical tests, such as the Monte Carlo test, to evaluate the impact of variable occupancy scenarios (ibid).

As this research focuses on detached houses, the occupancy effect will be examined in terms of this housing category only. The first issue that needs to be addressed is the number of occupants per household. According to the UK housing energy fact file (2011), the average number of households in the UK is decreasing annually (Palmer and Cooper 2011). The average number of occupants in the UK is approximately 2.4 per house, for all building types (Palmer and Cooper 2011). Detached houses have an average of 3 to 4 occupants, depending on the number of bedrooms available (Roys 2008). This figure is based on local government surveys; however, RIBA have published several publications that confirm this information, based on client and market demand surveys (RIBA 2011).

Another factor that affects energy consumption related to occupancy is the occupants' lifestyles, for instance, whether they work or not, and how many occupants are working 'normal' hours. Another factor is the age of the occupants, and whether there are any minors, school age children, working age adults, and elderly occupants. Various combinations of different aged occupants will determine the operation and schedule of appliances, heating demands and temperature within the house (Hamza and Gilroy 2011). The Department for Communities and Local Government has published a housing standard that correlates area, number of bedrooms and maximum occupancy; it states that two-storey detached houses will accommodate 4 to 6 occupants with a 3-bedroom limit (Department for Communities and Local Government 2015). Data published in previous sources are consistent with the 2012 Household Electricity Survey Final Report, which details the electrical demand of different domestic buildings, depending on occupancy and structural values (Zimmermann, Evans, Griggs, King, Harding, Roberts and Evans 2012). Figure 5-11, Figure 5-12, and Figure 5-13 illustrate the average hourly electrical demand of households with children during working days and holidays.

The last issue that needs to be addressed in regards to occupancy factors is energy efficiency and occupants' awareness of this. This issue is mainly governed by occupants' level of energy consumption, thus it is highly dependable on social and educational factors and the awareness of the occupants themselves (Janda 2011). This aspect will be difficult to simulate and so will be considered as a consistent uncertainty in the simulation scenario.

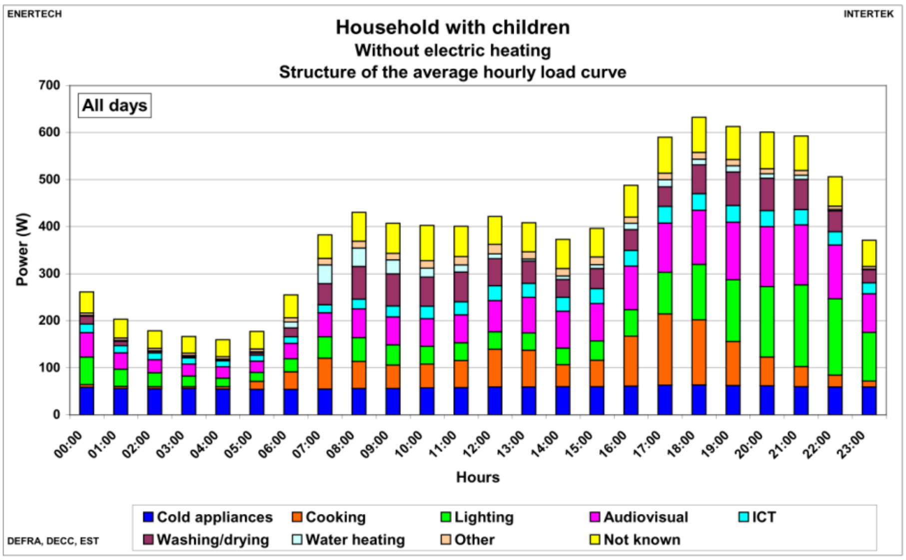


Figure 5-11: average household daily energy demand (Zimmermann, Evans, Griggs, King, Harding, Roberts and Evans 2012)

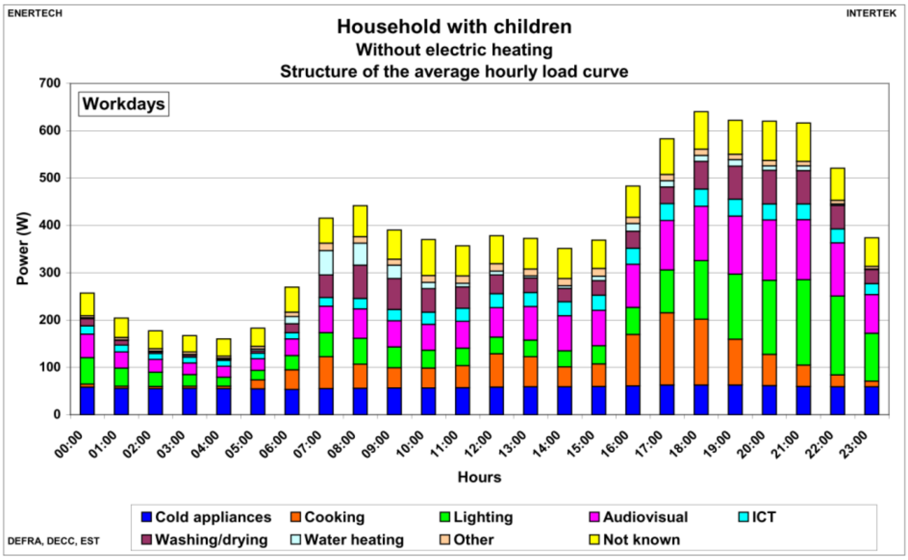


Figure 5-12: average household working days energy demand (Zimmermann, Evans, Griggs, King, Harding, Roberts and Evans 2012)

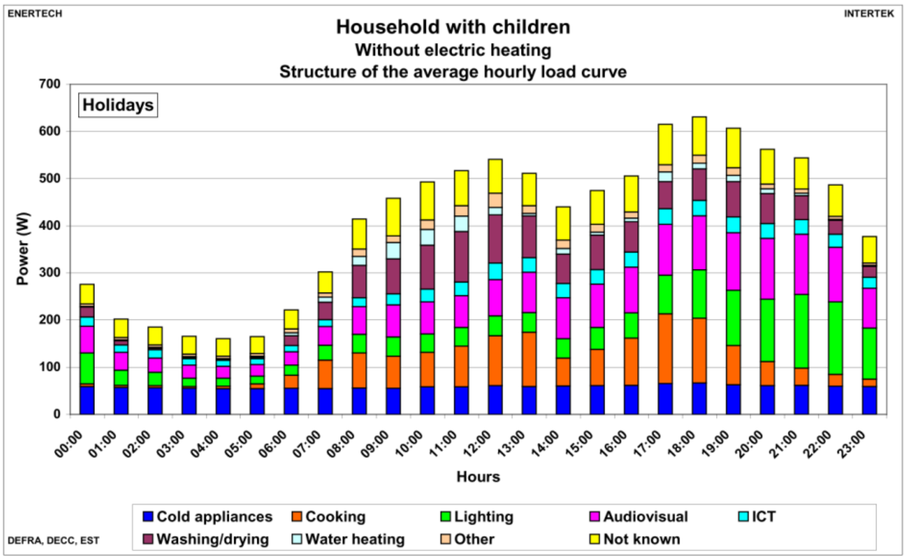


Figure 5-13: Average household holidays energy demand (Zimmermann, Evans, Griggs, King, Harding, Roberts and Evans 2012)

For this research model, based on the literature review, occupancy will follow the guide provided by the Department for Communities and Local Government in terms of number of occupants per area. Since the building model design is 100 m^2 in total, it can accommodate four occupants. A typical family with children is therefore used to simulate thermal energy demand: one working parent, two school age children, and a stay-at-home parent. This occupancy model will dictate the operation of the heater, lights, small power, DHW, and wet appliances. Later on, the operation schedule and operational levels will be explained in further sections in this chapter. Finally, a simple metabolism level indicator is used to represent internal heat gains from occupants whilst they are inside the house, in HTB2 files (see Table 5-4). It should be noted that the occupants' schedules will differ for working days and weekends; this variation is taken account of in the simulation schedule input within the HTB2 occupancy file.

Table 5-4: occupants schedule used in the HTB2 simulation model

Time (work days)	00 – 07	07 – 12	12 – 18	18 – 23	23 – 24
Occupants (no.)	4	1	2	4	4
Activity level (W)	50	90	90	90	50
Time (holidays)	00 – 08	08 – 12	12 – 16	16 – 23	23 – 24
Occupants (no.)	4	2	2	4	4
Activity level (W)	50	90	90	90	50

5.2.2 Small power devices

The small power devices included in this simulation model are common in most UK houses and contribute to the internal heat gains of the building. These small power devices include appliances that run in each room of the dwelling, cooking appliances, cold appliances, washing and drying machines, and water heaters. Since these devices are meant to be in high performance buildings, higher rating and more energy efficient appliances should be selected. The CIBSE Guide F provides the base figures and consumption levels required by the simulation model (CIBSE 2004). Furthermore, several publications by the Energy Saving Trust and the EU Energy Efficiency Labelling Scheme rate the energy efficiency of domestic appliances. These published figures will also contribute to the final energy consumption rating of the simulation.

HTB2 defines small power internal gains in the text input file within the main simulation folder. This includes the primary definition of the appliance, base energy consumption level, energy emission percentage, activity level, and operation schedule. Table 5-5 shows the main input values of the simulation for variable small power devices included in the model. Some of these categories include small user devices such as computers and miscellaneous electronic items. Further details of the operation schedule are presented in Table 5-4. The operation hours and demand levels are informed by the space operation and occupancy schedule examined previously.

Table 5-5: small power appliances and their associated heat energy output set in the HTB2's simulation model

Type	Heat output (W)	Convective (%)	Radiative (%)	Operation times (h)
Audio-visual	150	60	40	08 – 10, 19 – 23
Living room appliances	30	80	20	08 – 10, 19 – 23
Bedroom appliances	10	80	20	07 – 08, 23 – 24
Cooking appliances	1700	60	40	07:00 – 07:15, 12:00 – 12:30, 18:00 – 19:00
Washing machine\ dryer	500	80	20	18 – 20
Cold appliances (fridge)	200	80	20	00 – 24
Water heater	150	80	20	00 - 06

5.2.3 Lighting

Since the main energy performance concern of the simulation model design is thermal energy emissions and demand, lighting energy requirements will be measured mainly in terms of heat output. Both zero-carbon building standards and Passivhaus Trust standards primarily focus on building fabric insulation and limiting heating demand more than any other aspect of energy demand within the building itself. However, guideline strategies issued by Zero Carbon Hub state that there are allowable solutions that can be used to reduce the carbon emissions of the building; these allowable solutions include high efficiency lighting systems (Jefferson et al. 2013).

On the other hand, HTB2 simulation software includes lighting in the simulation and measures it in terms of circuit output in watts, convective and radiative energy emitted by the light source. This method of defining light sources allow for flexible input of different types of light, including high efficiency lighting with less convective and more radiative energy modes. While current lighting technologies offer several options for high efficiency lights, LED lighting is among the most promising with regards to low energy consumption, high light output, low heat output and affordability. Therefore, this type of lighting is used for the simulation model. As for the amount of lighting required per building type, the CIBSE guide provides lighting standards for detached houses, which includes high efficient lighting methods. The figures given in the guide are implemented in the simulation model (CIBSE 2004), where a total of 10W LED lighting sources are used, equivalent to 500W of incandescent light bulbs. The operational hours of these lights and the level of operation are determined by simulated occupants' diurnal habits. Further details regarding the operation schedule are presented in Table 5-6.

Table 5-6: Lighting operation schedule

Time (h)	00 – 05	05 – 07	07 – 16	16 – 23	23 – 24
Operation (%)	0	25	0	100	0

5.3 Energy supply parameters

The simulation model used in this research is based on a zero-carbon building principle, which can be achieved by implementing Passivhaus standards. However, the energy consumption figures and limits of the Passivhaus (120 kWh/m^2/year) far exceed the zero-carbon building statues (Passivhaus Trust 2011). While Passivhaus requirements can be satisfied by limiting energy consumption, a zero-carbon building is dependent on on-site energy generation to counter the actual energy consumption of the building. These on-site energy sources are typically solar, wind, air source and ground source heat pumps. In the UK, solar energy is limited due to the local weather, which is commonly cloudy, and its location in the northern hemisphere. Therefore, special design considerations must be given to maximize the outcome of this energy source.

Energy supply for the simulation model will be provided by two main sources, grid power and solar energy. The solar energy generated from the building should meet the majority of the energy demand, while grid power will be used to satisfy the demand where there is no solar energy available or thermal energy stored in the TES system. Wind power is excluded from consideration due to several variables that affect the energy generation capacities of that source greatly. For example, wind direction and speed varies from one location to another, depending on the surrounding environmental elements. Other variation arises due to the inconsistency of wind rates over time (Peacock et al. 2008; Drew et al. 2013). Restrictions relating to wind energy generators and laws governing wind turbines in urban environment introduce another layer of uncertainty. Therefore, the decision was made to exclude wind energy source from the simulation model. Some of these obstacles and limitations also apply to ground heat. This type of energy source is heavily dependent on location attributes, which can only be discovered through site testing. These limitations and the lack of any type of micro-climate database in this regard led to the decision to also exclude this source from the study.

By implementing solar energy technology in the simulation model design, the maximum output of this source can be expected. This is also assisted by the selection of the right system, which can increase the overall potential of this energy source. Several technologies have been reviewed in the literature and then tested in the initial run, such as thermal panels and PV. The results of the initial testing indicate a better outcome from the PV system over the other tested systems. Therefore, PV panels covering a total area of 40m^2 of PV are used in the simulation with an outcome efficiency level of 20%. The overall performance of this system will be expected to meet the requirements of zero-carbon buildings, and thus the research objectives.

5.4 Uncertainties

The building design and energy performance of the case study could be affected by several uncertainties. These uncertainties may give rise to questionable results, due to differences between the simulation model and reality. In this case, the simulation model may require further development to the design or the simulation mode in order to yield results comparable to the intended target. Addressing these uncertainties would require several trials, experimentations, comparisons, and a corresponding process of elimination. In general, these uncertainties can be classified into two types: aleatory (inherited from natural randomness) and epistemic (modelling and simulation variables) uncertainties (Hopfe and Hensen 2011). Since this research is based on energy simulation, the main issue that needs to be addressed is epistemic uncertainty. This kind of uncertainty can affect three parameters of the simulation: physical, design, and scenario (Hopfe and Hensen 2011).

Physical uncertainty can be defined as, “the standard input parameters in energy or thermal comfort simulation” (Hopfe and Hensen 2011). This uncertainty is linked to the physical material properties included in the model, in terms of thickness, density, and thermal properties. Physical uncertainty is unavoidable in any energy performance simulation because of its relation to the physical material, which is affected by variation in the material itself. The impact of physical uncertainty on the simulation model is significant, since it is present in every part of the simulation model, including roofs, floors, and walls. Addressing this uncertainty will ensure the quality of the simulation but will not alter the results entirely (Hopfe and Hensen 2011).

Design parameter uncertainties originate during the planning phase of the simulation model, which is affected mainly by the decision making of the designer, which in turn is influenced by his/her degree of knowledge, or the changing parameters of the design. In some cases, when several people are in charge of the design, this can generate this kind of uncertainty due to the various different design approaches (Hopfe and Hensen 2011). This type of uncertainty can take the form of model orientation, size, wall type, glazing layers, and so on. Addressing this kind of uncertainty would require validation of the simulation model with similar case studies and more expert designers (Hopfe and Hensen 2011).

Scenario uncertainty, or boundary uncertainty, is related to the operation of the simulation model or building during its lifetime. This kind of uncertainty relates more to the design decisions and their effect over time. There are two subtypes of this uncertainty: internal uncertainties and external uncertainties. Internal scenario uncertainties include internal heat gain in the building as a result of lighting, occupant behaviour, HVAC loads, ventilation, and operation schedules of internal components. External scenario uncertainties involve external factors influencing the simulation, such as weather data and climate change (Hopfe and Hensen 2011).

These three types of uncertainty apply, to some degree, to the topic of this research. Physical and design uncertainties would have the most impact on the results, since the purpose of this research simulation is to determine the thermal performance of the simulation case study under zero-carbon building conditions. Scenario uncertainties have a limited impact on the simulation results, due to the simulation limitations to meet the research objectives. Internal scenario uncertainties are the most relevant uncertainties within this category. This is because of the operation of internal loads that included in the simulation runs besides the variations in occupants' behaviour. Different settings can be implemented in the simulation, which may lead to different energy consumption figures for both annual and diurnal cycles. External scenario uncertainties in the simulation model of this study will be minimal since the weather is taken from the CIBSE design year, which is the standard for energy simulation in the UK. Climate change will have a minimal effect on the study results, since future projections are not a part of the research objectives.

To account for physical uncertainties in this study, several manuals, guides, and technical papers have been reviewed to ensure minimum levels of uncertainty in regards to the properties of selected materials. The reviewed materials include Passivhaus construction guides and case studies of energy efficient building simulations. Data regarding the selected material properties has been also compared to local manufacturing standards and advertised specifications in order to further validate current material properties.

Design uncertainties were minimised during the simulation model planning phase by validating decisions with HTB2 expert operators and in reference to past case studies. HTB2 expert input is based on their knowledge and background of the tool; local experts from the Welsh School of Architecture (Professor Phil Jones, Dr Simon Lannon, and Dr Joanne Patterson) provided helpful input into the building design processing into HTB2, simulation running and planning methods. Later, energy performance of the research case study will be validated with published work relating to similar buildings, either simulated or monitored. This comparison helped to identify few design flaws and accordingly several adjustments were made.

5.5 Optimisation

Several adjustments and optimisations were made to the research model to reach its current form. These optimisations were the result of uncertainty checking and tuning to achieve zero-carbon status. Although the Passivhaus standards were implemented in this simulation as a design reference, the final results might not comply with the stipulated energy consumption limit. This is because the selected benchmark is the zero-carbon standard, which is required to meet the objectives of this research. These optimisations mostly took place within the model components, walls, roof, floors, and so on, and material properties. Different thicknesses and types of insulations were also investigated to finally arrive at the current settings. The current implementation of polyurethane is based on case studies presented in literature that have successfully achieved zero-carbon levels.

Other adjustments were made to the model design to achieve realistic results. Such as the roof tilt angle and maximisation of the solar area on the southern facing roof (see Figure 5-8). The sources used provided enough information to form the initial design, beginning with the decision to select the detached house type to avoid further on-site variables that may affect the simulation results, for example, heat transfer between joint walls, shade overcasting, orientation, and designating roof area for renewables. Then, the rectangular geometry of the building was based on a RIBA report and survey (Roys 2008; RIBA 2011). A rectangular shaped building would provide additional benefits, such as better solar orientation with maximum allowable area for renewables (see Figure 5-7).

Model location and weather profiles were also optimised to achieve a valid result for this study. Weather data was taken from the CIBSE database for different locations within the UK. In terms of timing, the weather has proven to be an issue, since current weather is predicted to change in the future due to global warming. The final decision to use the current design year from the CIBSE was taken, since this would satisfy the objectives of the present research without any further complications or uncertainties added. Furthermore, the location for the simulation was selected according to the weather data availability and geographical relevance.

In order to meet the zero-carbon building standards, a specific selection of renewable on-site energy sources must be utilised. Several options were available, such as solar PV, solar thermal, wind, ground and air source heat pumps. Due to irregularity in performance, limited output ability, or location restrictions, several of these sources were excluded from the final simulation model such as GSHP, ASHP, and wind energy. Solar PV energy was selected due to its efficiency, predictability, adaptability, and availability. Furthermore, solar PV panels are the only on-site energy generator that is capable to produce enough energy to drive most thermal storage mediums selected in this study into reaction. With a maximum allowed area for this source on the roof of $40m^2$, it can confidently generate an annual energy levels that help achieve the zero-carbon house state along with all of the other selected design features.

Finally, internal energy loads and operational performance of the building were optimised after examining several available options. Selecting the model's occupancy properties was the first issue that needed to be addressed. While national surveys would provide good insight into average housing occupancies, occupants' behaviour proved to be difficult to predict, due to its stochastic nature. Therefore, common patterns identified in local case studies were used to optimise the simulation model. Appropriate differentiation between weekdays and weekends was integrated on an hourly level in the occupants' schedule to better predict internal loads and operational performance. In further research, sizing and optimising water heating demands, both daily demand and hourly demand figures, would provide more accurate results. The benefit of calculating the DHW hourly demand is to measure the hourly thermal demand compared with the hourly on-site energy supply and determine whether a TES system or grid energy would compensate for any deficit.

5.6 TES design parameters

Thermal energy storage (TES) system design parameters and materials included in this research will be detailed under this section. Furthermore, several TES technologies will be presented under this section as well to investigate the possible potential in domestic applications. The main factors that should be taken under consideration in designing a domestic scale TES system would be size, storage material, operation cycle, and storage container design. These design parameters will be discussed in detail in the following section of this chapter. While there are several other aspects that contribute to the effectiveness of the system such as energy transfer method and conversion, these aspects are related to the technical application of TES system into the building which is beyond this research aim and objectives.

5.6.1 Size

The first aspect of designing any TES system is to set the size of the system to be applicable to the chosen type of building. In this research, domestic scale building will control the size of the TES system implemented in this simulation. While the storage size is material and technology dependent as well, further investigation is required via published work. To determine the range of sizes that corresponds to domestic application, a review to different publications, technical specification, and guidelines have to be conducted first.

Hot Water Association has released a TES guideline to define thermal specification of thermal stores. This guide provides initial understanding of the domestic TES systems. The guide also provides a TES size estimation based on application, thermal demand, and service area. This estimation method can provide a base start to both sensible and phase change. This estimation method is illustrated in Figure 5-14. Although this guide provides a separate reference for each TES system according to the energy input method with minimum size requirement, the maximum size limit remain undefined.

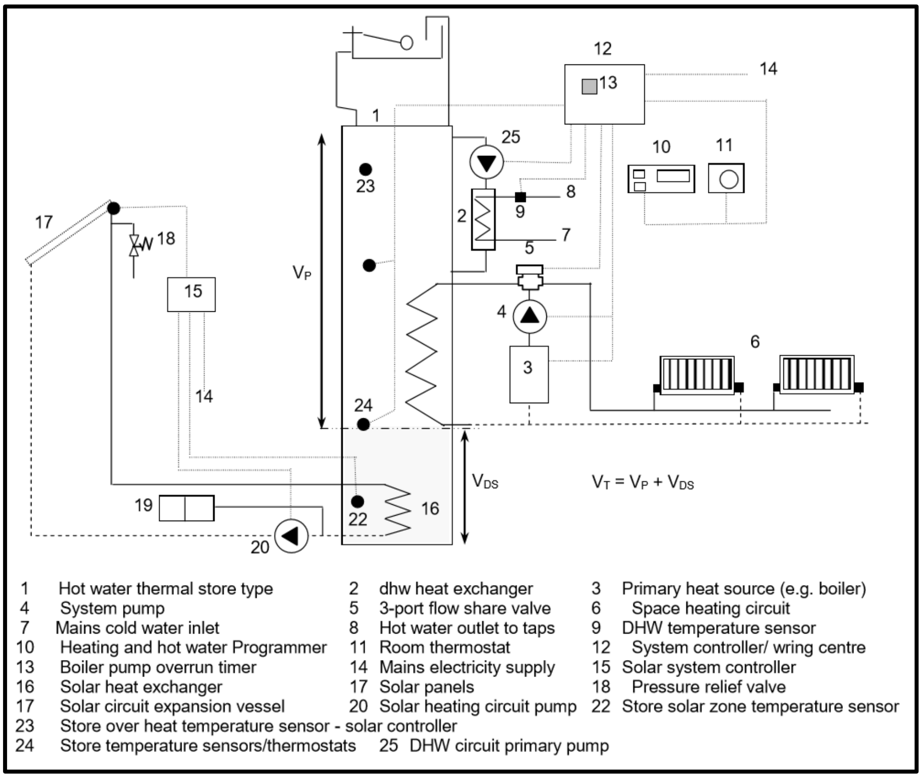


Figure 5-14: schematic of TES system integrated with solar PV (Hot Water Association 2010)

Further details can be taken from case studies projects that implement domestic scale TES system. In published research report from UK Energy Research Centre (UK ERC), volumetric size requirement of a single dwelling domestic building that utilise sensible materials can range between 2.6 m^3 to 0.56 m^3. The same study estimates PCM storage to demand two thirds of the sensible storage system. Although the case study used in this research is utilising TES for space heating only, it integrates on-site energy source (ground source heat pump) as the main source of stored energy (Eames et al. 2014). Other case studies from UK have shown that the preferred domestic TES size can range from 0.5 m^3 up to 3.2m^3 which is similarly consistence with the previous report (REFocus 2004; Barratt Developments PLC 2007b; Energy Saving Trust 2012; Welsh Government 2012; Bere:architects 2014).

To meet this research's aim and objectives, different volumes of TES system will be tested. These volumetric sizes will range from 0.5 m^3 to 3.0 m^3. The selection of this specific range comes from the reviewed literature and UK's common practice in high energy performance buildings. While the TES size is initially limited within this range, investigating several materials and storing technologies may propose an alternative volumes and capacities. This range will determine the initial starting simulation modelling for TES systems then adjusted accordingly.

5.6.2 TES material and thermal capacity calculations

Since the main objective of this research is to investigate the possible TES system input in zero-carbon domestic buildings, different materials and storage methodologies will be included in the simulation. Starting with the sensible thermal energy storage methods which can be considered as the most basic and commonly practiced in the building industry in the UK. In addition, different PCM materials with different thermal properties will be investigated as well as thermochemical materials. Comparing different technologies in terms of thermal performance and storage capacity under the same operational conditions will determine each system efficiency.

Sensible TES system

Sensible materials currently used in buildings in the UK range from solid materials like concrete or rocks, to liquid materials such as water (Chan and Russel 2011). While water has the highest thermal capacity of any sensible material commonly used in the UK, it has an affordable initial and operational costs as well. For these reasons, it will be included in this research's simulation along with concrete (see Table 5-7).

Table 5-7: thermal properties of water and concrete (Dincer and Rosen 2010; Chan and Russel 2011)

Material	**Mass**		**Energy density**	**Melting temp.**	**Latent heat enthalpy**	**Specific heat** (kJ/kg.K)		**Volumetric thermal expansion (%)**	
	Liquid	Solid	(kWh/m^3)	(°C)	(MJ/m^3)	60°C	90°C	60°C	90°C
Water	1000	916	53.97 (@60°C) 92.14 (@90°C)	0	334	4.2	4.2	0.028	0.053
Concrete @90°C	-	2240	52.73	-	-	-	1.13	-	-

To calculate the water's heat capacity or any other sensible material, the formula from section 3.2 is used in this study. While water's specific heat capacity is a predetermined value of 4.2 kJ/kg°K, other materials can be calculated using the same equation given heat capacity values.

PCM TES system

PCM thermal storage system's simulation method has to count for material phase changing stage which requires more energy to store while temperatures remain steady. This stage can be expressed as latent heat enthalpy (kJ/kg). The overall progress of storing thermal energy into a PCM material goes through three stages: sensible, latent, then sensible again after the material completes phase changing stage (see Figure 5-15). To determine the amount of energy can be stored in any PCM material, the following formula must be used (derived from the main formula from section 3.3.3):

$$Q = Q_1 + Q_2 + Q_3$$

Or:

$$Q = [C_{ps} \times m_1 \times (T_m - T_1)] + (m_1 \times H) + [C_{pl} \times m_2 \times (T_2 - T_m)]$$

Where:

- C_{ps} is specific heat capacity of solid phase material (kJ/kg K)
- C_{pl} is specific heat capacity of liquid phase material (kJ/kg K)
- m_1 is solid material's mass (kg)
- m_2 is liquid material's mass (kg)
- H is latent heat enthalpy (kJ/kg)
- T_1 is initial temperature (K)
- T_2 is final temperature (K)
- T_m is melting point temperature (K)

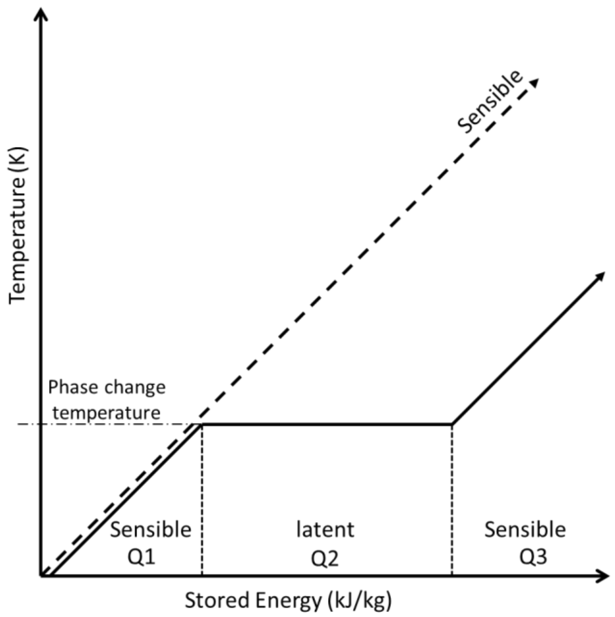


Figure 5-15: thermal energy storage in sensible and latent materials

PCM materials used in this research are based on reviewed literature that investigate the performance of these materials under controlled conditions to determine their thermal properties. Table 5-8 shows the selected materials used in this research and the thermal properties of each one. Further assessment to the performance of each material will be measured after implementing these materials into the simulation runs.

Table 5-8: different PCM materials and their thermal properties (Hirman et al. 1994; Ukrainczyk et al. 2010)

Material	Specific heat kJ/(kg·K) C_{pl} liquid	C_{ps} Solid	Latent heat enthalpy kJ/kg H	Mass kg m_l liquid	m_s Solid	Melting temp. °K T_m	Thermal conductivity W/(m.K) λ_l Liquid	λ_s Solid	volumetric thermal expansion ΔV %
paraffin wax C20	2.5	2.95	248	769	912	36	0.6	0.21	0.077-0.124
paraffin wax C25	2.5	2.95	184.48	775	915	54	0.6	0.21	0.075-0.125
paraffin wax C30	2.4	2.97	173.6	799	916	66	0.61	0.21	0.072-0.12

Thermochemical TES systems

Thermochemical TES systems can be classified into two main categories depending on their energy storage method which are: adsorption and absorption. Since adsorption method main applications are for cool thermal energy storage, it will be excluded from this research and only absorption methods are implemented. Several materials present a feasible potential for TES as an absorption method such as zeolite and silica gel (Chan and Russel 2011).

Since heat capacity of any thermochemical material depends on the material structure on a molecular level, these materials can be highly effected by the used manufacturing process. The source of the material and how porous the material's surface affect the heat storage performance expected (Chan and Russel 2011; Johannes et al. 2015). Therefore, predicting the performance of such materials would require a specifically selected type of material that been tested under controlled conditions as presented in section 3.4 and 3.4.4. Reviewed literature presents several options that has a certain level of performance and been tested to determine thermal energy storage capacities.

Table 5-9: thermochemical TES materials selected in this research and their thermal properties (Chan and Russel 2011; Yu et al. 2014; Johannes et al. 2015)

Material	**Energy density** (kWh/m^3)	**Heat of adsorption** (kWh/kg)	**Density** (kg/m3)	**Desorption temp.** (C)
Silica gel	63.88	0.09125	710	90°
Activated carbon	135.2	0.65	208	100°
Natural zeolite	103.5	0.075	1380	130°
Zeolite (AQSOA-Z02)	150.8	0.29	520	135°
Zeolite (A5)	142.5	0.19	720	150°
zeolite (13X)	226.8	0.36	≈ 700	150°
Salt hydrate ($CaCl_2.2H_2O$)	351.5	0.19	1850	95°
Composite ($CaCl_2$/Vermiculite)	347.26	1.17	-	95°

Table 5-9 show the selected types of thermochemical materials that will be included in this research's simulation. These materials will be used as a storage medium with water as the working pair. In the discharging cycle, water will be introduced to the storage tank in the form of vapour at ambient temperatures. The released heat is then transferred from the system via heat exchanger. The charging cycle operate in the reverse order. Thermal energy in the form of heat is transferred into the storage tank from a heat exchanger to separate the sorbate (storage medium) and sorbent (water). Water released from the storage tank will be in the form of vapour. The whole operation is run under vacuum pressure to reduce energy waste during discharging phase. The heat exchanger that drive heat in and from the system is assumed to have a COP (coefficient of performance) of 1 so the heat gain and loss is eliminated.

The thermochemical desorption reaction requires a precise temperature to occur. The desorption temperature is dependable on the nature of the thermochemical reaction and working pairs in that reaction. In this study's sample of thermochemical energy storage system, the range of temperatures required falls between 90°C and 150°C. While sensible heat and PCM TES systems can benefit from MVHR system returned heat if the storage temperature is below 90°C, thermochemical TES cannot utilise MVHR energy due to its low temperatures. In the case study TES system design, solar PV panels will be the only source of energy to drive the desorption reaction.

5.6.3 Heat loss factor

Heat loss from any thermal storage system poses a limiting factor of application. Therefore, reduced heat loss will produce a more effective TES system. The main causes of heat loss in any TES system would be the results of storage container insulation levels. Depending on the size and U-values of this container, heat losses can be measured and counted for in virtual environment. Although predicting TES heat loss is viable, setting acceptable loss limitations should be minimal. While TES systems in the UK lack current regulatory standards, several organisations have guides published to set heat loss limits and to help TES system designers predicting the output performance of any systems.

Hot Water Association guide named "Performance Specification for Thermal Stores" published in 2010 provides a TES heat loss method of good practice. This guide is directed to serve domestic scale TES systems that been used for providing DHW and space heating. Which in conclusion fulfils this research's requirements. The proposed prediction method can be expressed in the following formula (Hot Water Association 2010):

$$Q_{HL-MAX} = 1.28 \times [0.2 + (0.051 \times (V_T))]$$

Where:

- Q_{HL-MAX} is maximum heat loss per day (kWh/day)
- V_T is the volume of the TES system

This formula is proposed to set the maximum limit of heat loss in which the designed TES system should not exceed if the storage temperatures range between 60°C to 90°C. In this case study, this formula is used to predict the heat loss from sensible heat and PCM TES systems. Furthermore, an estimated heat loss calculation will also be carried in this study to measure heat loss. Assuming the TES container is cubic in shape with an equal area of exposure on every side, a known thermal conductivity of the walls of the enclosure (R-value = 8 W/(m^2K), and air temperature surrounding the TES is 20°C, this study can measure the heat loss according to the storage temperature for sensible and PCM TES systems. The formula used is as follows:

$$Q_{HL} = \left(\frac{a}{R - value}\right) \times (\Delta T) \times 24\ hr$$

Where:

- Q_{HL} is heat loss per day (kWh/day)
- a is the surface area of exposure for heat loss (m^2).
- *R-value* is the thermal resistance of the storage container's material (W/(m^2K))
- ΔT is the temperature difference between the internal of the storage and the surroundings (°C).

5.6.4 Energy flow direction

Thermal and electrical energy flow in this research can be in one of two directions. The first is the charging phase where the energy flow towards the TES system and there is no thermal energy demand. On the other hand, the other direction is intended to meet the thermal demand of the simulation model either from renewables and/or TES system. This method of energy flow prioritizes meeting thermal demand over thermal storage and will help storing energy over both diurnal and seasonal cycles. Furthermore, this method will provide a shorter response time in meeting the thermal demand and avoid rapid TES charge/discharge (N'Tsoukpoe et al. 2009; De Boer et al. 2014).

While the concept of charging the thermal energy storage directly is valid to most storage mediums, the generated amount of heat from on-site energy sources cannot reach the charging temperatures of some thermal storage mediums. the storage mediums that require certain range of temperatures to react are the thermochemical storage mediums (sorption and salt hydrate). Furthermore, the temperature rise required for each medium is different than the other (see Table 5-9). This temperature rise is beyond the ability to reach by MVHR but well within the range of both solar thermal collectors and solar PV panels (Chan and Russel 2011).

In this research's case study, the energy flow for the charging cycle will be conducted according to the thermal storage medium used in the system. If the medium used in either sensible heat or PCM, then the energy flow for the charging cycle will start from solar PV panels and MVHR into the TES system while the discharge is from solar PV, MVHR, and TES to demand. On the other hand, if the storage medium is thermochemical (sorption or slat hydrate), the energy flow of the charging cycle will be from solar PV only to TES system while discharge cycle is identical to the previous method. Figure 5-16 illustrates both methods in accordance to the TES system.

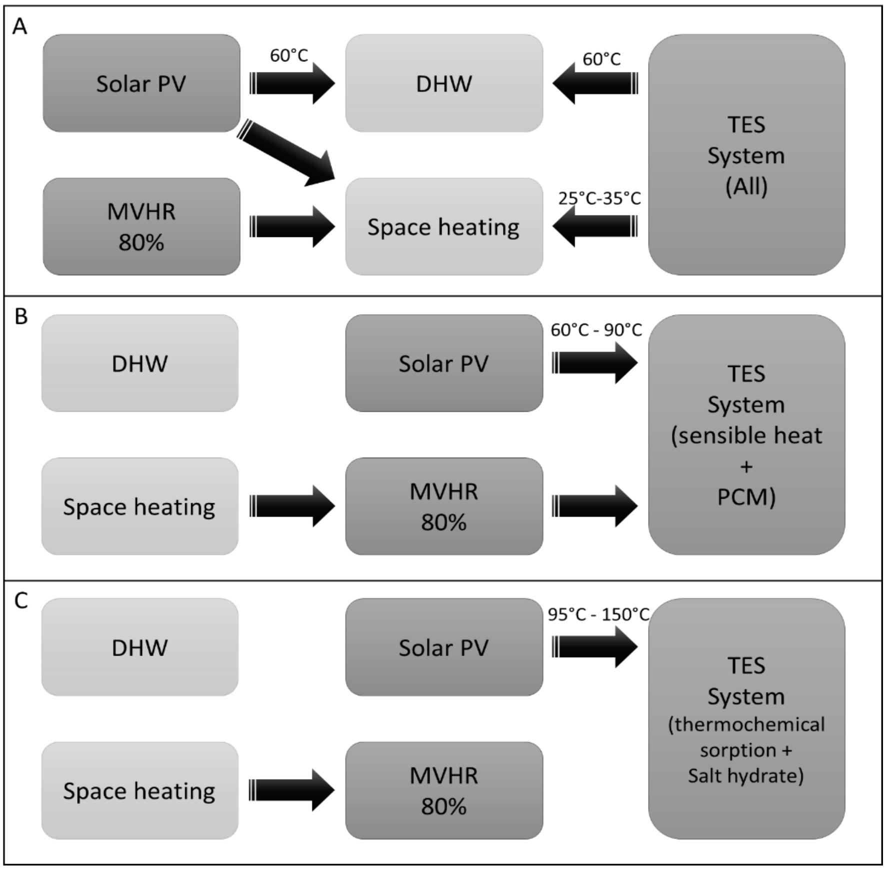


Figure 5-16: energy flow schematic A) discharging cycle and B) charging cycle for sensible heat and PCM, C) charging cycle for thermochemical storage

5.6.5 TES system design

To simulate the performance of TES systems in the case study, two system designs were developed including multiple control points and temperature settings. These different control points were arranged to control the amount of thermal energy channelled to and from the living space and the DHW tank. The first system design was developed for a sensible heat storage system and PCM, since the required storage temperatures were either 60°C or 90°C, based on the selected medium and pre-set testing temperature. In this design, the primary source of thermal energy is an electrical heater operated from 40m2 solar PV panels, and the secondary source of thermal energy is the MVHR system return. The quantity of energy return is calculated based on an efficiency rate of 80%, ranging between 25°C and 28°C. Figure 5-17 shows the first system design schematic and the operating temperatures set.

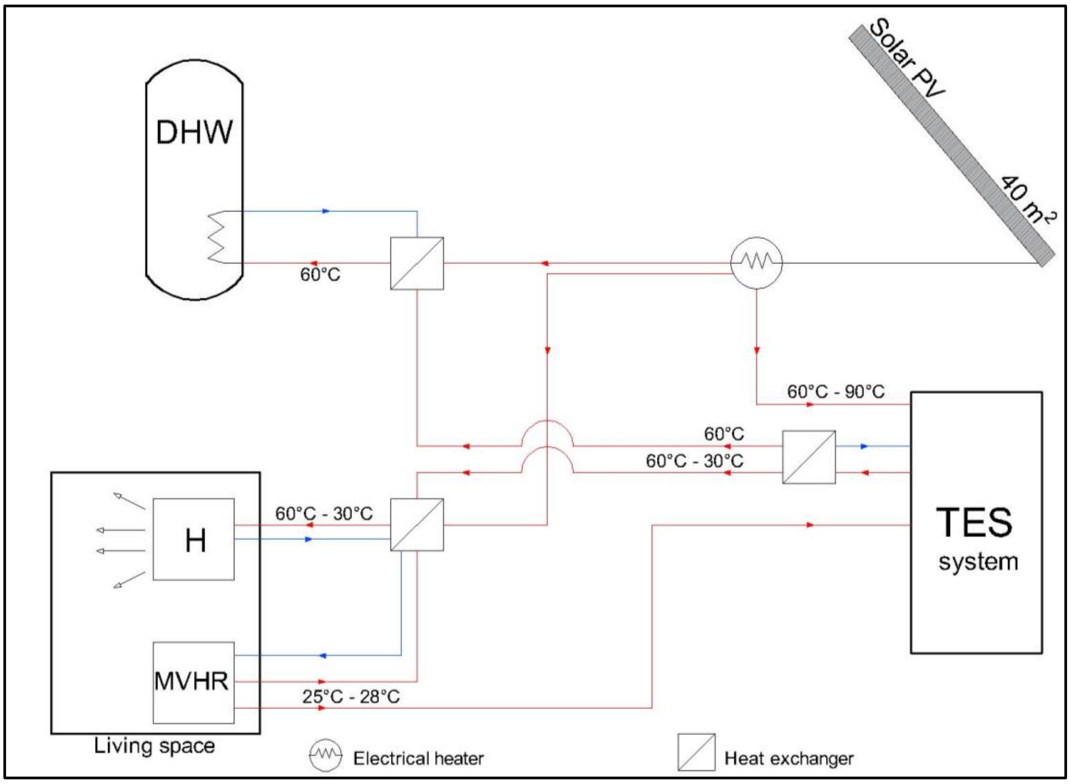


Figure 5-17: case study's sensible heat and PCM TES system design

The second system design was developed to operate with thermochemical energy storage mediums, which require a relatively higher temperature to react and initiate the charging cycle. The significant differences between the first and second system design are the charging temperatures arising from the solar panels and the energy supply from the MVHR system. Since the storage medium used in the second system design (thermochemical) requires a specific temperature to start a charging reaction, a low and gradual rise in temperatures from the MVHR holds no benefit for the TES. The return form MVHR will be utilised in space heating only. Furthermore, the output temperatures generated from the electrical heater attached to the solar panels will be higher than in the first design. The temperature range is then from 90°C to 150°C, depending on the properties of the storage medium. The higher the temperature required the higher the energy to be fulfilled by the solar panels. Figure 5-18 shows the second system design for the thermochemical energy storage system.

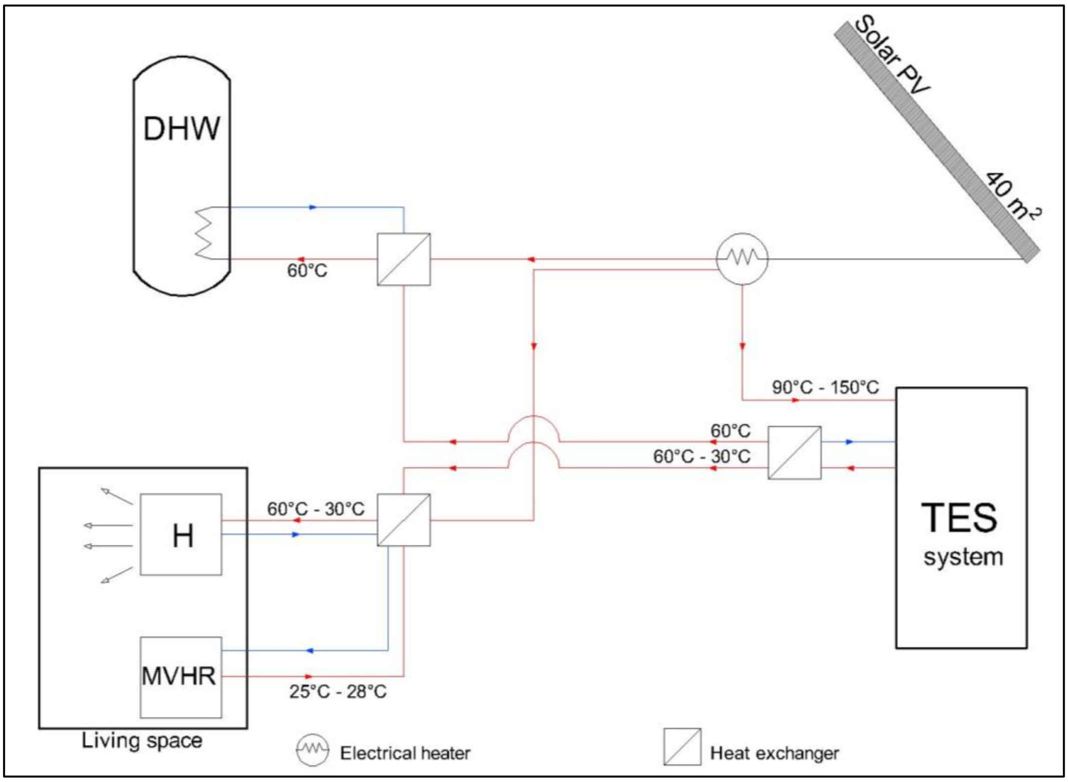


Figure 5-18:case study's thermochemical TES system design

The designs for the first and second system share the same thermal energy demand but differ at the supply level. Furthermore, both systems output temperatures that are set at the same temperature (60°C), in order to compare the performance of all the TES systems running under the same conditions. While the overall system design includes energy sources, control points, and energy demand conditions, the TES storage element is a major component of the system design. In this case study, TES storage was selected for all thermal storage mediums, and is in the form of a bulk storage tank, which will host all materials and working pairs in the study. Furthermore, the heat transfer method from and to the storage tank will be by utilising a heat exchanger through conduction from the storage boundaries rather than exchanging heat from the storage internally. Although this method raises several issues regarding heat distribution and extrusion, it was chosen to help determine the capacity and volume requirement per TES medium without modifying the storage tank. The bulk storage method is applicable to domestic scale buildings without further adjustment, but the benefits of heat distribution will increase the efficiency of the output from the TES medium. And since the system design limits energy output to 60°C, the effects of other storage methods and improvements (such as micro-encapsulation, heat sinks, fins, etc.) will not alter the results describing the total energy capacity of the system.

5.7 Summary

The process of creating a simulation model presented several issues that must be addressed before initiating simulation runs. These issues vary from model design and planning decisions, to setting heating and energy load parameters during each simulation run. Whilst creating a virtually functioning model is relatively simple, a model that accurately predicts zero-carbon results is more challenging. Several uncertainties must be addressed and eliminated in order to achieve reliable results. The first factor to address is the location of and weather data for the simulation model. By selecting a suitable location in the UK, weather and solar data can be predicted and accounted for in the simulation runs and thus increase the accuracy of the simulation outcomes. For this study, Cardiff and London were selected to fulfil this category, drawing on currently available location data.

The physical attributes of the simulation model have also been investigated in this chapter. It is important to construct a realistic model in order to provide results that reflect as closely as possible an actual zero-carbon building under the same circumstances. The model must represent the physical attributes of an average UK detached domestic building, and using an actual building plan taken from national surveys satisfied this requirement. Furthermore, the building size and number of occupants set in the simulation is a response to relevant UK national surveys.

The energy demand parameters of zero-carbon building have been examined thoroughly to ensure the simulation model would achieve an efficient and realistic performance and demand. The selected properties of small power appliances, lighting, HVAC, and DHW were informed by various sources and literature. Most importantly, complying with high efficiency regulation from UK local authorities, building regulations, and energy guides was an important factor in determining the energy demand parameters for this simulation model. Furthermore, limiting the thermal energy demand of the simulation model to meet the requirements of the zero-carbon principle also contributed to the setting of these parameters.

Acknowledging present and potential uncertainties in the simulation model can improve simulation results and credibility. Most of the physical and design uncertainties have been identified through reviewing literature, and validating with case studies during the initial simulation runs. However, scenario uncertainties posed more of a challenge, as these include occupancy related behaviour. Simulating occupants' daily schedule is feasible with HTB2, but accounting for occupants' consumption levels proved difficult due to the random and stochastic nature of this factor. Other scenario uncertainties, such as weather data accuracy and climate change, have been dismissed since they fall outside of the scope of the research aim and objectives.

Lastly, setting TES system design parameters and selected storage method determine the system performance under domestic scale operation. Predicting TES system performance will require a database of technical specification of different TES materials, sizes, and storage methods. This database is from reviewed case studies which will form the base of TES system performance calculations in this research. Further on, storage heat loss must be acknowledged and counted for in the simulation runs.

In conclusion, this chapter has provided a brief but detailed analysis in relation to creating and setting a simulation model. Furthermore, different aspects of the model design have been investigated and design decisions have been justified accordingly. Performance parameters and internal thermal energy demands have been identified and set in accordance with current regulations, while complying to high efficiency standards. In addition, simulation modelling uncertainties have been explored, suggesting potential optimisations and adjustments to achieve the research objectives and aim. Finally, TES system design parameters investigation and selected materials have been included to help predict domestic scale TES system performance for this research.

6 Results

This chapter discusses the results and findings of the previous chapters regarding the zero-carbon building simulation and TES modelling. Furthermore, it also presents a detailed analysis of the results concluded. The first section presents the results for the energy performance of the zero-carbon building simulation (section 6.1). The second section shows the modelled TES systems and compares the performance between the different simulated systems (section 6.2). The third and final section is then dedicated to discussing design elements and factors effecting the performance of the TES system model (section 6.3).

6.1 Building energy simulation results

The following section outlines the details of the simulated building model, giving its performance over diurnal and seasonal cycles. Furthermore, it provides the thermal energy performance for the simulated model, in conjunction with its compliance to Passivhaus standards and as a zero-carbon house as well. By analysing the general thermal demand initially, figures were obtained providing information regarding the possible input supply from renewables. Subsequently, a detailed investigation into space heating energy and DHW demand is outlined. Finally, a thermal energy performance analysis, encompassing both diurnal and inter-seasonal cycles is included to determine energy levels and the patterns that emerged in the simulated model.

6.1.1 Thermal energy demand

The simulation model for this research is based on the standards of Passivhaus, which provide a benchmark for net zero carbon buildings. The simulated model's annual operation under domestic conditions complies with both standards (Passivhaus and zero carbon). Moreover, space heating demand summed to 2573.3 kWh/year without energy feedback from the MVHR system, reducing the total heat demand to 1419.1 kWh/year. The annual space heating demand per area would be 13.9 kWh/m^2.year, which is within the basic requirements for Passivhaus standards (less than 15 kWh/m^2.year). Furthermore, the space heating demand are well within the zero-carbon limit of 25 kWh/m^2.year. Table 6-1 summarises the figures for performance in the energy simulation.

Table 6-1: Simulated model's annual energy performance

Energy type	Space heating	Space heating with MVHR	DHW	Thermal demand	Solar energy	MVHR	Excess energy	Grid supply
Annual energy (kWh/year)	**2573.3**	**1419.1**	**2739.6**	**4158.7**	**6200.1**	**3048.6**	**3935.7**	**1724.1**
				(Space heating with MVHR) + (DHW)			(solar energy + MVHR) – (space heating + DHW)	

Although the annual energy figures from the simulation show relatively low thermal energy demand and high input from renewables exceeding demand, a grid dependency is apparent. This grid supply results from the mismatch between demand and supply peak loads. Furthermore, although zero carbon house standards allow for some grid dependency (which can be offset by energy production), total energy independence from the grid is possible relative to on-site energy generation. A further investigation will therefore be carried out in the following sections, to determine those factors influencing demand.

6.1.1.1 Space heating energy demand

As the simulated model location is in the UK, some space heating demands are expected. Although demand is reduced by the model design and by implementing Passivhaus standards, space heating is necessary during the winter and early months of spring (November to March). Furthermore, energy returned from the MVHR system into space reduces the space heating demand by 45%. The rating for heat return from MVHR system is assigned as 80% (as required by Passivhaus standards). In addition, the simulated heat loss due to mechanical ventilation is approximately 3810 kWh/year without heat recovery system. Heat returned from ventilation via the MVHR system is 3048 kWh/year, which is higher than the overall space heat demand of 2573.3 kWh/year. The majority of the heat extracted by the MVHR is extracted during times when low to no heat demand is present.

Figure **6-1** shows the annual total thermal energy demand for space heating and domestic hot water. Furthermore, Figure 6-2 shows the annual space heating demand compared to energy returned by mechanical ventilation heat recovery (MVHR) system.

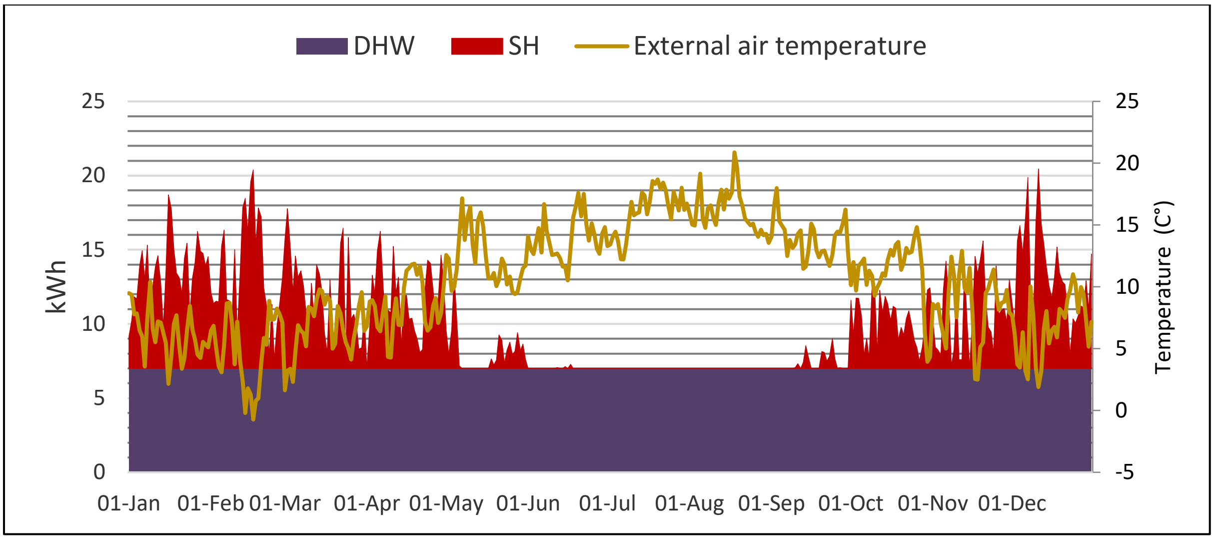


Figure 6-1: daily thermal energy demand results (space heating and DHW)

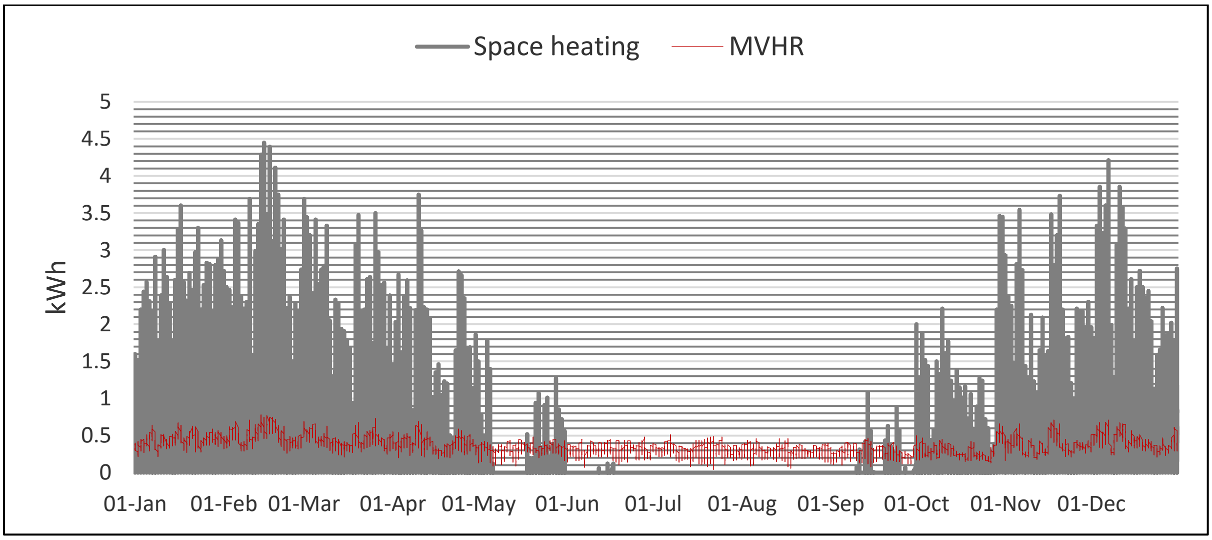


Figure 6-2: hourly space heating demand and MVHR energy return

6.1.1.2 DHW demand levels

Since the domestic hot water demand figures used in this research result from post simulation input based on surveyed data, the general demand figures are generated external to the simulation run. Furthermore, the input of the DHW demand is used to calculate hourly demand levels alongside diurnal, seasonal and annual figures. The general demand figures can also be illustrated in figures 1 and 5. Daily demand level is in the region of 7.5 kWh/day, which complies with standards issued by the Hot Water Association.

6.1.2 Diurnal thermal energy demand

The energy performance of the simulated model shows several patterns across diurnal cycles. These patterns result from seasonal weather changes and daily weather conditions. Several days were selected to represents the sky conditions during winter and summer months along with the change in thermal energy demand. Furthermore, the selected days also show different sky conditions (either clear or overcast) to illustrate the effect of sky conditions on the thermal demand and the ability of on-site energy generation. These sample days are selected from the weather data file based on the records of whole week with similar conditions to insure temperature stability in the simulation model. The selected summer days are June 29th (overcast sky) and August 15th (clear sky). Further on, winter days are December 29th (clear sky) and January 16th (overcast sky). The simulated performance of these day are presented in Figure 6-3, Figure 6-4, Figure 6-5, and Figure 6-6. These selected days are used frequently in the study's results to compare the operational performance of the case study's model under different weather profiles. Weather conditions that influence the performance are related to the external air temperatures and the amount of solar radiations exposure.

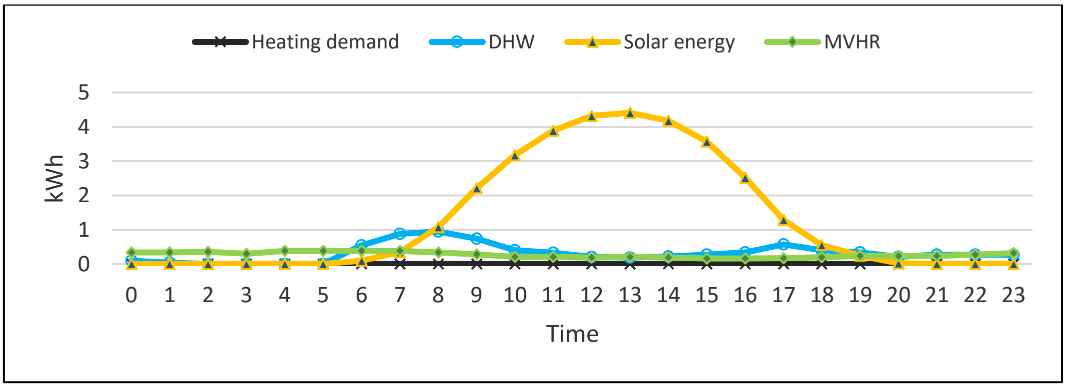


Figure 6-3: energy performance on the 15th of August (clear sky)

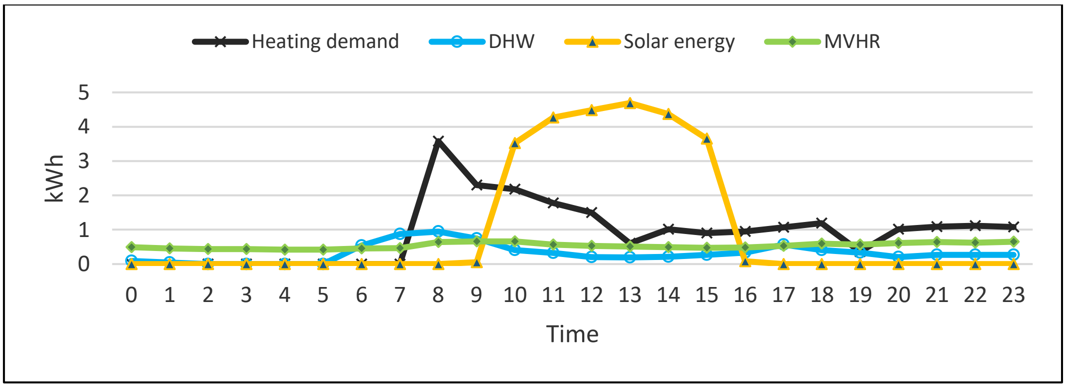


Figure 6-4: Energy performance on the 12th of December (clear sky)

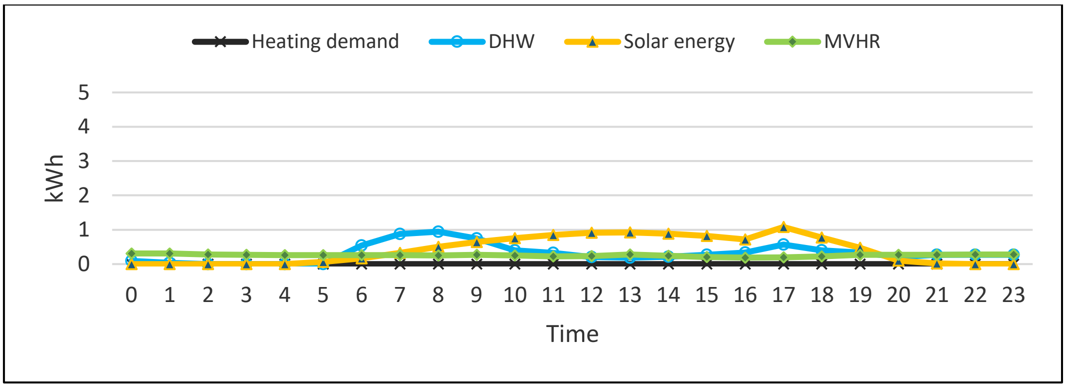


Figure 6-5: Energy performance on the 29th of June (overcast sky)

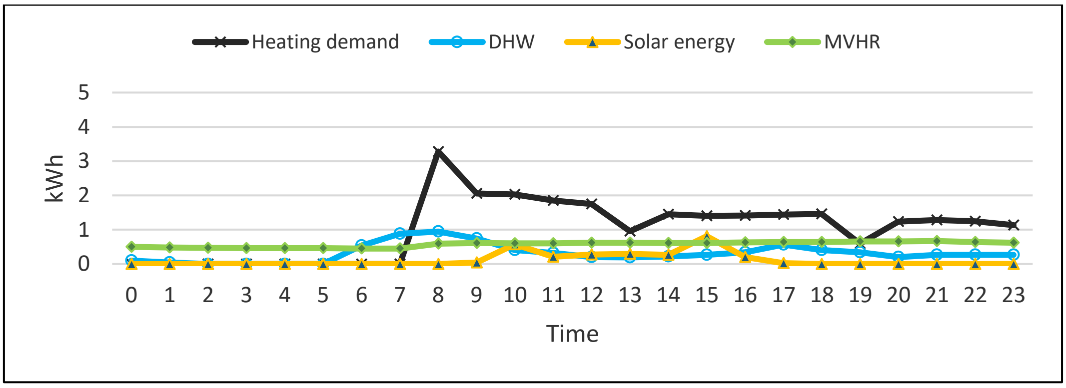


Figure 6-6: Energy performance on the 16th of January (overcast sky)

Resulting from this daily change, solar heat gains and possible input from renewables are effected. In summer months, clear sky raises the solar radiation levels although there are limited thermal energy demand (the only thermal energy demand is required by DHW). In addition, winter days with clear sky also offers solar radiation but for shorter periods and lower energy due to the lower angle of exposure. The return from the solar panels are not enough during the winter months to meet the thermal demand of the case study's building. The same can be observed in the overcast days whither these days are in winter or summer. The solar panels cannot generate enough energy to meet the thermal demand during overcast days. Furthermore, heat recovered from the MVHR system changes according to solar heat gain, internal heat loads, and heater gains. The quantity of energy recovered varies over time, although it remains within expected values, based on a return value of 80%. The highest rate for recovered heat can be observed in the wintertime, when the heater function is activated.

The diurnal cycle of simulated thermal energy of the study's model can be compared to the monitored thermal energy demand from the Camden passive house in London which shows a similar behaviour of increase demand from 6 am to 9 pm especially for space heating and DHW (Ridley et al. 2013). Furthermore, the spike in thermal energy demand starting from 6 am to 8 am in the Camden passive house is associated with the start of the programmable space heater and the water heater running in the morning. In addition to the morning spike, a second spike of thermal energy demand rise after 8 pm which can be contributed to the rise of demand for DHW for showering and dish washing (ibid). It should be noted that the Camden passive house monitored consumption of DHW per resident was less than the average UK consumption levels of 150 L per day per person by 40% (about 98 L per day) (ibid). Figure 6-7 shows the monitored average daily demand for space heating and DHW. The Camden passive house results can be compared to this study's simulated model for the similar construction method and weather conditions. There are several other similarities can be observed from the comparison including the daily energy demand profile (see Figure 6-8). Furthermore, similar energy demand patterns for space heating and DHW also exists between the Camden passive house and the simulated model. The morning spike and the evening spike of thermal energy demand is due to the increased activity of the residents and the operation schedule of the heating system caused these spikes to exist in both houses.

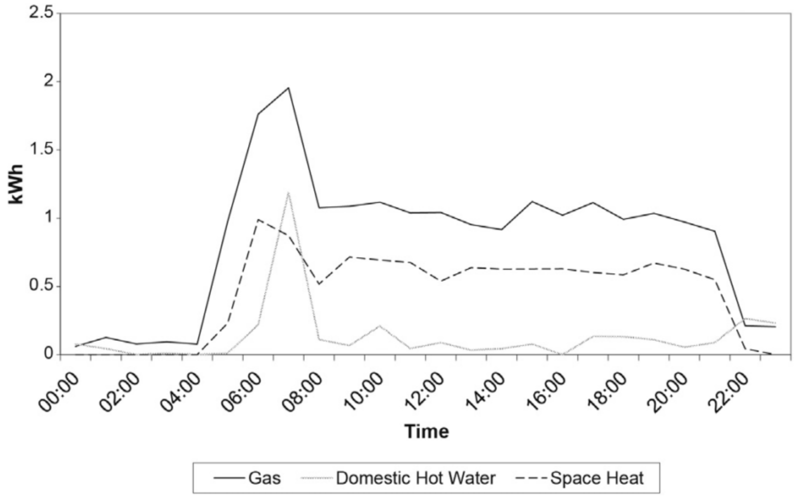


Figure 6-7: Camden passive house in London average daily thermal energy demand profile (Ridley et al. 2013)

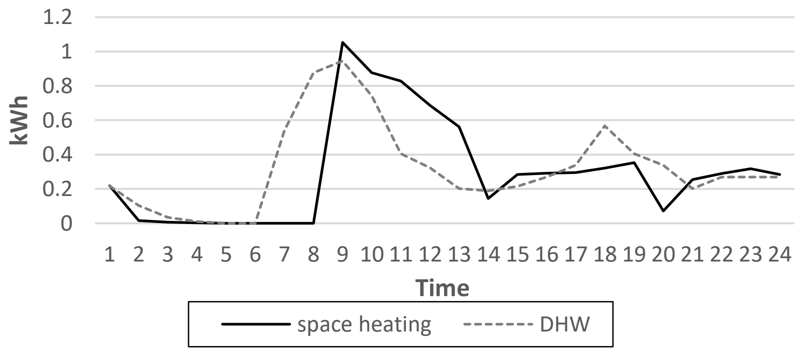


Figure 6-8: simulated building daily's average of thermal energy demand profile of space heating and DHW

6.1.3 Monthly thermal energy demand

The monthly energy performance of the simulation model follows the same trends as those witnessed in the daily figures from reduced solar energy generation and increased thermal demand during winter months. These changes to the energy demand and supply is a cause of the seasonal weather change. While DHW energy demand shows relative consistency, space heating demonstrates different levels, depending on external air temperatures and levels of solar radiation. Furthermore, changes to the space heating thermal energy demand during the simulation period fluctuate in terms of general thermal energy demand. The highest demand was observed during the winter months and in early spring (from November to March). In general, thermal energy demand appears to surpass the supply during the winter months, December and January. On the other hand, the MVHR system performance fluctuates less than space heat demand and solar energy over the simulation period, although there is a noticeable increase in heat recovery during periods when space heat demand occurs. This is due to the recovered heat from the heating system being applied into the space. Figure 6-9 illustrates the monthly energy performance for the simulation model, showing the demand side and the possible energy supply. This figure also shows the increase in energy generation during summer months while this generation is reduced during winter and spring months.

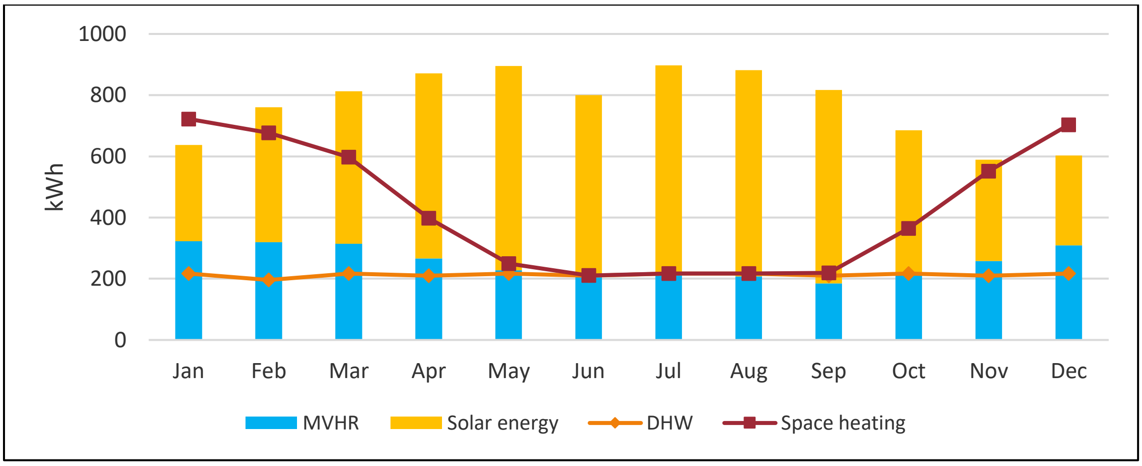


Figure 6-9: monthly energy performance of the simulation model

6.1.4 Overall grid supply

The grid supply occurs when thermal energy demand surpasses the supply from on-site energy sources. Grid supply figures and the performance mark offer important inputs for this study, and these can be used to determine the amount of energy the TES system needs to store. Furthermore, this demand marks the period of time over which energy demand can be met by means other than on-site renewables.

Simulation output data shows increased demand in winter, as a response to the increase in thermal energy demand and the reduction in solar energy available during these months. As a result, a notable spike in grid supply is evident during winter and spring, which corresponds to external weather conditions. These surges in energy demand have a low average of 0.2 kWh, but can signify a high demand of 4.6 kWh (as on the 15th of February). The highest frequency of grid supply occurs during the early morning hours, because of increasing space heating demand, while solar gain and incidental gains are low. Figure 6-10 demonstrates the amount of energy demand and the frequency over the simulation run. Furthermore, Figure 6-11 and Figure 6-12 illustrate two different sample days from winter days (sunny and overcast), energy performance including grid supply. Although energy supply from on-site solar PV is lower than the demand, this reduces the demand from the grid to some degree indicating the need for an auxiliary system during winter to reduce grid supply further.

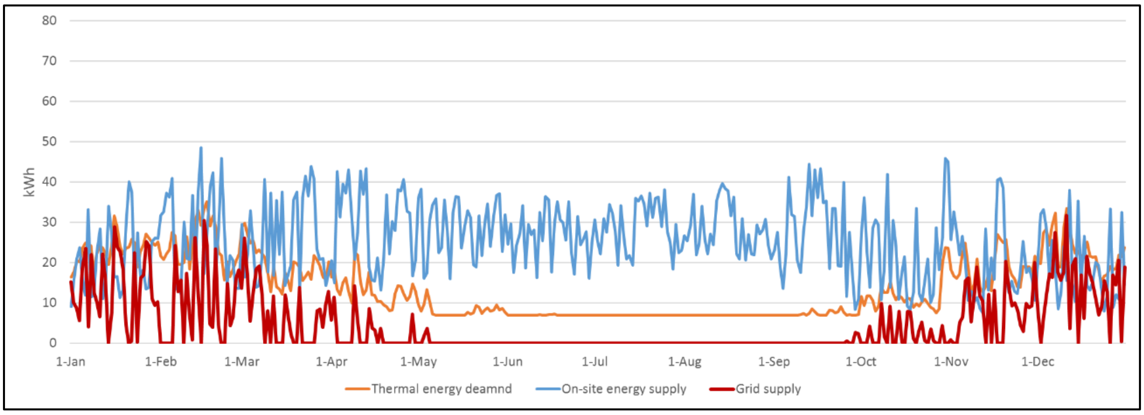


Figure 6-10: Annual grid supply and building's energy performance (based on daily figures)

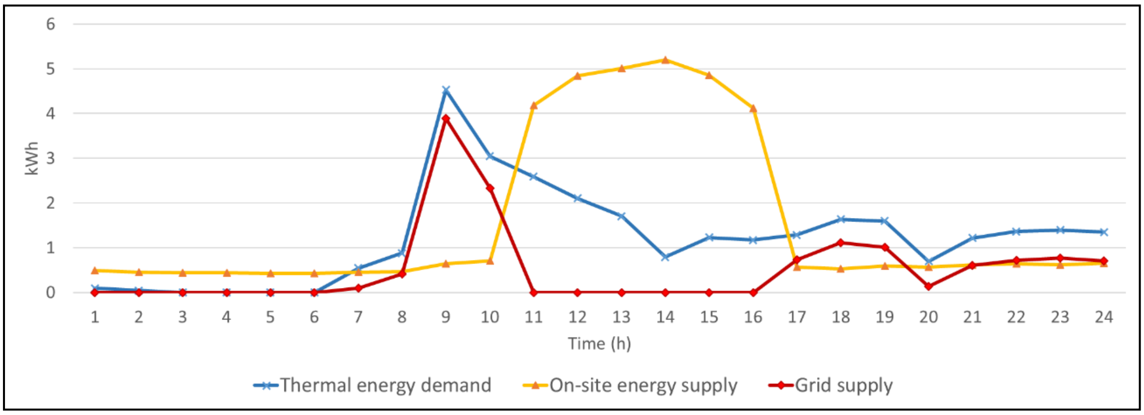


Figure 6-11: Sunny winter's day and grid supply (12th of December)

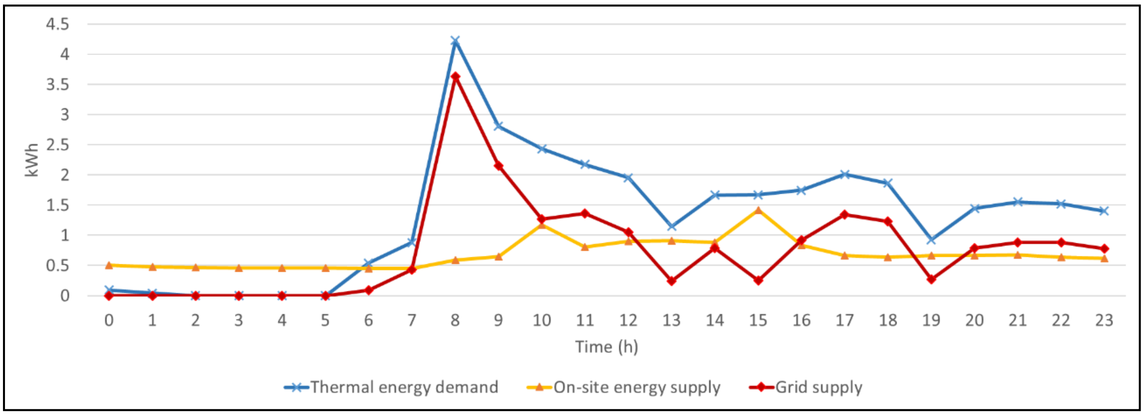


Figure 6-12: Overcast winter's day and grid supply (16th of January)

6.1.5 Overheating compliance

Overheating issues are expected in most high-energy performance buildings, since insulation and air tightness introduce the risk of living spaces and bedrooms becoming overheated during the summer months. In compliance to CIBSE guide A for overheating in domestic buildings, the simulated model reveals that overheating issue is a concern during the period from July to late August.

The total number of hours of overheating in the living room equates to 423 hours of the total 8760 hours of the simulation run. It is also equal to 4.8% of the total time the space was occupied (see Figure 6-13). Furthermore, bedroom overheating totalled 87 hours, which is slightly below 1% of occupancy time (0.9%). While the level of bedroom overheating is within the CIBSE guidelines, living room overheating is higher than recommended by 3.8 percent. The overheating issue cannot be avoided, however, without the implementation of an active cooling system. This confirms results from Ampatzi and Knight (2007) concerning to cooling demand for dwellings in the UK. Furthermore, while overheating is higher than the standards, it is not untypical for an energy efficient building in the UK (Energy Saving Trust 2005; Roberts 2008; Peacock et al. 2010; Ridley et al. 2014). This issue needed to be addressed in the design of zero carbon buildings but since this issue is beyond the scope and objectives of the research it has been excluded.

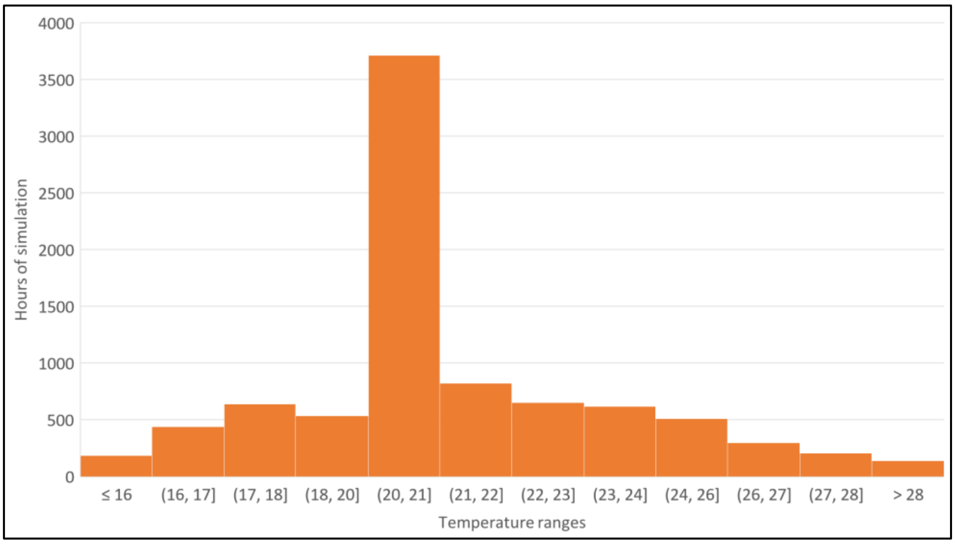


Figure 6-13: histogram of the simulation case study showing temperatures frequency over the simulation run

6.2 TES system simulation results

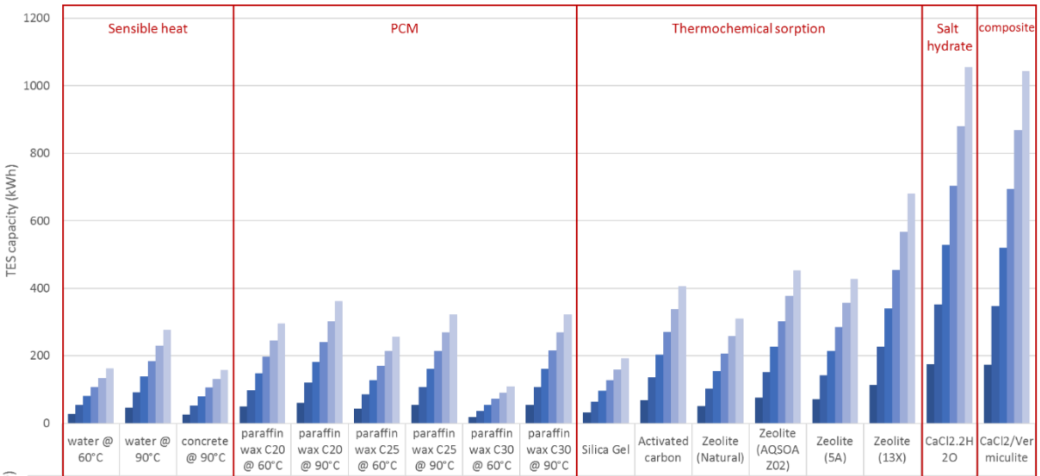
The results for the TES model are introduced in this chapter and are based on the mathematical calculation model presented in the previous chapters. These results are segmented into two parts: TES thermal energy capacity, and TES operational performance in the simulated building. Furthermore, a further investigation will be conducted to determine performance variations when testing different TES systems, based on storage duration, storage heat loss, and finally charging/discharging cycles.

In general, the mathematical calculation process can be conducted in three major steps: 1) calculate the energy storage density of each material, 2) plot storage capacities based on storage size, and 3) calculate the energy deficit and grid supply after TES implementation.

6.2.1 TES system maximum energy capacity comparisons

The TES capacity calculation for the selected mediums is based on the thermal energy density of each storage medium. While variations between different types of TES systems were presented, these variations were predicted due to differences in energy density between types and energy storing methods. For example, sensible heat TES systems have a lower energy density than the other system types, therefore necessitating a greater storage volume to fulfil energy demands. By contrast, salt hydrate and composite systems have the highest energy densities from among the selected mediums, which means they can meet the energy demand with relatively smaller storage volumes. Although the applicability of salt hydrate and its composite systems into domestic applications can be difficult due to the corrosive and degradation nature of these materials. Figure 6-14 illustrates the differences between each of the TES mediums, in relation to the storage volumes. Phase changing materials present a potential for higher capacity TES, although paraffin C30 at 60°C has the lowest energy capacity when compared to all the mediums tested. This is due to the low sensible heat the paraffin C30, which is below the melting temperature of 66°C. Furthermore, paraffin C20 has the highest storage density from among the PCM group under both the tested temperatures (60°C and 90°C).

Sorption TES systems have a higher energy density than sensible PCM systems, while silica gel recorded the lowest density among the sorption group, natural and artificial zeolites varied in terms of storage, depending on their physical properties and manufacturing specifications. Zeolite 13X was ranked highest among the zeolite group and highest among the sorption group in general. Moreover, silica gel has a low energy density in addition to a short operational temperature range, due to the base water content within the silica gel. The limits of operational temperature (charging – discharging temperatures) also limit its usage under domestic applications to cooling applications, where charging temperatures are below 200°C (Tatsidjodoung et al. 2013; Aristov 2015).



Storage volume (m^3)	water @ 60°C	water @ 90°C	concrete @ 90°C	paraffin wax C20 @ 60°C	paraffin wax C20 @ 90°C	paraffin wax C25 @ 60°C	paraffin wax C25 @ 90°C	paraffin wax C30 @ 60°C	paraffin wax C30 @ 90°C	Silica Gel	Activated carbon	Zeolite (Natural)	Zeolite (AQSOA Z02)	Zeolite (5A)	Zeolite (13X)	CaCl2.2H2O	CaCl2/Vermiculite
0.5	26.985	46.07	26.365	49.185	60.335	42.735	53.675	18.19	53.82	31.94	67.6	51.75	75.4	71.25	113.4	175.75	173.63
1	53.97	92.14	52.73	98.37	120.67	85.47	107.35	36.38	107.64	63.88	135.2	103.5	150.8	142.5	226.8	351.5	347.26
1.5	80.955	138.21	79.095	147.555	181.005	128.205	161.025	54.57	161.46	95.82	202.8	155.25	226.2	213.75	340.2	527.25	520.89
2	107.94	184.28	105.46	196.74	241.34	170.94	214.7	72.76	215.28	127.76	270.4	207	301.6	285	453.6	703	694.52
2.5	134.925	230.35	131.825	245.925	301.675	213.675	268.375	90.95	269.1	159.7	338	258.75	377	356.25	567	878.75	868.15
3	161.91	276.42	158.19	295.11	362.01	256.41	322.05	109.14	322.92	191.64	405.6	310.5	452.4	427.5	680.4	1054.5	1041.78

Figure 6-14: TES systems' energy storage in relation to storage volume

6.2.2 Operational performance of TES systems

The results for the TES systems operational performance in the case study simulation are presented here. The obtained results are based on hourly energy calculations, either for diurnal or annual durations. Major points of interest that are represented include annual energy storage levels, grid supply levels, and TES storage size, and are arranged to meet zero carbon thermal demand.

6.2.2.1 Annual energy levels

Annual TES storage levels are presented as a direct response to energy demand and supply from the simulated building in this study. While demand remained constant for the duration of this simulation, due to the ongoing demand for DHW, space heating was the principal factor determining TES storage size. Furthermore, space heating during winter and early spring (from November to March) caused storage levels in TES systems to deplete beyond their ability to recover immediately from a renewed energy supply. In addition, the late spring to autumn period presents a better opportunity for the TES to store energy, due to the increased availability of solar radiation and the reduced thermal demand. Figure 6-15 shows the annual performance for the different TES systems included in this study, based on hourly energy demand and supply provided via the simulated case study.

For 1 m^3 of volumetric storage size, most of the systems depleted completely during the period from late December to late January. An exception was the zeolite 13X, calcium chloride hydrate, and $CaCl_2$/vermiculite composite systems. These three systems maintained low thermal energy storage levels, beyond the increased seasonal demand. On the other hand, sensible TES systems and PCM require a higher storage capacity, to accommodate demand and heat loss as well. The same requirement can be applied to the majority of sorption materials, with the exception of zeolite 13X, which met the thermal demand for under 1 m^3 of storage.

Finally, further investigation of the required storage volume was undertaken, as described in section 6.2.2.5, to ensure the thermal demand for the simulated building could be achieved. This determined the lowest volume required per TES system to meet thermal demand, with no grid energy supply.

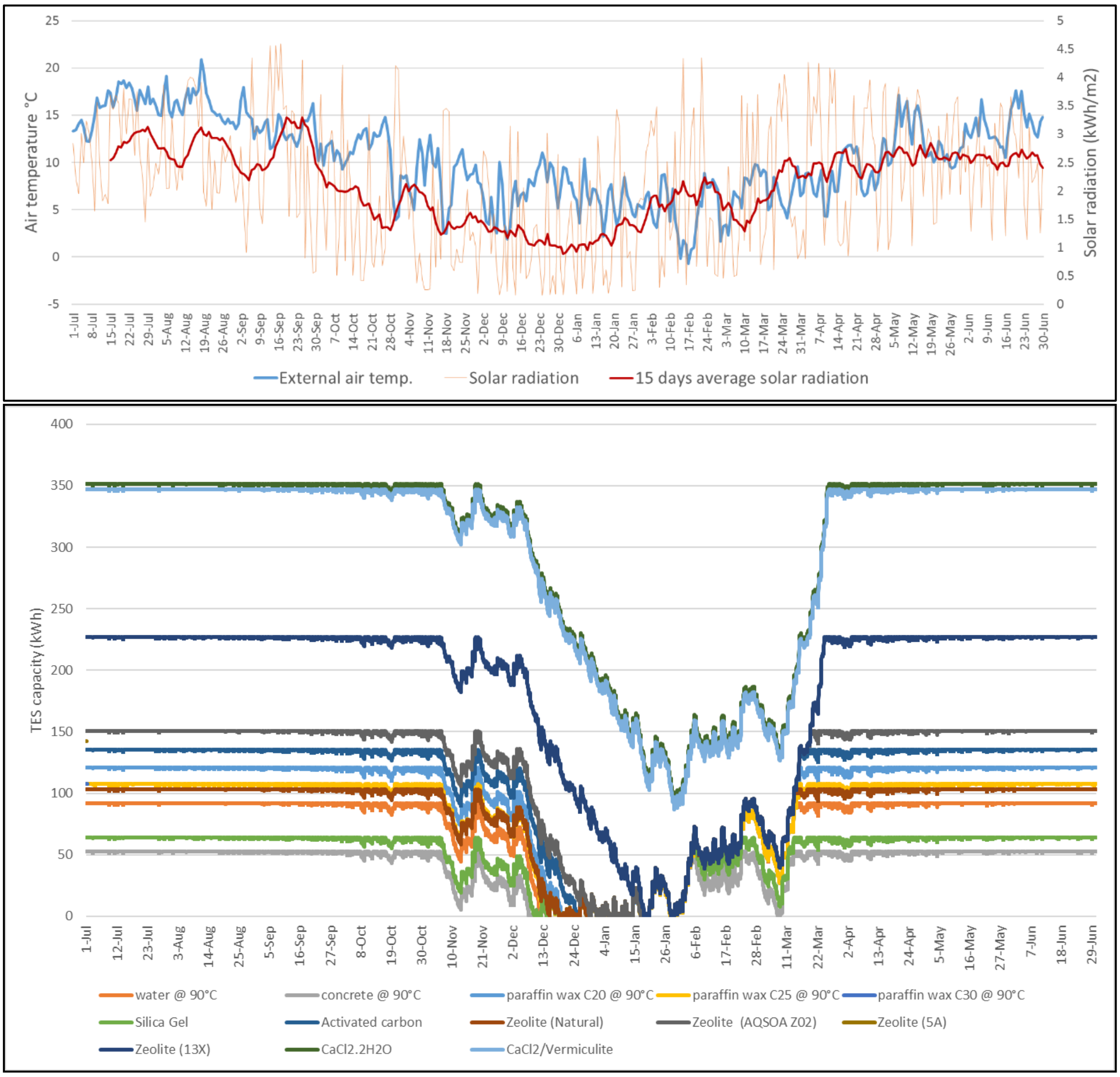


Figure 6-15: Daily external air temp. and solar radiation (top), TES systems annual storage levels for a 1 m^3 of storage volume (bottom)

6.2.2.2 Diurnal energy levels

The diurnal cycle of energy demand and supply takes on a major role when determining TES capacity required to meet thermal demand. The TES storage systems modelled performed similarly in terms of charge and discharge during diurnal cycles. The main factors influencing the performance of the TES systems were thermal energy's fluctuation (demand and supply) over the year during which the simulation was run. For example, when thermal energy demand is low and the hours of exposure to solar radiation are high, the TES system experiences low demand, which reduces energy depletion and increases storage charging significantly. Furthermore, when energy demand and supply are reversed during the winter months, thermal energy storage levels within the TES system dwindle, and it becomes harder to recharge the system fully if these conditions persist. Figure 6-16 and Figure 6-17 depict the difference in TES storage levels over two different days during which there is a low energy supply in winter (winter sample days of clear and overcast sky). Although both charts show TES storage levels drop below the maximum capacities of the TES system, increased discharge is noticeable on the overcast day, since energy supply from solar PV would not then meet thermal demand.

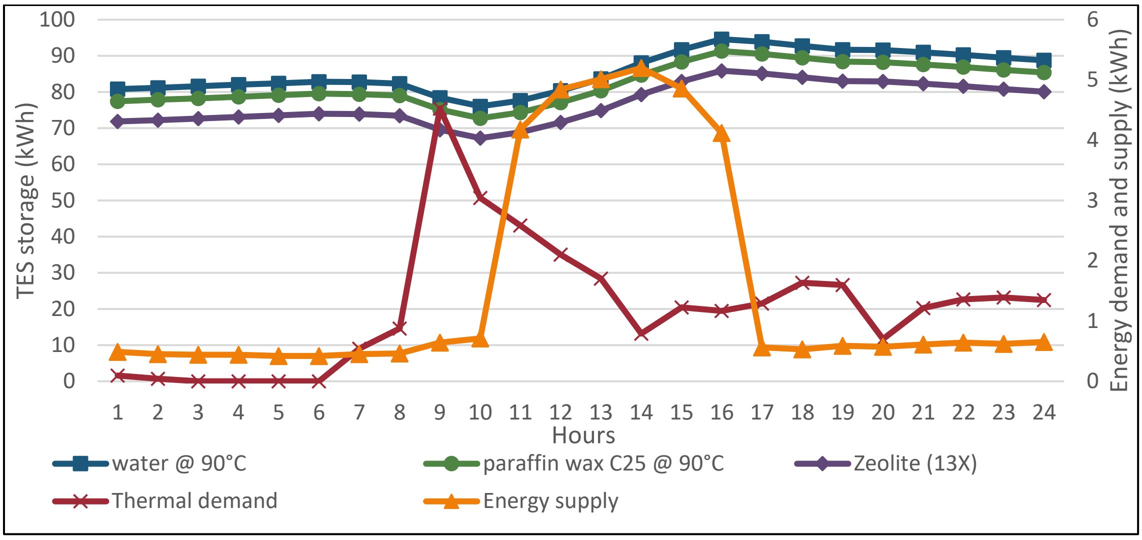


Figure 6-16: TES energy storage levels for a 1 m^3 of volume during a sunny winter day (12th of December)

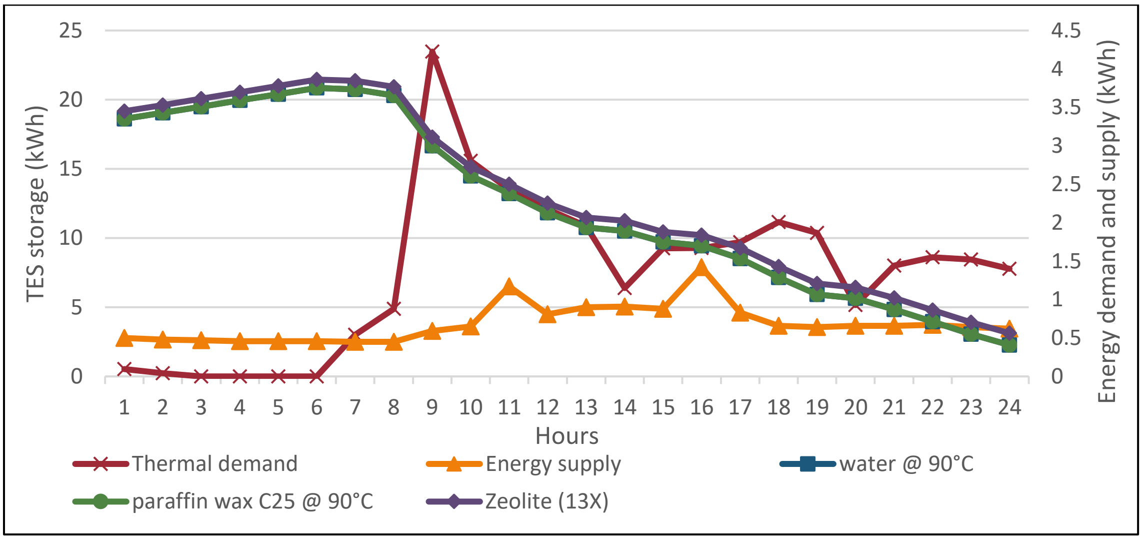


Figure 6-17: TES energy storage levels for a 1 m^3 of volume during an overcast winter day (16th of January)

6.2.2.3 Charge/discharge cycle

Charging and discharging different TES systems with different mediums of various thermal conductivity and heat distribution methods are a contributing factor when calculating TES system effectiveness to reduce grid supply. Furthermore, the time required to fully charge or discharge a TES system is also dependent on the heat transfer rate and method used (e.g. heat exchange rate and heat pump COP). In the case of this study, thermal conductivity is measured in sensible heat TES systems and PCM materials when stored using a bulk storage method. Furthermore, the storage temperature will define the state of the storage in terms of charge/discharge. A fully charged PCM or sensible heat storage system is set a when the storage reaches the maximum temperatures (either 60°C or 90°C). While a fully discharged storage system is set when the storage temperatures reaches 15°C which is the average temperature for inlet water used for DHW. This limits variability but enhances potential performance based on the results. As for the sorption methods, the time taken to fully charge and discharge the system ranges from 2000 seconds to 6000 seconds per cycle, based on the case studies reviewed (N'Tsoukpoe et al. 2009; De Boer et al. 2014; Aristov 2015), which fall in the range of 0.5 hour and 1.6 hour. This range satisfies the research requirement, since the simulation iteration relies on an hourly segment.

6.2.2.4 Seasonal energy depletion

Seasonal energy levels for every TES system show a significant reduction due to fluctuations in and intermittent solar radiation, especially over the winter months. The majority of systems tested with 1 m^3 of volumetric storage size reached significantly low energy levels or total energy depletion, in their reservoirs. In addition, the lack of solar radiation during the winter months increases dependency on TES systems, as the system struggles to meet thermal demand (see Figure 6-18). Furthermore, all the TES systems tested reached full capacity during the summer and autumn months, with only a solar PV system. Therefore, to meet thermal energy demand during winter months, there should be a larger storage volume and/or other on-site energy supply to assist in heightened energy regeneration during winter period.

A continuous simulation run shows every TES system within the tested group recovered lost energy during early spring (March) due to the increase in energy supply. The seasonal depletion period from November to March can be used to measure high energy demand from the TES system and to estimate the required size for the simulated building. Furthermore, sensible heat TES systems were the first group to demonstrate total energy depletion, which contributed to their shared low energy densities. The PCM and sorption TES systems depleted over several days from mid-December to early January, in response to the energy density variation present in the storage mediums and heat losses to the surrounding environment. Although these results are based on the energy analysis of TES performance, a further investigation of the exergy efficiency of the sensible and PCM TES systems in future studies will help estimate the size requirements for actual domestic building. Finally, salt hydrates TES systems, e.g. $CaCl_2.2H_2O$, and its composite variants, exhibit the same trend except that a total depletion was not achieved within the tested storage volume. These components met the demand from the simulated building with a storage size under 1 m^3, as investigated more fully in the next section.

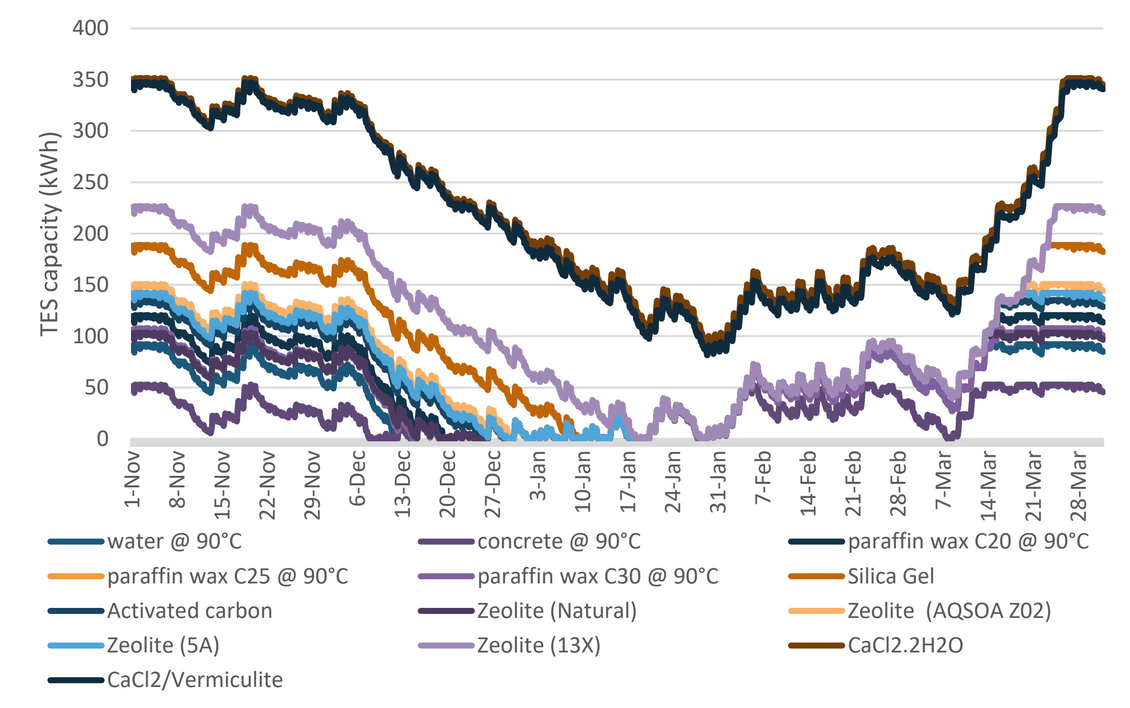


Figure 6-18: Winter and spring months' storage levels for each TES system based on a 1 m^3 volume storage size

6.2.2.5 TES storage size for zero carbon house

While TES performance is calculated in terms of energy density per storage medium, the main aspect to consider here is how to reduce grid supply in a domestic net zero carbon building. Based on the simulation results and TES annual performance per system, the following section presents the results of storage size, as required for each TES system designed to achieve zero grid supply. The results obtained when applying an increment of 0.05 m^3 per testing run, are presented in Table 6-2. These results are also effected by heat loss (for sensible and PCM mediums), energy density per medium, and the charge/discharge cycles of the simulation model.

Although a high requirement for storage volume is set by several sensible mediums, such as water at 60°C and concrete at 90°C, these were surpassed by a PCM medium of paraffin C30 at 60°C. This was because the low melting point of that medium rendered the energy storage within it sensible to heat only. Furthermore, other PCM mediums required relatively smaller storage volumes than sensible mediums, i.e. by two thirds. The least demanding medium in this test was paraffin C25 at 90°C. Moreover, sorption mediums marked the lowest volume requirements and specifically zeolites as 13X. The differences between the storage volume requirements among the sorption group ranged from 2.47 m^3 for silica gel to 0.70 m^3 for zeolite 13X. Although silica gel storage was within a low-range in the group tested, the practical performance expected should be lower, as required storage volume should be higher. This is due to several aspects of silica gel degradation and the limited operational temperature range.

The quantity of heat lost from TES storage to the surrounding environment was calculated for each system type relating to sensible heat and the PCM TES systems. The governing condition of this lost energy was the volume selected for the particular TES system. The higher the volumetric storage system, the larger area of heat dissipation exposure, the higher the energy loss expected. Heat loss figures are generated based on the maximum allowed by the Hot Water Association formula (Hot Water Association 2010), and the estimated heat loss form the thermal storage tank considering the temperature difference and area of exposure. It should be noted that these results do not count for the occurrence of heat loss outside the storage tank (e.g. heat loss from heat exchange efficiency, heat loss from the heat pump, and during energy conversion). Table 6-2 summarizes the resulting heat loss when a zero-grid supply storage is implemented as a component of the building design.

Table 6-2: TES storage size required by each TES system to reach zero grid supply

TES system	water at 60°C	water at 90°C	concrete at 90°C	paraffin wax C20 at 60°C	paraffin wax C20 at 90°C	paraffin wax C25 at 60°C	paraffin wax C25 at 90°C	paraffin wax C30 at 60°C	paraffin wax C30 at 90°C	Silica Gel	Activated carbon	Zeolite (Natural)	Zeolite (AQSOA Z02)	Zeolite (5A)	Zeolite (13X)	$CaCl_2$	CaCl2/Vermiculite
Storage size (m^3)	**3.25**	**1.9**	**3.25**	**1.75**	**1.45**	**2.1**	**1.6**	**4.7**	**1.6**	**2.47**	**1.2**	**1.65**	**1.1**	**1.15**	**0.7**	**0.65**	**0.74**
Maximum heat loss (Q_{HL-MAX}) (kWh/year)	**381.1**	**222.8**	**381.1**	**205.2**	**170**	**246.2**	**187.6**	**551.1**	**187.6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Calculated heat loss (Q_{HL}) (kWh/year)	**168.9**	**206.7**	**295.6**	**111.8**	**172.7**	**126.3**	**184.4**	**216.2**	**184.4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

The annual performance of each TES system was adjusted to its optimum storage size for zero carbon building simulations, and the results are shown in Figure 6-19. All the systems exhibit no grid supply, although depletion levels were high during times of high demand (winter). In the final TES system design, the weather variations and prolonged thermal demand was considered by allowing higher storage volumes per system. Finally, the several TES systems, requiring a greater storage volume cannot be hosted by the building due to restrictions. In terms of this study's aim and objectives, these options will not be included; although, it is proposed that they be examined in future studies.

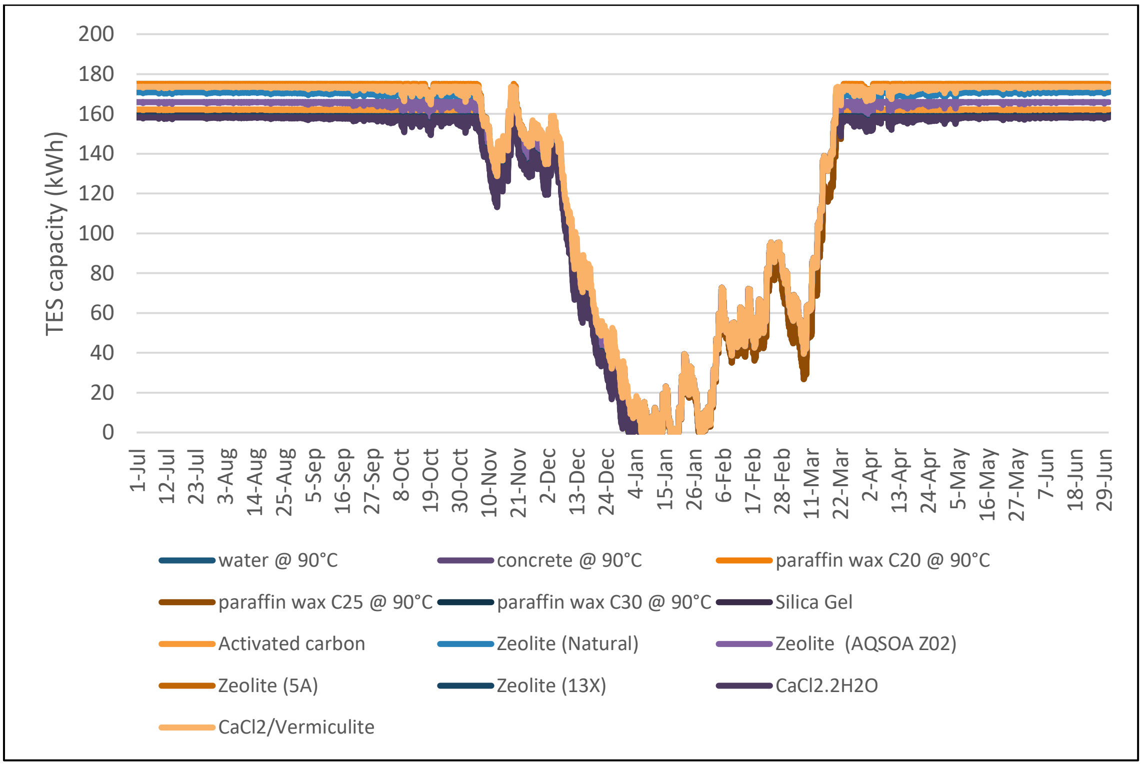


Figure 6-19: TES storage levels per TES system modelled with no grid supply as of table 6-2

6.3 Thermal energy storage modelling software development

During this study, a software tool was developed to assist in the process of calculating the energy performance of thermal energy storage systems. This tool was developed using the C# programming language, which operates under the MS Windows environment. Although the main objective when creating this tool was to assist in generating the study results, it can be further developed for use in other fields of research and system design employed to implement TES. Moreover, the tool's operational processes commence with an exploration of building data input, TES specification input, calculation process, and finally the presentation of results in both numerical and graphical form. The building data includes location, weather profile, solar energy type, area of solar panels, MVHR heat return rate, and finally number of occupants. TES specifications determine the storage type, storage temperature (for sensible and PCM TES systems), storage volume, and the initial state of any storage when the simulation commences. Finally, although the results are presented in numerical form, they can be represented graphically if necessary. Detailed results and hourly figures are exported to a worksheet file that can be opened externally to support further analysis. This tool processes the simulation results for the HTB2 output files and calculates the TES's energy performance, based on input from the user. Figure 6-20 shows the GUI for the final version of the tool.

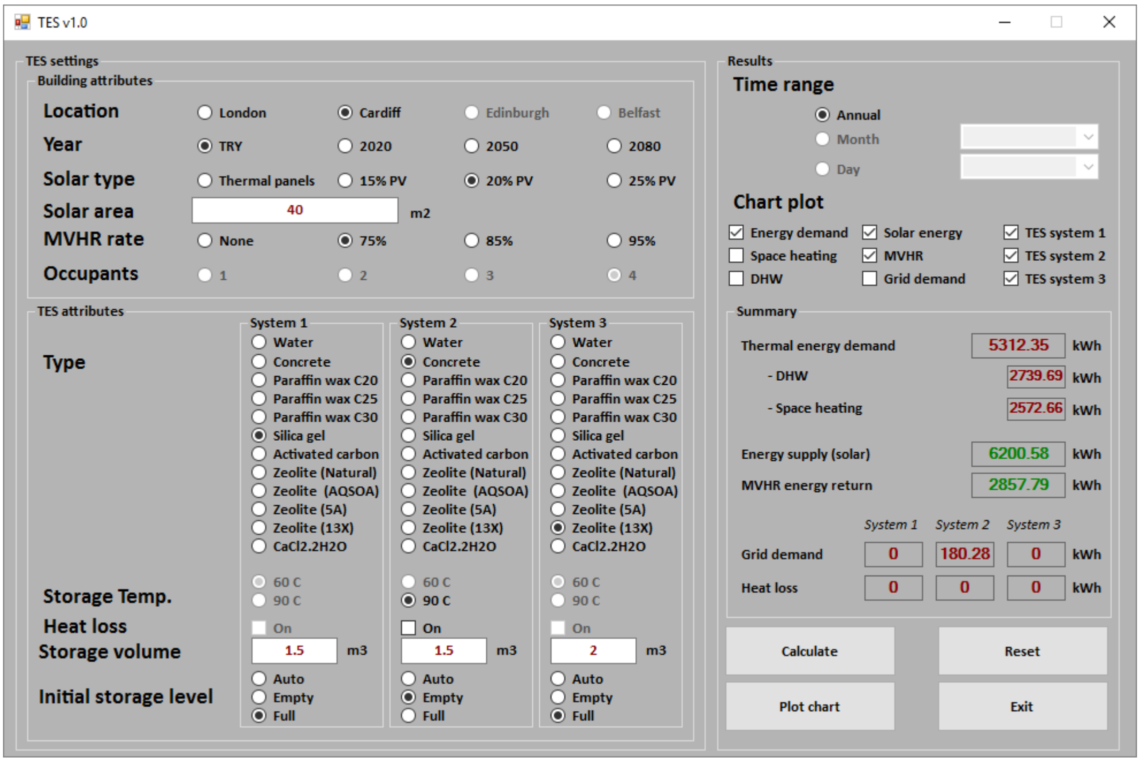


Figure 6-20: TES energy performance calculation tool

6.4 Summary of findings

The results presented in this chapter detailed the outcome of the building energy simulation, giving the TES calculation for size and performance to meet thermal energy demand with a simulated model. While the energy simulation model run was based on an hourly iteration, values for diurnal and seasonal energy performance were calculated and extracted from these results. Furthermore, the TES calculations were based on hourly results to predict the values for energy storage and grid supply accurately across the entire simulation run. While a full heating and cooling system design with TES and solar PV integrations working in the domestic building would provide a more precise size estimation with the help of exergy analysis, this study focuses on the energy performance of the TES systems under hourly operation of a zero-carbon house.

In the case study’s energy simulation model, the results comply with the Passivhaus standards and zero carbon buildings. Although these results show there is an overheating issue affecting living areas, it is within acceptable levels for this study. Furthermore, the simulation results show an insufficient thermal energy supply from on-site generation to meet demand, especially in the high demand season (winter months).

With regard to the TES systems, the modelling and calculation illustrated a variance in performance between all the TES systems when meeting both diurnal and seasonal thermal energy demand. Sensible heat storage mediums proved to be capable to meet the demand but required much larger volume for storage compared to the other groups. Of these, the PCM mediums presented mid-range potential in terms of storage volume and energy density. Furthermore, the PCM materials have versatile system designs, developed principally to maximise performance when exposed to low storage volumes, to improve heat conductivity, and reduce phase separation concerns.

Finally, thermochemical TES systems offer excellent potential, since they require low storage volumes, and have a short charging/discharging cycle, not subject to heat loss to the surrounding environment. These properties are desirable when designing TES systems for energy efficient buildings such as Passivhaus and zero-carbon buildings. In addition, thermochemical TES systems sorption methods are considered among the safest storage mediums for application in domestic environments.

7 Conclusion and discussion

This chapter discusses the general results obtained from the building performance simulation and TES modelling. In addition, domestic zero-carbon buildings and the potential for implementing thermal energy storage are also reviewed in relation to the research findings. The first section of this chapter (section 7.1) describes the energy demand and supply of domestic zero-carbon buildings and discusses the potential for development and performance enhancement. The second section of the chapter (section 7.2) discusses TES input and its contribution as a tool to reduce the thermal demand of zero-carbon buildings. Furthermore, several conditions associated with operating TES under high energy performance buildings will highlight the potential limitations when implementing different TES systems. The final and third sections of this chapter (section 7.3) contains final recommendations and suggestions for future work relating to the integration of TES systems into high-energy performance domestic buildings.

7.1 Thermal energy performance simulation

Thermal energy performance simulations for zero-carbon buildings using software tools such as HTB2 are highly promising according to the reviewed literature and the simulation results. Furthermore, thermal energy demand in this study complies with both zero-carbon buildings and Passivhaus standards, demonstrating limited space heating demand and thermal energy demand in general. The ability to achieve these standards results directly from the building's physical attributes, increased thermal insulation in the envelope, and the implementation of high efficiency small power devices and lighting fixtures.

Although limiting thermal energy demand in a building design and simulation run has a major impact on general energy demand, this limitation is typically accompanied by occurrences of overheating. The greater the thermal insulation of a building in the UK, the higher the potential that an overheating issue could rise. In this study, some overheating was observed in living areas during the summer months. This overheating was intensified by solar gains from the southern façade of the simulation model. The orientation of the simulation model, whereby the length of the building faced south, was intended primarily to maximise energy generation from solar radiation. Thus, solar heat gains via the southern façade were predicted on a diurnal basis.

Additionally, energy generation from renewables in this study's case primarily utilised solar PV energy. Although solar energy harvesting technologies can be surpassed by combining other sources of renewable energy technologies, the combined systems that include solar energy and heat pumps (either air, geothermal, or ground source heat pump) generally have a higher energy yield than solar energy systems alone (Anderson 1990; Weiss 2003; Prasad and Snow 2005; Lynn 2010). However, combining solar energy with other renewable forms of technology would require a more complicated system design to achieve the desired results. For example, it would be necessary to include an electrical energy storage method to help operate heat pumps during hours of darkness, and a grid feed to the heat pump during energy depletion periods (Greening and Azapagic 2012). Moreover, the added heat pump system would increase the required space and cost to the building's initial design, reducing the applicability of the combined systems. The temperature rise required to charge some of the thermochemical storage mediums would exceed the ability of most on-site energy sources, with the exception of solar collectors and solar PV (Chan and Russel 2011; Herrando et al. 2014). In this study, a standalone solar PV system was implemented as an energy generation source. This was expected to limit energy conversion inefficiencies, reduce the probability of error due to increased system complication, and finally create a more distinct diurnal demand and supply cycle requiring a TES system contribution. Additionally, the implementation of a standalone PV system would comply with both zero-carbon building and Passivhaus' standards, delivering acceptable results.

Several additional factors can alter simulation results if evaluated. One of the main factors relates to the impact of occupancy patterns and behaviour during a building energy simulation. The reviewed literature reveals the extent of this factor to alter energy demand levels for both the simulation level and real-time monitoring. Furthermore, occupancy awareness and engagement when conserving energy could have a significant impact on a building's general energy demand levels (Wilhite et al. 1996; Hitchings and Day 2011; Janda 2011; Alsaadani and Souza 2012; Oldewurtel et al. 2013; Kelly et al. 2016). Furthermore, the variability of the occupancy factor on the buildings general energy demand could be high, due to irregularities in lifestyle and seasonal changes. Therefore, this factor is highly unpredictable and difficult to simulate. Finally, since the study aim and objectives are focused on creating reliable thermal energy demand profiles that can be used as a basis for TES system calculations, the occupancy variable factor was limited in this study. This limitation will not affect overall energy demand nor alter the general pattern of energy demand or associated profile.

In conclusion, the chosen energy simulation method and the tools used in this study were selected as the most effective means to achieve the research aim and objectives. The selection of this approach helped the researcher generate basic thermal energy consumption data for a zero-carbon building (under Passivhaus standards), and for further TES modelling and performance calculation. The following points will summarise decisions and approach used to improve a building's energy performance:

1. An engineering bottom-up method was adopted to acquire thermal energy figures for high-energy performance buildings.
2. HTB2.0 was selected as a tool of choice for thermal energy simulations and modelling for support availability, reliability, and established knowledge.
3. Passivhaus standards were adopted to help achieve a zero-carbon state for energy demand limitations and detailed building physical attributions requirements.
4. Solar PV was the selected on-site energy generation method, chosen for its availability, simplicity, performance predictability, and minimal energy conversion loss.
5. Building size and occupancy were selected based on surveys from local government agencies and associates. Additional consideration was undertaken to minimise factors influencing the simulation's results, such as avoiding shared walls and overshadowing from neighbouring buildings.

7.2 TES system integration with zero-carbon building

The thermal energy storage systems included in this study were selected based on a literature review including available operational information pertaining to domestic buildings. Therefore, a well-established database was created detailing physical and thermal properties is included in TES systems and storage mediums. While there have been attempts to implement the TES systems included in this study into a domestic building, there is a dearth of studies comparing TES systems in terms of performance, required size, and potential energy reduction, especially for zero-carbon buildings.

Sensible heat TES systems have been extensively studied in the past, and their implementation into actual or virtual case studies is apparent in the literature. Furthermore, since water is considered a desirable medium for thermal storage in this category, it has been included here using two different temperatures. In addition to water, concrete is also added as it has broad application under this type of TES. Although few other materials exist that are commonly used as sensible heat TES, these materials were excluded from this study, either for their low thermal capacity, their low thermal conductivity, or the lack of essential information pertaining to them.

This study presents the results when implementing TES systems into zero-carbon buildings, as the performance of sensible materials was on the lower side of the scale. This low performance level was expected as a result in relation to low thermal energy capacity associated with these sensible TES mediums. Furthermore, the study also shows the relatively high storage volume requirements for materials compared with PCM and thermochemical storage.

Since PCM mediums possess a higher thermal energy storage capacity than sensible heat TES mediums, PCM mediums are gaining in popularity among researchers and practitioners. Although these mediums can be categorised into two main types (organic and non-organic), this study examines organic materials, such as paraffin, only. The inclusion of organic PCM mediums is based on the applicability of these materials for use in domestic building applications. They offer long term chemical stability, have a low melting point, are safe for domestic applications, and are widely available. Although their desired properties have increased the popularity and application of organic PCM, the materials suffer from issues with poor thermal conductivity and phase separation. Both of which have been addressed by improving the PCM medium storage design. This involved adding heat diffusers and encapsulating the PCM medium within other materials known to have a higher thermal conductivity.

Although these methods of improving the performance of PCM materials were previously reviewed in the literature, they have been excluded here, to avoid the variability of performance and its effect on the storage volume. The mediums used in this study were assumed to be pure in substance and stored in bulk in a tank. By calculating required storage volume and energy reduction in this setup, the output of this study can generate comparable results in relation to other TES mediums that do not share the same properties and are not subject to the same conditions. The results of this study also show the effect of melting temperature on the selected PCM medium as it affects the general performance of the TES system and its possible potential. Among the three selected paraffin materials, operating under the same conditions, paraffin C20 performed better than the two other types (C25 and C30). The reason for the improvement in performance is the low melting temperature (36°C) and the higher the latent heat of fusion of this medium. Furthermore, the performance of this form of paraffin exceeds all mediums in the group and every material in the sensible heat TES group.

In the case of the thermochemical TES tested in this study, the thermochemical sorption method presented produced some highly variable results. These showed a range from a low (silica gel) to a relatively high (zeolite 13X) performance when reducing thermal energy demand from the grid. It should be noted that the silica gel presented in this study as a TES medium produces conflicting data in the reviewed literature in terms of thermal energy density. The majority of the reviewed literature refers to it as most suitable for thermal cooling applications rather than for heating applications due to its low temperature tolerance. This low temperature tolerance limits its application to below 200° to 150°C operational temperature, to avoid it entering a non-reversible reaction that permanently damages the material itself. Its inclusion in this research is intended cautiously, as it raises further questions about the potential for energy reduction in zero-carbon buildings.

Thermochemical sorption mediums can also benefit from a storage system design that improves thermal conductivity and heat diffusivity within a storage enclosure. These design solutions can take the form of encapsulation, impregnation, heat diffusers, or a combination of different methods. For the purpose of this study, all these solutions were excluded to present a less complicated system design, delivering comparable results.

The final test group in this study consists of thermochemical salt hydrates and its composites. Although the reaction of salt hydration can charge/discharge relatively large amount of thermal energy, most of the reviewed literature does not recommend it due to its poor reaction stability, which questions its applicability in domestic applications. Furthermore, the nature of the thermochemical reaction involved in salt hydration is commonly associated with corrosion and material deterioration over prolonged periods of operation. The decision to include salt hydrates in this study as a TES mediums was to support comparison with its performance under zero-carbon building thermal energy demand with other TES mediums utilising different technologies. The possibility of implementing these mediums in an actual TES system extends beyond the aim and objectives of this study. Another notable issue related to the salt hydrate method in this study concerns required storage volume. This issue related to the storage qualities of this medium under heat conditions (dry state). Specifically, it requires a very low bulk storage volume when dry, but when dissolved or hydrated it requires 3 times the previous storage space. In this study, the main focus is on the storage of the medium during the charged state (or dried state), as described by the figure for bulk medium storage size by volume.

In summary, the TES systems and mediums chosen in this study were selected to serve the main aim and objectives of the research, with the fewest possible complications, to minimize variables, generate comparable results, and reduce the probability of error. The results generated from this study were compared and measured according to the TES's volume size requirements, and to meet the thermal energy demands of the selected building, and the extent of the grid energy supply reduction. The five groups of TES systems tested in this study include sensible heat storage, phase change material (PCM), thermochemical sorption, thermochemical salt hydrates, and finally a composite system. Each group possesses certain attributes that inform its feasibility, operation, or performance, making it worthy of consideration as a thermal storage medium. While the attention in this study is directed towards performance and operation factors associated with the TES medium and system design, the general feasibility of application of the TES medium within a domestic building is also evaluated.

The testing of the five groups of TES systems produced findings showing variable performance and thermal energy demand reduction levels under the same operational loads. Furthermore, each group of TES system tested achieved zero grid's energy supply, although with different storage volumetric requirements. The smallest required volumes to meet the demand for the study building were of the thermochemical salt hydrates system, when utilising $CaCl_2.2H_2O$ as a medium in a dry or charged state. But the volume requirement of this medium changes by two times as the material gets hydrated. The thermochemical sorption group was second in terms of its reduced size requirement, leading with a zeolite 13X compound. The third group was the PCM paraffin group, with paraffin C20 at 90°C and a sensible heat group with water at 90°C.

Several points were addressed when creating a working TES model. These points can be summarised thus:

1. Water and concrete were included in the study at different temperatures, as TES mediums, to compare size requirements with other groups.

2. Paraffin was selected as a PCM TES medium, designed with different melting temperatures and storing thermal energy at different temperatures.
3. Inorganic PCM mediums were excluded from this study due to their inapplicability to domestic buildings.
4. The thermochemical sorption reactants chosen for this study were selected based on applicable and available information presented in earlier case studies and published work.
5. Thermochemical salt hydrate reactants were excluded from this study, with the exception of calcium chloride hydrate, which was selected based on the availability of its thermal properties in published work and its relatively less hazardous nature when compared to other salt hydrates.
6. Heat diffusive elements, thermal conductive improvements, and accelerators that can be implemented when using TES storage tanks were all excluded, since they alter storage tank volume, and vary depending in terms of storage medium, affecting the overall energy density of the TES medium.

7.3 Recommendations and suggestions for future study

This study has investigated the thermal energy performance of zero-carbon buildings, testing several thermal energy storage systems to determine their effect on the overall thermal energy demand profile. While this study utilises the design year weather profile from CIBSE, further investigation can be carried out to ascertain the effect of weather change on thermal energy demand profiles. A weather change could be induced either by the effect of global warming in the original location (Cardiff), or by changing the weather profile to match a new location. Furthermore, a different building layout with possible input from on-site renewables could provide different energy demand profiles also.

TES storage mediums can also benefit from storage improvements, as these introduce more balanced heat distribution within the storage medium. Since improvements have been noted in the literature and also tested in the laboratory environment, a further study can be undertaken to investigate the performance improvement for the improved TES system under zero-carbon building thermal energy demand. The overall calculation of the TES system energy density and performance can be compared with an operational built model and monitored to determine affective factors that might exist under operational conditions.

Since this study examined the implementation of solar PV as the principal source of on-site energy generation, a limitation arose in relation to weather conditions and the availability of solar radiation. Future studies might usefully explore possible input from air source heat pumps, ground source heat pumps, and wind energy alongside solar energy, and the impact on the performance of TES system operation when implementing these different sources and when aiming to meet general requirements.

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Appendices

Appendix A – Building energy simulation files

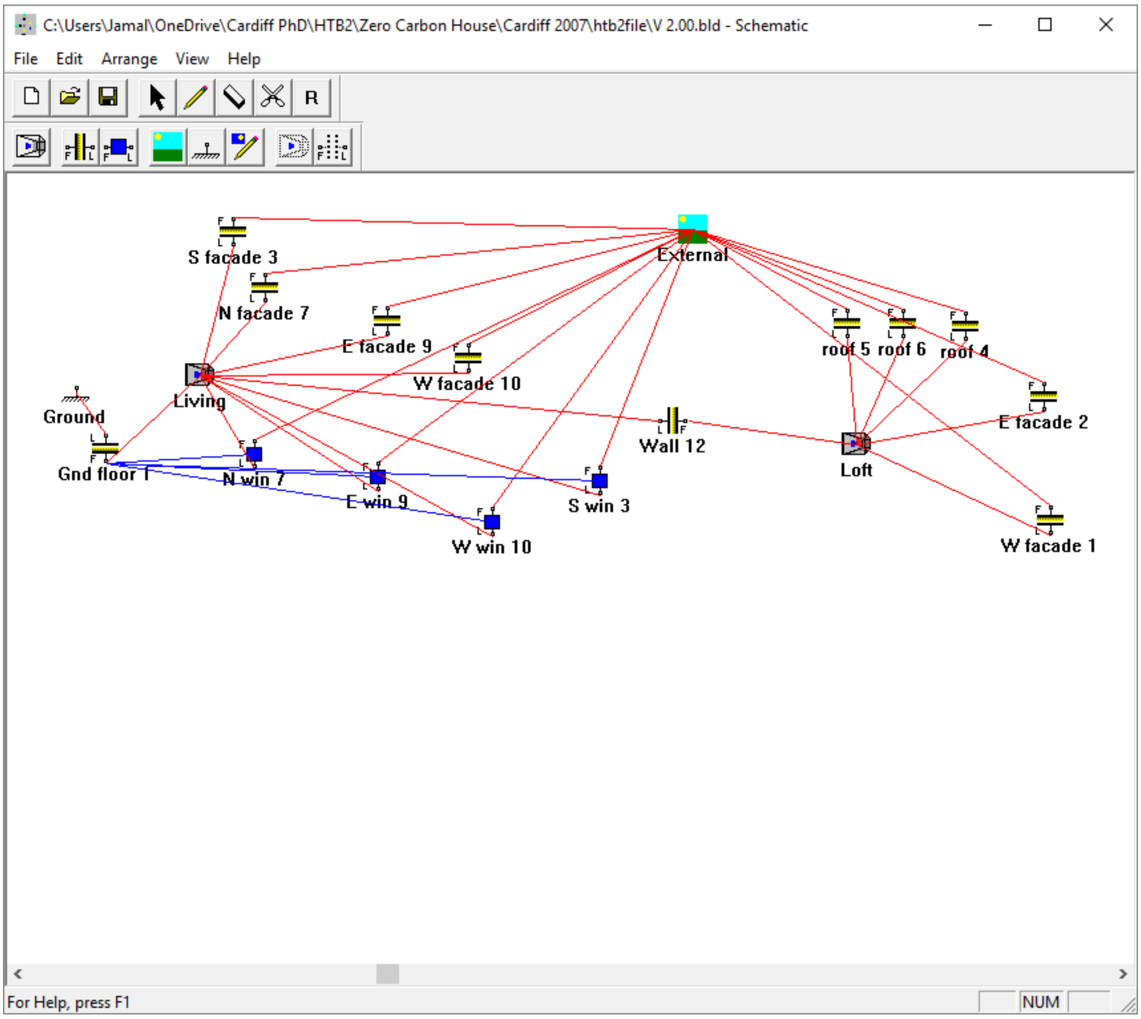
Appendix B – HTB2 simulation results

Appendix C – Thermal energy storage system calculations

Appendix D – TES modelling software

Appendix A – Building energy simulation files

A.1. HTB2 building layout schematic



A.2. HTB2 construction file format

V 2.00.con - Notepad

File Edit Format View Help

```
!MATERIALS FILE = 'V 2.00STDMAT.LBY'
!MATERIALS USER FILE = 'V 2.00user.lby'

!CONSTRUCTION 'ext wall 1 res'
!TYPE OPAQUE
!PARTS
_ 1 =       48      0.025      0           * WEATHERBOARD
_ 2 =       50      0.015      0           * PLYWOOD
_ 3 =       63      0.250      0           * POLYSTYRENE
_ 4 =       50      0.015      0           * PLYWOOD
_ 5 =       36      0.015      0           * GYPSUM PLASTERBOARD
}
!END

!CONSTRUCTION 'intwall 2 res'
!TYPE OPAQUE
!PARTS
_ 1 =       50      0.015      0           * PLYWOOD
_ 2 =       36      0.015      0           * GYPSUM PLASTERBOARD
}
!END

!CONSTRUCTION 'roof 3 res'
!TYPE OPAQUE
!PARTS
_ 1 =       24      0.004      0           * PLASTIC TILES
_ 2 =       60      0.080      0           * POLYURETHANE FOAM BOARD
_ 3 =       9      0.002      0           * MASTIC ROOFING
_ 4 =       50      0.012      0           * PLYWOOD
_ 5 =       63      0.150      0           * POLYSTYRENE
_ 6 =       50      0.012      0           * PLYWOOD
}
!END

!CONSTRUCTION 'flo-ceiling 4 res'
!TYPE OPAQUE
!PARTS
_ 1 =      @8      0.030      0           * FINE AGGREGATE CONCRETE 2300
_ 2 =      @4      0.010      0           * INORGANIC THERMAL PRESERVATION MORTAR
_ 3 =      @6      0.100      0           * REINFORCED CONCRETE
}
!END

!CONSTRUCTION 'ground 5 res'
!TYPE OPAQUE
!PARTS
_ 1 =       45      0.015      0           * FLOORING BOARD
_ 2 =       20      0.060      0           * CEMENT SCREED
_ 3 =       60      0.200      0           * POLYURETHANE FOAM BOARD
_ 4 =       20      0.150      0           * CEMENT SCREED
_ 5 =       7      0.005      0           * BITUMEN FELT
_ 6 =       66      0.200      0           * EARTH
}
!END
```

A.3. HTB2 lighting file format

V 2.00.LGT - Notepad

File Edit Format View Help

```
*  single space house lighting, on/off  5:00 to 8:00, 18:00 to 24:00
*

!LIGHTSYS 'Living'

   !HEAT OUTPUT = 82.0                * 10 10W led lighting (heat output = 82%)
   !SPLIT =   0.1     ,    0.9        * LED

   !CONVECTIVE CONNECTIONS
      _#1 = 1.0                        * convective to space 1
      }
   !RADIANT CONNECTIONS
      _#1 = 1.0                        * radiant to zone 1
      }


   !CLOCK START TIME #1 = 05:00:00     * dawn
   !CLOCK STOP TIME #1  = 07:30:00     * sun rise and gone working
   !CLOCK PROPORTION #1 = 0.25          * 25% on

   !CLOCK START TIME #2 = 18:00:00     * sun set
   !CLOCK STOP TIME #2  = 23:00:00     * bed time
   !CLOCK PROPORTION #2 = 1.0          * all on

!END
```

A.4. HTB2 occupancy file format

V 2.00.OCC - Notepad

File Edit Format View Help

```
*  simple single space house occupancy conditions

!OCCUPANCY SPACE  = 1
  !ACTIVITY LEVEL #1 = 50.0 , 0.0
  !ACTIVITY LEVEL #2 = 90.0 , 0.0
  !ACTIVITY LEVEL #3 = 150.0 , 0.0
  !SPLIT = 0.80 , 0.20
  !INITIAL = 0.0
  !CLOCK START TIME #1 = 00:00:00
  !CLOCK STOP TIME #1 = 07:00:00
  !CLOCK ACTIVITY LEVEL #1 = 1
  !CLOCK OCCUPANCY #1 = 4
  !CLOCK START TIME #2 = 07:00:00
  !CLOCK STOP TIME #2 = 12:00:00
  !CLOCK ACTIVITY LEVEL #2 = 2
  !CLOCK OCCUPANCY #2 = 1
  !CLOCK START TIME #3 = 12:00:00
  !CLOCK STOP TIME #3 = 18:00:00
  !CLOCK ACTIVITY LEVEL #3 = 2
  !CLOCK OCCUPANCY #3 = 2
  !CLOCK START TIME #4 = 18:00:00
  !CLOCK STOP TIME #4 = 23:00:00
  !CLOCK ACTIVITY LEVEL #4 = 2
  !CLOCK OCCUPANCY #4 = 4
  !CLOCK START TIME #5 = 23:00:00
  !CLOCK STOP TIME #5 = 24:00:00
  !CLOCK ACTIVITY LEVEL #5 = 1
  !CLOCK OCCUPANCY #5 = 4

!END
```

A.5. HTB2 heater setting file format

V 2.00.htr - Notepad

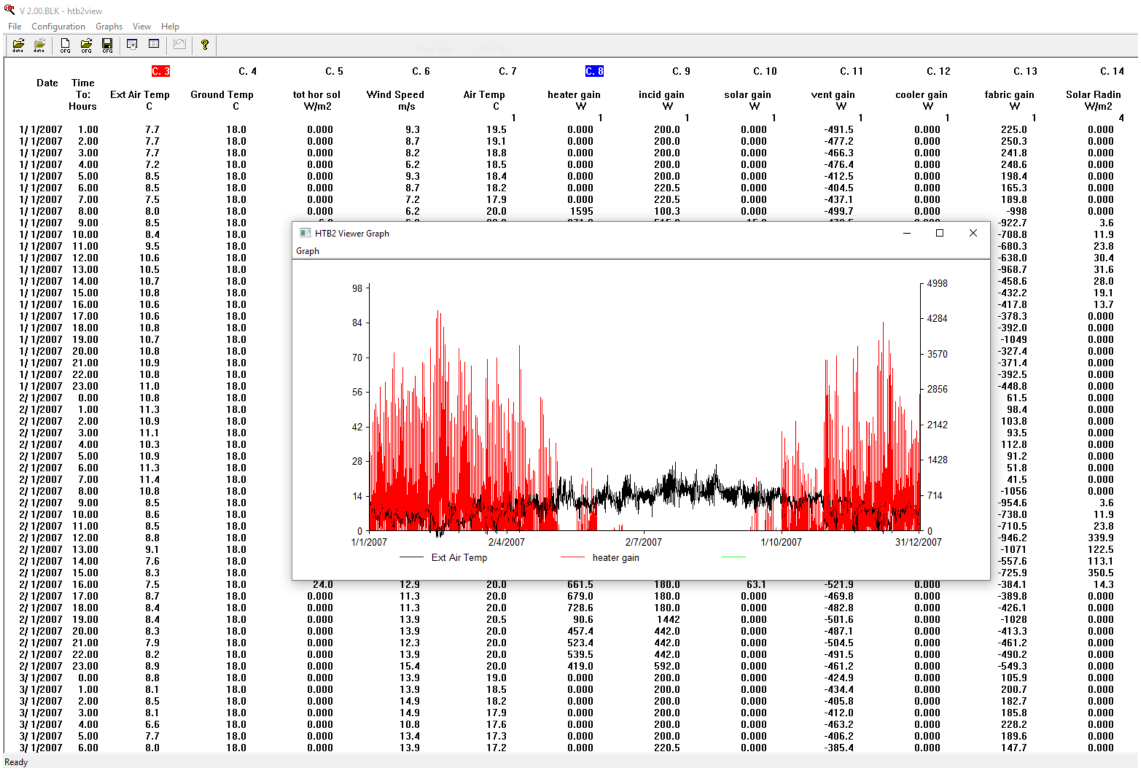
File Edit Format View Help

```
*  ideal single space heating system, fully convective,
*     heat to 18 oC, cool to 23 oC   0  til 24
!HEATSYS 'RESI 1'
 !STAT TYPE IDEAL                      * force to maintain air temp.

   !POWER OUTPUT = -1                * in kw/-1 is unlimited
   !CONVECTIVE CONNECTIONS
      _#1 = 1.0                        * convective to building 1
      }

   !SETPOINT HEAT = 20.0                * start heating
   !SETPOINT COOL = 29.0                * start cooling
   !STAT AIR CONNECTIONS
      _#1 = 1.0                        * stat monitoring building 1
      }
!CLOCK START TIME #1 = 07:00:00 |MTWTF--     * control 7-23
!CLOCK START TIME #1 = 08:00:00 |-----ss     * control 8-24
!CLOCK STOP TIME #1  = 23:00:00 |MTWTF--
!CLOCK STOP TIME #1  = 23:59:59 |-----ss
*!CLOCK START TIME #2 = 18:00:00 |MTWTF--     * control18-24
*!CLOCK STOP TIME #2  = 24:00:00 |MTWTF--
!END
```

A.6. HTB2 Simulation results view



Appendix B – HTB2 simulation results

B.1. Building energy simulation's hourly results

time			Heating demand	DHW demand	Thermal demand	Solar energy	MVHR	Energy supply	Energy surplus	Grid demand
No.	Day	Hour	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
1	1-Jan	1	0	0.0405	0.0405	0	0.39	0.39	0.3495	0
2		2	0	0	0	0	0.38	0.38	0.38	0
3		3	0	0	0	0	0.37	0.37	0.37	0
4		4	0	0	0	0	0.38	0.38	0.38	0
5		5	0	0	0	0	0.33	0.33	0.33	0
6		6	0	0.54	0.54	0	0.32	0.32	-0.22	0.22
7		7	0	0.8775	0.8775	0	0.35	0.35	-0.5275	0.5275
8		8	1.6	0.945	2.545	0	0.4	0.4	-2.145	2.145
9		9	0.87	0.7425	1.6125	0.03	0.38	0.41	-1.2025	1.2025
10		10	1.05	0.405	1.455	0.1	0.39	0.49	-0.965	0.965
11		11	0.92	0.324	1.244	0.19	0.35	0.54	-0.704	0.704
12		12	0.8	0.2025	1.0025	0.24	0.31	0.55	-0.4525	0.4525
13		13	0.21	0.189	0.399	0.25	0.32	0.57	0.171	0
14		14	0.54	0.216	0.756	0.22	0.31	0.53	-0.226	0.226
15		15	0.55	0.27	0.82	0.15	0.3	0.45	-0.37	0.37
16		16	0.57	0.3375	0.9075	0.11	0.31	0.42	-0.4875	0.4875
17		17	0.59	0.567	1.157	0	0.31	0.31	-0.847	0.847
18		18	0.59	0.405	0.995	0	0.3	0.3	-0.695	0.695
19		19	0.02	0.3375	0.3575	0	0.33	0.33	-0.0275	0.0275
20		20	0.26	0.2025	0.4625	0	0.3	0.3	-0.1625	0.1625
21		21	0.3	0.27	0.57	0	0.3	0.3	-0.27	0.27
22		22	0.33	0.27	0.6	0	0.3	0.3	-0.3	0.3
23		23	0.23	0.27	0.5	0	0.3	0.3	-0.2	0.2
24	2-Jan	0	0	0.0945	0.0945	0	0.28	0.28	0.1855	0
25		1	0	0.0405	0.0405	0	0.25	0.25	0.2095	0
26		2	0	0	0	0	0.26	0.26	0.26	0
27		3	0	0	0	0	0.25	0.25	0.25	0
28		4	0	0	0	0	0.27	0.27	0.27	0
29		5	0	0	0	0	0.24	0.24	0.24	0
30		6	0	0.54	0.54	0	0.22	0.22	-0.32	0.32
31		7	0	0.8775	0.8775	0	0.22	0.22	-0.6575	0.6575
32		8	1.52	0.945	2.465	0	0.3	0.3	-2.165	2.165
33		9	0.9	0.7425	1.6425	0.03	0.38	0.41	-1.2325	1.2325
34		10	1.07	0.405	1.475	0.1	0.38	0.48	-0.995	0.995
35		11	0.99	0.324	1.314	0.19	0.38	0.57	-0.744	0.744
36		12	0.84	0.2025	1.0425	2.72	0.37	3.09	2.0475	0
37		13	0.21	0.189	0.399	0.98	0.37	1.35	0.951	0
38		14	0.62	0.216	0.836	0.9	0.41	1.31	0.474	0
39		15	0.58	0.27	0.85	2.8	0.39	3.19	2.34	0
40		16	0.66	0.3375	0.9975	0.11	0.42	0.53	-0.4675	0.4675
41		17	0.68	0.567	1.247	0	0.38	0.38	-0.867	0.867
42		18	0.73	0.405	1.135	0	0.39	0.39	-0.745	0.745
43		19	0.09	0.3375	0.4275	0	0.4	0.4	-0.0275	0.0275
44		20	0.46	0.2025	0.6625	0	0.39	0.39	-0.2725	0.2725
45		21	0.52	0.27	0.79	0	0.4	0.4	-0.39	0.39
46		22	0.54	0.27	0.81	0	0.39	0.39	-0.42	0.42

Appendix C – Thermal energy storage system calculations

C.1. Thermal energy storage capacities calculations

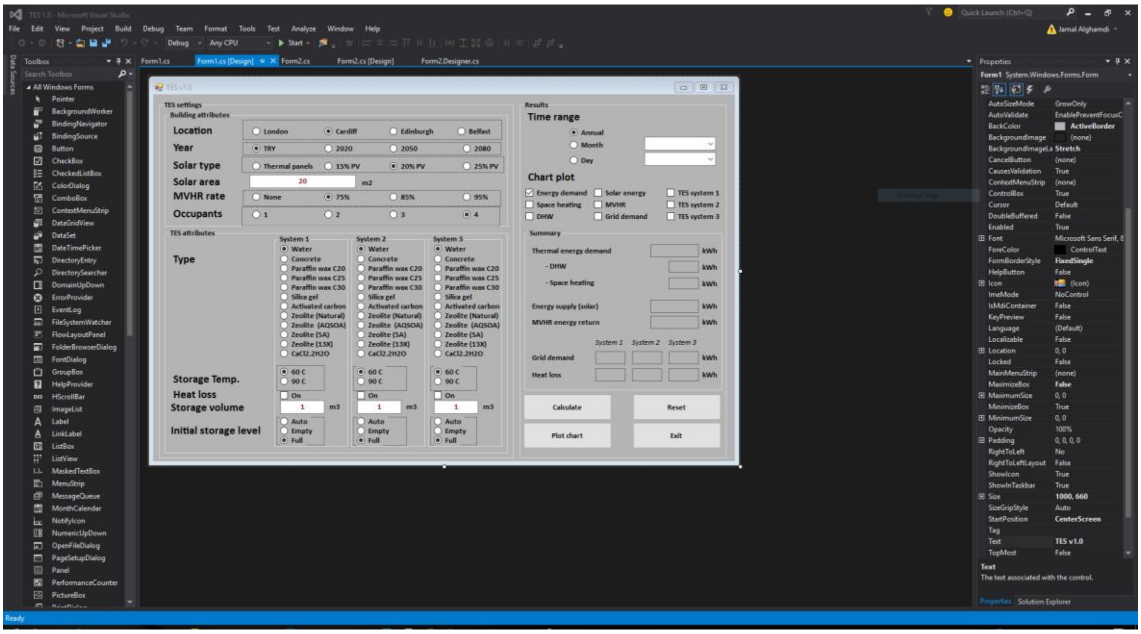
material	base temp.	melting temp.	high temp.	Density		latent heat enthalpy	specific heat		Heat capacity		Thermal conductivity		volumetric thermal expansion	volume	energy storage	Heat Loss
				liquid	solid		liquid	solid			liquid	solid				
	T1	Tm	T2	M	M	H	Cp-l	Cp-s	Q/m3		λ	λ	Δv	V	Es	$Q_{HL\text{-}MAX}$
	C°	C°	C°	(kg/m3)	(kg/m3)	kJ/kg	kJ/(kg·K)		kJ/m3	MJ/m3	W/(m.K)		(%)	m3	kWh/m3	kWh/24h
Sensible heat storage																
water @ 60°C	15	0	60	1000	0	334	4.2	4.19	189000	189	0.63	0	0.028	1	53.97	0.32128
water @ 90°C	15	0	90	1000	0	334	4.2	4.19	315000	315	0.63	0	0.053	1	92.14	0.32128
concrete @ 90°C	15	nul	90	0	2240	0	0	1.13	189840	189.84	0	0	0	1	52.73	0.32128
PCM																
paraffin wax C20 @ 60°C	15	36	60	769	912	248	2.5	2.95	328814.4	328.8144	0.6	0.21	0.077	1	98.37	0.32128
paraffin wax C20 @ 90°C	15	36	90	769	912	248	2.5	2.95	386489.4	386.4894	0.6	0.21	0.124	1	120.67	0.32128
paraffin wax C25 @ 60°C	15	54	60	775	915	184.48	2.5	2.95	285695	285.695	0.6	0.21	0.077	1	85.47	0.32128
paraffin wax C25 @ 90°C	15	54	90	775	915	184.48	2.5	2.95	343820	343.82	0.6	0.21	0.124	1	107.35	0.32128
paraffin wax C30 @ 60°C	15	66	60	799	916	173.6	2.5	2.95	121599	121.599	0.6	0.21	0.077	1	36.38	0.32128
paraffin wax C30 @ 90°C	15	66	90	799	916	173.6	2.5	2.95	344769.8	344.7698	0.6	0.21	0.124	1	107.64	0.32128
TCS																
				Density (kg/m3)					kWh/kg	MJ/kg						
Silica Gel				710					0.09125	0.33				1	64.79	0
Activated carbon				208					0.65	2.34				1	135.2	0
Zeolite (Natural)				1380					0.075	0.27				1	103.5	0
Zeolite (AQSOA Z02)				520					0.29	1.04				1	150.8	0
Zeolite (5A)				750					0.19	0.68				1	142.5	0
Zeolite (13X)				630					0.36	1.3				1	226.8	0
CaCl2.2H2O				1850					0.19	0.68				1	351.5	0
CaCl2/Vermiculite				296.8					1.17	4.21				1	347.26	0
(MgSO4 + MgCl2)/Attapulgite									0.44	1.58				1	0	0

C.2. Thermal energy storage hourly storage calculations

	1		2		3		4		5		6		7		8	
TES medium	water @ 60°C		water @ 90°C		concrete @ 90°		paraffin wax C20 @ 60°		paraffin wax C20 @ 90°		paraffin wax C25 @ 60°		paraffin wax C25 @ 90°		paraffin wax C30 @ 60°	
Q (kWh/m3)	53.97		92.14		52.73		98.37		120.67		85.47		107.35		36.38	
Storage volume	1		1		1		1		1		1		1		1	
Toatal Q (kWh)	53.97		92.14		52.73		98.37		120.67		85.47		107.35		36.38	
Initial charge	3.5		3.5		3.5		3.5		3.5		3.5		3.5		3.5	
Heat loss per h	-0.015		-0.015		-0.015		-0.015		-0.015		-0.015		-0.015		-0.015	
Total heat loss																
Total grid demand	291.68		237.82		293.46		232.63		201.46		244.24		218.16		354.82	
Hours	Q	Grid	Q	Grid	Q	Grid	Q	Grid	Q	Grid	Q	Grid	Q	Grid	Q	Grid
1	3.83	0	3.83	0	3.83	0	3.83	0	3.83	0	3.83	0	3.83	0	3.83	0
2	4.2	0	4.2	0	4.2	0	4.2	0	4.2	0	4.2	0	4.2	0	4.2	0
3	4.56	0	4.56	0	4.56	0	4.56	0	4.56	0	4.56	0	4.56	0	4.56	0
4	4.93	0	4.93	0	4.93	0	4.93	0	4.93	0	4.93	0	4.93	0	4.93	0
5	5.25	0	5.25	0	5.25	0	5.25	0	5.25	0	5.25	0	5.25	0	5.25	0
6	5.02	0	5.02	0	5.02	0	5.02	0	5.02	0	5.02	0	5.02	0	5.02	0
7	4.48	0	4.48	0	4.48	0	4.48	0	4.48	0	4.48	0	4.48	0	4.48	0
8	2.32	0	2.32	0	2.32	0	2.32	0	2.32	0	2.32	0	2.32	0	2.32	0
9	1.1	-0.1	1.1	-0.1	1.1	-0.1	1.1	-0.1	1.1	-0.1	1.1	-0.1	1.1	-0.1	1.1	-0.1
10	0.12	-0.85	0.12	-0.85	0.12	-0.85	0.12	-0.85	0.12	-0.85	0.12	-0.85	0.12	-0.85	0.12	-0.85
11	0	-0.7	0	-0.7	0	-0.7	0	-0.7	0	-0.7	0	-0.7	0	-0.7	0	-0.7
12	0	-0.45	0	-0.45	0	-0.45	0	-0.45	0	-0.45	0	-0.45	0	-0.45	0	-0.45
13	0.16	0	0.16	0	0.16	0	0.16	0	0.16	0	0.16	0	0.16	0	0.16	0
14	0	-0.23	0	-0.23	0	-0.23	0	-0.23	0	-0.23	0	-0.23	0	-0.23	0	-0.23
15	0	-0.37	0	-0.37	0	-0.37	0	-0.37	0	-0.37	0	-0.37	0	-0.37	0	-0.37
16	0	-0.49	0	-0.49	0	-0.49	0	-0.49	0	-0.49	0	-0.49	0	-0.49	0	-0.49
17	0	-0.85	0	-0.85	0	-0.85	0	-0.85	0	-0.85	0	-0.85	0	-0.85	0	-0.85
18	0	-0.7	0	-0.7	0	-0.7	0	-0.7	0	-0.7	0	-0.7	0	-0.7	0	-0.7
19	0	-0.03	0	-0.03	0	-0.03	0	-0.03	0	-0.03	0	-0.03	0	-0.03	0	-0.03
20	0	-0.16	0	-0.16	0	-0.16	0	-0.16	0	-0.16	0	-0.16	0	-0.16	0	-0.16
21	0	-0.27	0	-0.27	0	-0.27	0	-0.27	0	-0.27	0	-0.27	0	-0.27	0	-0.27
22	0	-0.3	0	-0.3	0	-0.3	0	-0.3	0	-0.3	0	-0.3	0	-0.3	0	-0.3
23	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2	0	-0.2
24	0.17	0	0.17	0	0.17	0	0.17	0	0.17	0	0.17	0	0.17	0	0.17	0
25	0.36	0	0.36	0	0.36	0	0.36	0	0.36	0	0.36	0	0.36	0	0.36	0
26	0.61	0	0.61	0	0.61	0	0.61	0	0.61	0	0.61	0	0.61	0	0.61	0
27	0.85	0	0.85	0	0.85	0	0.85	0	0.85	0	0.85	0	0.85	0	0.85	0
28	1.11	0	1.11	0	1.11	0	1.11	0	1.11	0	1.11	0	1.11	0	1.11	0
29	1.34	0	1.34	0	1.34	0	1.34	0	1.34	0	1.34	0	1.34	0	1.34	0
30	1.01	0	1.01	0	1.01	0	1.01	0	1.01	0	1.01	0	1.01	0	1.01	0
31	0.34	-0.32	0.34	-0.32	0.34	-0.32	0.34	-0.32	0.34	-0.32	0.34	-0.32	0.34	-0.32	0.34	-0.32
32	0	-2.17	0	-2.17	0	-2.17	0	-2.17	0	-2.17	0	-2.17	0	-2.17	0	-2.17
33	0	-1.23	0	-1.23	0	-1.23	0	-1.23	0	-1.23	0	-1.23	0	-1.23	0	-1.23

Appendix D - TES modelling software

D.1. GUI design tools in the Microsoft Visual Studio 2015



D.2. coding sample from the TES modelling tool developed in Microsoft Visual Studio 2015