Thermal Energy Storage in Residential Buildings:
A study of the benefits and impacts

by

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This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

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ABSTRACT

Residential space and water heating accounts for around 13% of the greenhouse gas emissions of the UK. Reducing this is essential for meeting the national emission reduction target of 80% by 2050 from the 1990 baseline. One of the strategies adopted for achieving this is focused around large scale shift towards electrical heating. This could lead to unsustainable disparity between the daily peak and off-peak electricity loads, large seasonal variation in electricity demands, and challenges of matching the short and long term supply with the demands. These challenges could impact the security and resilience of UK electricity supply, and needs to be addressed. Rechargeable Thermal Energy Storage (TES) in residential buildings can help overcome these challenges by enabling Heat Demand Shifts (HDS) to off-peak times, reducing the magnitude of the peak loads, and the difference between the peak and off-peak loads. To be effective a wide scale uptake of TES would be needed. For this to happen, the benefits and impacts of TES both for the demand side and the supply side have to be explored, which could vary considerably given the diverse physical, thermal, operational and occupancy characteristics of the UK housing stock. A greater understanding of the potential consequence of TES in buildings is necessary. Such knowledge could enable appropriate policy development to help drive the uptake of TES or to encourage development of alternative solutions.

Through dynamic building simulation in TRNSYS, this work generated predictions of the space and water heating energy and power demands, and indoor temperature characteristics of the UK housing stock. Twelve building archetypes were created consisting of: Detached, semi-detached, mid-terrace and flat built forms with thermal insulation corresponding to the 1990 building regulation, and occupied floor areas of 70m^2, 90m^2 and 150m^2. Typical occupancy and operational conditions were used to create twelve Base Case scenarios, and simulations performed for 60 winter days from 2nd January. HDS of 2, 3 and 4 hours from the grid peak time of 17:00 were simulated with sensible TES system sizes of 0.25m^3, 0.5m^3 and 0.75m^3, and water storage temperatures of 75°C and 95°C. Parametric analysis were performed to determine the impacts and benefits of: thermal insulation equivalent to 1980, 1990 (Base Case), 2002 and 2010 building regulation; locations of Gatwick (Base Case) and Aberdeen; heating durations of 6, 9 (Base Case), 12 and 16 hours per day; thermostat settings of 19°C, 21°C (Base Case) and 23°C, and number of occupiers of 1 person and 3 persons (Base Case) per household.

Good correlation was observed between the simulated results and published heat energy consumption data for buildings with similar thermal, physical, occupancy and operational conditions. The results allowed occupied space temperatures and overall daily and grid peak time energy consumption to be predicted for the range of building archetypes and parameter values considered, and the TES size necessary for a desired HDS to be determined. The main conclusions drawn include:

- The overall daily energy consumption predictions varied from 36.8kWh to 159.7kWh. During the critical grid peak time (17:00 to 21:00) the heat consumption varied from 4.2kWh to 58.7kWh, indicating the range of energy demands which could be shifted to off-peak times.
- On average, semi-detached, mid-terrace, and flat built forms consumed 7.0%, 13.8% and 22.7% less energy for space heating than the detached built form respectively.
- Thermal insulation changing from the 1990 building regulation level to the 1980 and 2010 building regulation levels could change the mean energy use by +14.7% and -19.6% respectively.
- A 0.25m^3 TES size with 75°C water storage temperature could enable a 2 hour HDS, shifting 4.3kWh to 11.7kWh (mean 8.7kWh) to off peak times, in all 70m^2 Base Case archetypes with the 60 day mean thermal comfort of 100%, but with the minimum space temperature occasionally dropping below an 18°C thermal comfort limit.
- A 0.5m^3 TES size and water storage of 95°C could allow a 3 hour HDS, shifting 9.8kWh to 28.2kWh (mean 18.7kWh) to off peak times, in all 90m^2 Base Case archetypes without thermal comfort degradation below 18°C.
- A 0.75m^3 TES with a 95°C water temperature could provide 4 hour HDS, shifting 13.9kWh to 47.7kWh (mean 27.2kWh) to off peak times, in all 150m^2 Base Case archetypes with 100% mean thermal comfort but with the 60 day minimum temperature occasionally dropping below the 18°C thermal comfort limit in the detached built form.
- Improving the thermal insulation of the buildings was found to be the best way to improve the effectiveness of HDS with TES, in terms of the demand shift period achievable with minimal thermal comfort impact. A 4 hour HDS with 100% thermal comfort is possible in all 90m^2 floor area buildings with a 0.25m^3 tank and a water storage temperature of 75°C provided that the thermal insulation is as per 2010 building regulation.

Recommendations for further research include: 1) creating larger number of archetype models to reflect the housing stock; 2) using heat pumps as the heat source so that the mean effect on the grid from electric heating loads can be predicted; 3) taking into account the costs associated with taking up HDS with TES, in terms of capital expenses and space requirement for housing the TES system; 4) considering alternative methods of heat storage such as latent heat storage to enhance the storage capacity per unit volume; and 5) incorporating zonal temperature control, for example, only heating rooms that are occupied during the demand shift period, which could ensure better thermal comfort in the occupied space and extend the demand shift period.

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ABBREVIATIONS

ABS	Actual Building Sample
ACH	Air Change per Hour
ASHRAE	American Society of Heating Refrigeration and Air-Conditioning
BER	Building Energy Rating
BRE	Building Research Establishment
BREDEM	Building Research Establishment Domestic Energy Model
BSI	British Standards Institution
CAES	Compressed Air Energy Storage
CCC	Committee on Climate Change
CDEM	Community Domestic Energy Model
CHM	Cambridge Housing Model
CHP	Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of Performance
CTES	Cold Thermal Energy Storage
DCLG	Department of Communities and Local Government
DECC	Department of Energy and Climate Change
DHW	Domestic Hot water
DSM	Demand Side Management
DSP	Demand Shift Period
DUKES	Digest of United Kingdom Energy Statistics
ECUK	Energy Consumption UK
EER	Energy Efficiency Rating

EES	Electrical Energy Storage
EHS	English Housing Survey
EIA	Energy Information Administration
EM	Engineering Method
EMR	Electricity Market Reform
EPW	EnergyPlus Weather
ERP	Energy Research Partnership
EST	Energy Saving Trust
EV	Electric Vehicle
FF	First Floor
GF	Ground Floor
GHG	Green House Gas
HDS	Heat Demand Shift
HLC	Heat Loss Coefficient
HLP	Heat Loss Parameter
HP	Heat Pump
HRP	Household Reference Person
HVAC	Heating Ventilation Air Conditioning
IES-VE	Integrated Environmental Systems – Virtual Environment
IMechE	Institution of Mechanical Engineers
MKEP	Milton Keynes Energy Park
NASA	National Aeronautics and Space Administration
NTS	National Travel Survey
OECD	Organisation for Economic Cooperation and Development
ONS	Office of National Statistics

PCM	Phase Change Material
PCS	Phase Change Slurry
PHS	Pumped Hydro Storage
RET	Renewable Energy Technology
SAP	Standard Assessment Procedure
SDHW	Solar Domestic Hot Water Systems
SEL	Solar Energy Laboratory
SM	Statistical Method
SMES	Superconducting Magnetic Energy Storage
TES	Thermal Energy Storage
TMY	Typical Metrological Year
TRNSYS	Transient Systems
TRV	Thermostatic Radiator Valve
TTP	Top-up Period
TUS	Time-Use Survey
UKDCM	UK Domestic Carbon Model
UKEALR	Electricity Associate Load Research
UKERC	UK Energy Research Centre
UKHEFF	United Kingdom Housing Energy Fact File
UNCED	United Nations Conference on Environment and Development
UNFCCC	United Nations Framework Convention on Climate Change

1 CHAPTER ONE: INTRODUCTION

Heat demand management in residential buildings, through demand shifting, can play a crucial role in overcoming the load balancing challenges of a future electricity grid with large residential heating loads (CCC, 2016; Eames et al., 2014; ERP, 2011). Rechargeable Thermal Energy Storage (TES) in domestic buildings can be used to shift the peak time electric heating loads to off-peak times, to match the demand with the supply, and enable the load balancing challenges to be mitigated. Using dynamic modelling and simulation of domestic buildings, their heating systems, and their operational and occupancy conditions, this thesis explores the potential impacts and benefits domestic TES can provide for both the demand and supply sides. These include energy consumption and cost, heating load and energy profile uniformity, thermal comfort parameters of the occupied spaces, and their sensitivity to different building archetypes, operational conditions and occupancy scenarios. This thesis also identifies and recommends domestic TES strategies which can aid policy development to enhance the security and resilience of the future electricity system in the UK.

1.1 Research Context

Climate change mitigation and energy security are amongst the most important issues in the energy policy agenda. An example of this is an extract from the annual energy statement of the UK government concerning energy and climate change published in 2010 which reads:

> *"The mission of this Government is to support the transition to a secure, safe, low-carbon, affordable energy system in the UK, and mobilise commitment to ambitious action on climate change….."* (DECC, 2010)

The result of such goals by successive governments during the last two decades resulted in the adoption of the Climate Change Act 2008 (HM Government, 2008). This legally binds the UK to reduce the national greenhouse gas emission by 80% by 2050, compared to the 1990 level, and derive 15% of our total energy consumption from renewable sources by 2020. This commitment was further cemented by becoming a signatory of the recent earth summit (COP21) which took place in Paris in December 2015, that legally binds the signatory countries to recognise and take necessary actions to limit the global average temperature rise to below 2°C above pre-industrial levels (UN, 2015). UK's targets and policy for achieving them have been ambitious, and among a group of leading nations (Bassi et al., 2016). However, despite the targets remaining unchanged, there have been signs, recently, that the policy and drive for achieving them might be weakening. For example, the current government has abolished the Department of Energy and Climate Change (DECC) and replacing it with Department for Business, Energy and Industrial Strategy (BEIS) in which energy and climate change is a relatively small part (Johnston, I., 2015).

To meet the obligations, all energy demand sectors will need to be decarbonised[1] by at least 80% and the use of energy from renewable sources increased. Such ambitions will require major changes in the way energy is used by individuals, by the private sector and by the public sector, towards a path of reduced dependence on fossil fuels and increased use of renewables. A sustained shift in this direction could lead to an energy system with a more diverse energy generation mix including for example nuclear, gas, coal, solar, wind, biomass, wave and tidal power (CCC, 2016; CCC, 2008; DECC, 2011). Greater deployment of renewables could mean large variability in electricity supply due to the intermittency in renewable generation such as wind and solar power, resulting in under and over production. The quality of the electricity supply could also degrade due to the aggregation of electricity from a large number of distributed renewable generators (Wilson et al., 2013; ERP, 2011; Hall, 2008).

The UK's 2050 energy policy ambitions could increase the demand for electricity due to the greater electrification of energy demand sectors which rely on fossil fuels, such as residential space heating and transportation. This view is supported by the fact that the scenarios developed by the Committee on Climate Change[2] (CCC) for achieving the UK's interim carbon budgets[3] and the 2050 emissions targets focus largely on the UK moving to a 'highly-electric' future (Foxon, 2013). The electrification of such energy demand sectors may be necessary to transfer the corresponding greenhouse gas emissions to more centralised locations, for example to centralised electricity power plants. The relating emissions could then be abated through the

[1] Decarbonisation refers to energy with no or a low level of CO_2 emission in its conversion process, used to power systems such as a domestic building.

[2] An independent body of experts which advises the UK Government on tackling and preparing for climate change.

[3] Carbon budgets are set based on recommendations by the CCC, to ensure the UK remains on target to meet its greenhouse gas emission obligations.

deployment of technologies such as low carbon generation methods and carbon capture and storage (Wilson et al., 2013; CCC, 2008).

The combined impact of the increased intermittent renewable generation and greater demand for electricity could provide significant challenges for the grid to meet the requirements, both in terms of supply quality and quantity, affecting the security and resilience of the future energy system (Wilson et al., 2013; ERP, 2011; Hall, 2008;).

The energy consumption and the greenhouse gas emission in the UK domestic building sector is second highest after the transportation sector. Around 79% of the energy demand in domestic buildings comes from space and water heating. Therefore a substantial proportion of the national greenhouse gas emission is directly related to domestic heating (CCC, 2016; HM Government, 2009; DECC, 2011a). According to the BEIS (formerly DECC) it would be impossible to meet the 2050 emission target without changing the emissions from homes, and that decarbonisation of space heating has to be part of any emission reduction solution (DECC, 2011a). As previously mentioned, this action could involve electrification of domestic space and water heating. Due to the large, complex and diverse nature of the UK domestic building stock, and the large demand for heat during the winter season, even a partial electrification of heating could pose serious implication for the electricity generation and distribution networks (Wilson et al., 2013). The building stock and its thermal and energy performance characteristics will dictate the nature of the future electric heating load, and the challenges for the future electricity grid. Therefore it is necessary to appreciate the nature of the building stock in order to better understand the potential consequences of electrifying the space and water heating.

The UK residential building sector comprised of over 27 million homes in 2014 (DCLG, 2014). Over 90% of these homes use natural gas for heating. Consequently heating (space heating, water heating and cooking) in the residential building sector is one of the main contributors of greenhouse gases in the UK. In 2015, 66.3 $MtCO_2e$[4] of greenhouse gas emissions resulted from space and water heating in residential buildings, equivalent to approximately 13% of the total 2015 emissions in the UK of 495.7 $MtCO_2e$. The primary constituent of greenhouse gas emissions from heating domestic buildings is carbon dioxide (CO_2) although methane, nitrous oxide

[4] MtCO2e refers to Million Tonnes of Carbon Dioxide Equivalent.

and fluorinated gases are also found, but only represent less than 1% of the total emissions (BEIS, 2017).

Lowe (2007) describes various options and strategies which could be employed in decarbonising the UK housing stock. One of these options is electrifying heating, more specifically Domestic Hot Water (DHW) and space heating, and ensuring that the electricity used is sourced from low carbon or renewable generation. This could be particularly effective considering that DHW and space heating account for 17% and 66% of the total energy use in the homes respectively (HM Government, 2009; DECC, 2011a). The use of heat pumps is an example of the technology that could electrify heating, which are widely used in many countries, for example France and Sweden (CCC, 2016). Arteconi et al., (2013) discuss the role and uses of heat pumps in this context, indicating opportunities and potential for adoption in both new and existing buildings. Research by the Energy Research Partnership (ERP, 2011) predicts that heat pumps could attain over 50% penetration by 2030 and over 75% by 2050. Strbac et al., (2010) indicated that a maximum penetration of heat pumps could mean the grid load increasing by an additional 45GW, which could coincide with the existing system peak of around 60GW. The aggregated daily demand from heat pumps for a cold winter day was estimated at around 460GWh, representing over 40% of the existing winter daily demand. Other options for electrifying heating include resistive storage[5] and direct resistive[6] heating.

The effect of all of these options will be to exert new challenges to the grid in the form of strong seasonal electricity load variation, given that there is a considerably larger winter time heat demand compared to the summer time. As shown in Figure 1-1, the maximum half hourly winter time low grade heat demand, as typically used in DHW and space heating, is around 300GW (domestic and industrial), and is considerably higher than the summer time peak figure of around 60GW, indicating seasonal variation. The electricity demand on the other hand is relatively similar throughout the year. As can be seen, the winter time weekly peak electricity load is around 60GW and cycles, due to low weekend and high weekday demands, which can be between 20-30GW. Daily electricity load variation also exists, due to higher daytime demand compared to the night time demand, which can again vary by 20-30GW.

[5] Using electrical resistive elements for heating and storing heat, as per the existing electrical storage heating.
[6] Using electrical resistive elements for directly heating the living spaces, without storage.

Considering the difference between the hourly electricity and heat load during the winter days, transferring the daily heating load over to the electricity grid could render the matching of the short-term peak demand and supply unsustainable. Domestic heating systems are used during similar occupied hours in the mornings and evenings throughout the UK. Therefore heating using electricity could potentially create large disparity between the daily peak and off-peak loads (Wilson et al., 2013; ERP, 2011). The effect of this disparity could be minimised by spreading the daily heating load (or the times when energy is drawn from the grid) over a longer time period or entirely shifting it to an off-peak time. However, this has to be done with the DHW provision and the space heating still being available during the occupied hours, to prevent disruption to the thermal comfort levels. This means that the temporal link between the heat demand and supply has to be removed, in other words the link between the real-time use of heat in the dwellings and the time when energy is drawn from the grid to meet this demand has to be de-coupled.

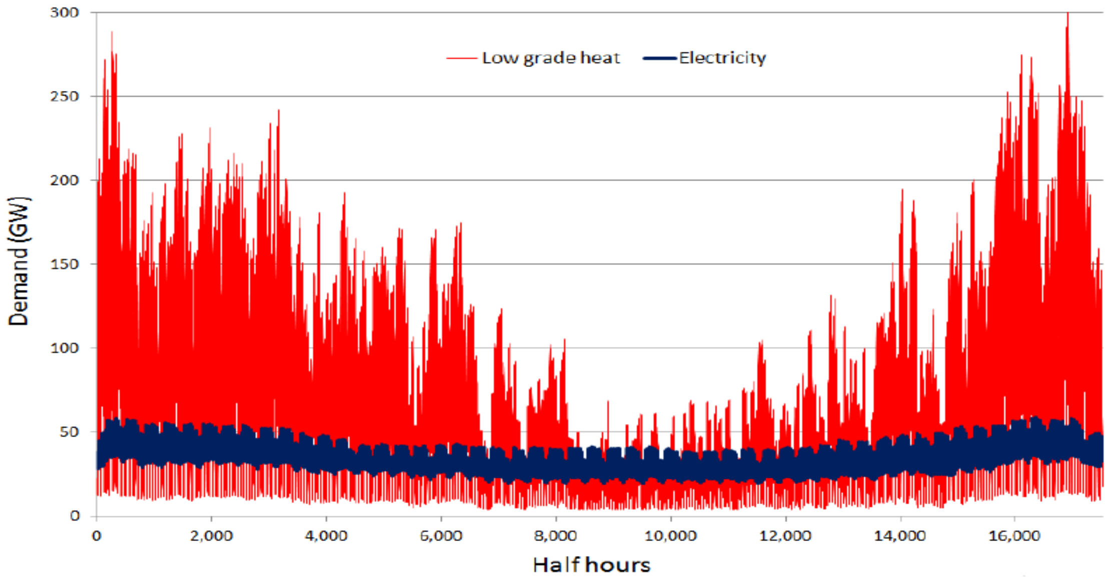


Figure 1-1. Comparison of half hourly UK heat and electricity demand over one year (domestic and industrial). (Source: Imperial College)

One way to overcome these challenges is to have grid connected rechargeable TES capability in the dwellings. The principle behind a rechargeable TES system is to supply heat (during charging) to a storage device, such as a hot water storage tank, and remove the heat (during discharging) for use at a later time (Arteconi et al., 2013). An example of a rechargeable TES system is the solar thermal hot water storage tank which stores heat (charging) during the day, and the stored heat is removed (discharging) to serve the DHW needs at other times. Grid connected rechargeable TES systems (for DHW and space heating) can be charged up during low demand and/or off-peak times. The stored heat can be used later during the grid peak time to service the space heating and DHW demand, without the need to draw energy from the grid during the peak time. Figure 1-2 demonstrates how TES could be used to mitigate and minimise the impact of greater electrification of heating using a real electricity load curve for a November 2011 weekday (blue trace) (National Grid, 2014). It can be seen that the demand peaks during 16.30 to 20.30 'Grid Peak' whilst it is lowest during the period 00.00 to 07.00 'Grid Off-Peak'. In a future grid, the demand in the morning and the evening periods may be higher due to the increased use of electricity for heating, an arbitrary example of which is shown by the red trace in Figure 1-2. The peak load in this scenario is larger compared to the current peak load. So, to accommodate the extra demand additional generation capacity will be required, which may not always be financially viable. The capital cost of providing the extra capacity could be avoided by using the existing generators to charge up the TES systems during the grid off-peak times or 'Top-up Period'. The stored energy could then be used later during the grid peak period or the 'Demand Shift Period' to heat the living spaces and the DHW, thereby shifting the demand from the Grid Peak time to the Grid Off-peak Time as shown by the green zones in Figure 1-2. This would have a load flattening effect. Such an approach would ensure the running of existing electricity generators at higher load factors[7] during low demand times, and therefore operating more cost effectively.

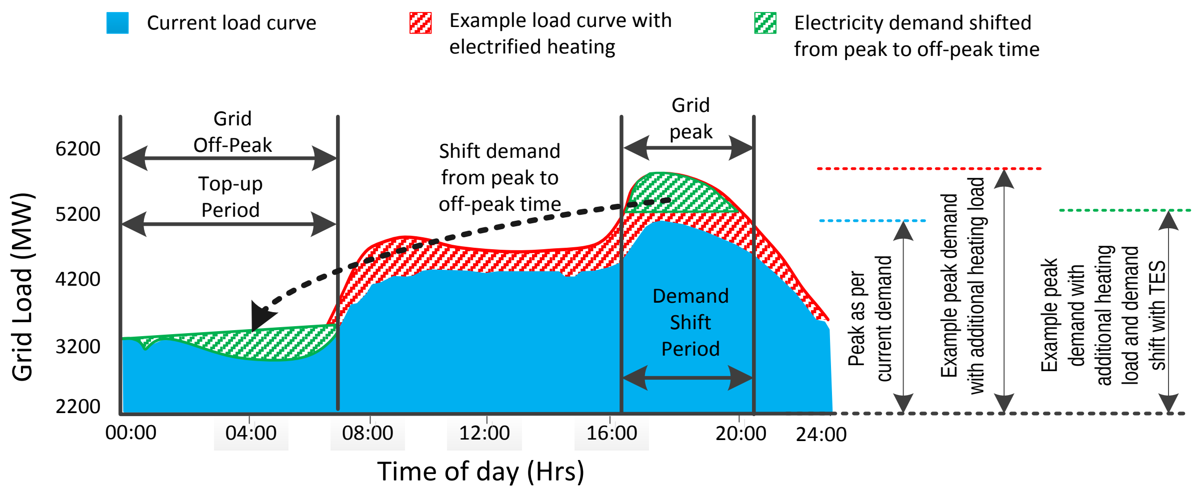


Figure 1-2. Illustration of a real diurnal grid load curve for a November 2011 weekday, the daily peak and off-peak periods, the potential heat demand shift period and an example of the effect of electrification of domestic heating, and how a future peak demand could be reduced by demand shifting in time using rechargeable TES. (Source of load curve: National Grid, 2014).

[7] Load factor is a ratio of the average and the peak load in a specified time period. Low load factor means that the peak capacity sits idle for long periods imposing higher costs on the system.

Research by the energy regulator Ofgem indicated that a 5.7GW peak demand shift could translate into an annual capital cost saving of £330 to £540m. Also, a 5% to 10% reduction in the peak demand could result in an annual network investment cost savings of £14m to £28m, and an estimated annual emission reduction of 492 ktCO_2 to 792 ktCO_2 respectively (Ofgem, 2010).

Rechargeable TES systems can also be arranged to absorb surplus electricity generated by the intermittent renewables such as solar and wind farms. These renewable sources are often switched off at times of high generation and low demand, at a considerable cost, to avoid spilling[8]. A recent example of this is a wind farm which was paid £1m to shut down for one day because of a lack of demand for the electricity it generated (Johnson, 2013). Avoiding such occurrences through the use of TES could make the renewable infrastructure more cost effective, reduce the carbon content of the electricity and also enable the grid to accommodate more renewable generators.

Demand Side Management (DSM) techniques are described in the literature as essential, especially in the presence of a dynamic electricity generation and demand regimes, which could be used to achieve the load flattening effect as illustrated in Figure 1-2. DSM includes activities such as energy efficiency improvement of domestic appliances and demand side response, designed to influence the end user's energy use, in terms of magnitude and timings. The focus is mainly on changing the shape of the load and thereby helping to balance the supply side with the demand side of the electricity system (Ofgem, 2010; Arteconi et al., 2013). In a future scenario with greater electric heating in homes, TES could be a particularly effective tool for DSM given that nearly 80% of the total energy demand in homes comes for heating. This view is strengthened by the assertion of Strbac et al., (2010) that the heat demand sector has significant inherent storage capabilities which presents us with *'unprecedented opportunities for utilising demand side response, not only to optimise electricity production capacity but also to enhance the efficient provision of network capacity'*. This shows that TES could provide a significant economic, technical and carbon reduction benefits. The overall benefit to the energy system will be of greater value with larger uptake of TES by the households. To encourage uptake into the existing and the new buildings there must be direct

[8] Spilling refers to the production of more electricity than the demand

benefits for the participating households (Hewitt, 2012), and the benefits have to be demonstrated at the individual household level.

In 2016, over 11 million homes in the UK already had a hot water storage tank installed for providing DHW services (BEIS, 2016). Therefore, a great opportunity exists to achieve a high level of TES uptake through upgrading the existing hot water storage tanks to TES systems which are connected to both space heating and DHW. The upgrade could include, for example, replacing the existing water tanks with ones which can store water at higher temperatures and have lower heat loss, thereby increasing the energy storage capacity and efficiency of the system.

There are a number of ways households can derive benefits through the use of TES. For example, Hewitt, (2012) states that households could take advantage of different electricity tariffs prices for peak and off-peak hours, such as those provided by the Economy7[9] and Economy10[10], to charge up the TES and therefore reduce the heating bills. Ofgem's review of trials involving DSM in domestic buildings outside of the UK highlighted various benefits, including savings on electricity bills between 7% and 10% in addition to the carbon and network investment savings as already mentioned (Ofgem, 2010). Applying DSM in the UK in conjunction with effective TES systems, the benefits could be considerably higher given that heating accounts for around 80% of the total energy use in homes. Furthermore, surplus electricity from onsite micro generation such as solar PV and micro wind turbines could be utilised locally to charge up the TES, removing the need to export the excess output to the grid, improving the efficiency and cost effectiveness of these systems.

Clearly there are benefits to be gained from the use of TES in buildings. However there are drawbacks as well, for example in terms of technology and infrastructure costs, as well as the costs and inconvenience associated with using up space in the buildings to accommodate the TES system. Also, there would be a cost in terms of 'hassle' during the installation and commissioning of the systems. Furthermore, there may be a reduction in the thermal comfort level in the dwellings if the TES is relied upon to provide the heating for too long. This could happen in cases where, for example, the stored heat in the TES system is depleted too quickly and no energy is drawn from the mains grid to heat the living spaces to the required temperature in

[9] Economy 7 provides electricity at a discounted rate for 7 hours; from 12 midnight to 7am.

[10] Economy 10 provides electricity at a discounted rate for 10 hours; for example 3 hours in the afternoon, 2 hours in the evening and 5 hours over night depending on the supplier

order to avoid high peak time electricity prices. Also for similar reasons, the TES may not be able to adequately maintain the space temperature to the required level when the external ambient temperature drops too low, thus degrading the thermal comfort levels. These are areas which need greater understanding to fully appreciate the potential of domestic building scale TES and are the focus of this work.

1.2 Research Questions

The challenges and opportunities in decarbonising domestic buildings in the UK, and overcoming the undesirable consequences of a highly electrified future are widely debated by the relevant scientific, political and business communities (CCC, 2016; Eames et al., 2014; Foxon, 2013; Wilson et al., 2013; ERP, 2011). This thesis contributes to this debate, particularly in the area of short-term matching of the future electricity supply and demand, through the use of residential building scale TES. The need for further research in this area is echoed in many recent reviews of energy storage in the UK, and calls have been made for deeper and better understanding of the scope, impacts and benefits of thermal storage in buildings through modelling and simulation (Eames et al., 2014; UKERC, 2011; ERP, 2011; Strbac et al., 2010; IMechE, 2014). The knowledge gained could enable informed decision making at the government, business and household levels, which may encourage (or discourage) the development and uptake of domestic building scale TES.

The following research questions will be addressed by this research;

1. ***What roles could small scale TES play in domestic heat demand management?***

   This research question inquires into the nature of the domestic building heating practices and its links to the wider energy system in terms of heat demand and supply: how this is expected to change in the future; what challenges and opportunities would be presented as a result; and how residential building scale TES can be used to exploit the opportunities and help overcome the challenges?

2. ***What TES technologies are available for application in residential buildings?***

   This includes conducting a review of TES technologies which are suitable for heat demand management application in residential buildings. TES application in residential buildings will be dependent upon factors such as size, cost and health and safety constrains. This question will ensure that research and development resources are appropriately focused.

3. ***What are the dynamics of heat demand in buildings and how do they vary with building typologies, their thermal characteristics, and the variation in occupancy and operational conditions?***

   This will prompt exploration of the heating characteristics of domestic buildings and how it changes with factors such as different build-forms, size, thermal performance, occupant behaviour, household demography, and weather conditions. Good understanding of the heating characteristics of the buildings is necessary as it will dictate the suitability and the functional requirements of the TES.

4. ***What is the scope of heat demand shifting in time by using residential building scale TES, and what are the potential benefits and impacts of using residential building scale TES?***

   The extent to which heat demand management could be achieved is a critical factor in their successful deployment. This research question enquires the impact of parameters such as the building fabric construction details, building use and occupant behaviour, household demographics and weather conditions, on the sensitivity and effectiveness of the TES.

5. ***What are the key building, occupancy, operational and TES parameters which could affect the effectiveness of heat demand shifting in domestic buildings using TES?***

   This research question inquires into the benefits and impacts of residential heat demand management using TES, both for the demand and supply sides stakeholders, for example energy bill savings and/or thermal comfort degradation for the households, and the amount of energy shifted from peak to off-peak times assisting grid balancing for the supply side. This is necessary to enable informed decision making to encourage/discourage uptake of TES and/or the development of alternative grid balancing solutions.

1.3 Aims and Objectives

The aim of this research programme is:

To investigate the demand for thermal energy in domestic buildings and the impacts of shifting this demand in time through the use of sensible thermal energy storage.

This aim is achieved through successful completion of the following six objectives:

1. *To review the potential role of domestic scale thermal energy storage in the UK energy system, and its relevance to the national energy policy.*

   This involves the relevant national energy policy and research publications relating to the present and the future direction of thermal energy use in domestic buildings, the potential impact on the energy system and how residential building scale TES can be used to drive the national energy policy agenda.

2. *To review the academic and non-academic literature relating to: the thermal performance and energy use characteristics of residential buildings in the UK; the TES technologies which are suitable for domestic heat demand management application; and the modelling and simulation of TES for heat demand management in domestic buildings.*

   This involves identifying the thermal performance and energy consumption driving factors and indicators in domestic buildings; identifying the physical and operational conditions such as build-form, building fabric construction and occupancy to represent the UK building stock and its use; and identifying the domestic buildings suitable thermal storage options, considering factors such as storage capacity, size and cost.

3. *To develop dynamic building, heating and TES system models to simulate the thermal and energy performance of residential buildings and the effects of heat demand shifting using TES in UK homes.*

   This involves: creating models of domestic buildings, and the related heating and TES system components, and the environment to which they are subjected (such as the weather conditions, occupancy and internal gains); development of a heat demand management performance assessment criteria; and validating the models through the comparison of inter-model performances and published domestic building heat energy consumption results.

4. *To simulate the winter time heat demand and thermal performance characteristics of common UK home types and how they are affected by varying building fabric thermal insulation, occupancy and operational conditions.*

This involves: simulating the occupied space thermal conditions and the energy performance parameters of residential buildings of a range of archetypes, studying the impact of different operational environments and occupancy scenarios; and identifying the sensitivity of these variables.

5. *To simulate heat demand management capabilities in domestic buildings using TES, to shift heat demand from the grid peak times to the grid off-peak times. To assess the benefits and trade-offs and how these change with varying TES sizes, building archetypes, operational conditions and occupancy scenarios.*

   This involves simulating the thermal and energy performance parameters of residential buildings with the heat energy source switched from the mains grid to the TES system during the grid peak times, and with the TES system replenished the during the grid off-peak times. The impacts and benefits in terms of energy consumption, heating load profile flatness, thermal comfort parameters of the occupied spaces are investigated, and their sensitivity to different building archetypes, operational conditions and occupancy scenarios are analysed.

6. *To identify and recommend further research, and recommend domestic thermal energy storage strategy to aid policy development to enhance the security and resilience of the UK energy system.*

   This involves analysis of the results to highlight the area of strengths and weaknesses of applying TES for domestic heat demand management, identifying how the weaknesses could be overcome and the strengths could be enhanced; synthesizing TES strategy for the domestic built environment which could improve its effectiveness, increase uptake and provide options to overcome the future electricity grid balancing challenges.

1.4 Thesis structure

This thesis is divided into eight chapters (see Figure 1-3). Each chapter begins with an introduction and ends with a summary.

Chapter 1: Provides an introduction to the research programme, describing the project and its context, justification of the subject as a research topic, the aims and objectives of the research, and a breakdown and a plan of this thesis for the benefit of the reader.

Chapter 2: Provides results of the literature review. The outcome of the analysis of the relevant academic literature are provided covering areas relating to the research topic, such as the demand for thermal energy in UK buildings and the role TES can play to enable this demand to be met, the TES technologies available and their application in this context, the academic research to date, and the methodologies and tools which can be used to help the researcher achieve the objectives of this research.

Chapter 3: Presents the research questions generated form the literature search, methodology and the methods used to ensure the execution of four research activities designed to provide answers to the research questions, ensure a timely meeting of goals which combine into meeting the set objectives, and ultimately results in achieving the aim of the research. The modelling tools and techniques used during the research are described providing evidence of the validity of the methods used.

Chapter 4: Presents the results of the simulation carried out to a range of building archetypes representing the UK housing stock (Base Case), with various occupancy and operational conditions, to determine their heat demand and thermal performance characteristics. Parameters analysed included energy consumption and costs, heating load profiles, occupied space heating and cooling transient responses and the daily occupied space thermal performance.

Chapter 5: Presents the results of the simulation performed to determine the heat demand shifting capability and its impact on the heating load, energy consumption and the occupied space thermal condition for a TES Reference Case level of TES and heat demand shifting intervention. The results include the heat demand and thermal performance measurements such as: energy consumption and costs, heating load profiles; occupied space temperature profiles and the impact on the heating load uniformity caused by the demand shift.

Chapter 6: Presents the results of the simulations carried to determine the impacts of the key energy consumption influencing: building, occupancy and operational parameters on the thermal condition of the occupied space, the power and the energy consumption. The results include the heat demand and thermal performance measurements such as: energy consumption, heating load profiles; occupied space temperature profiles, and identifying combinations of TES and building occupancy and operational parameters that could make heat demand shifting in domestic building more or less effective.

Chapter 7: Provides a detailed discussion and analysis of the results.

Chapter 8: Summarises and concludes the research and the findings, highlighting the contribution to knowledge and recommendation for further research.

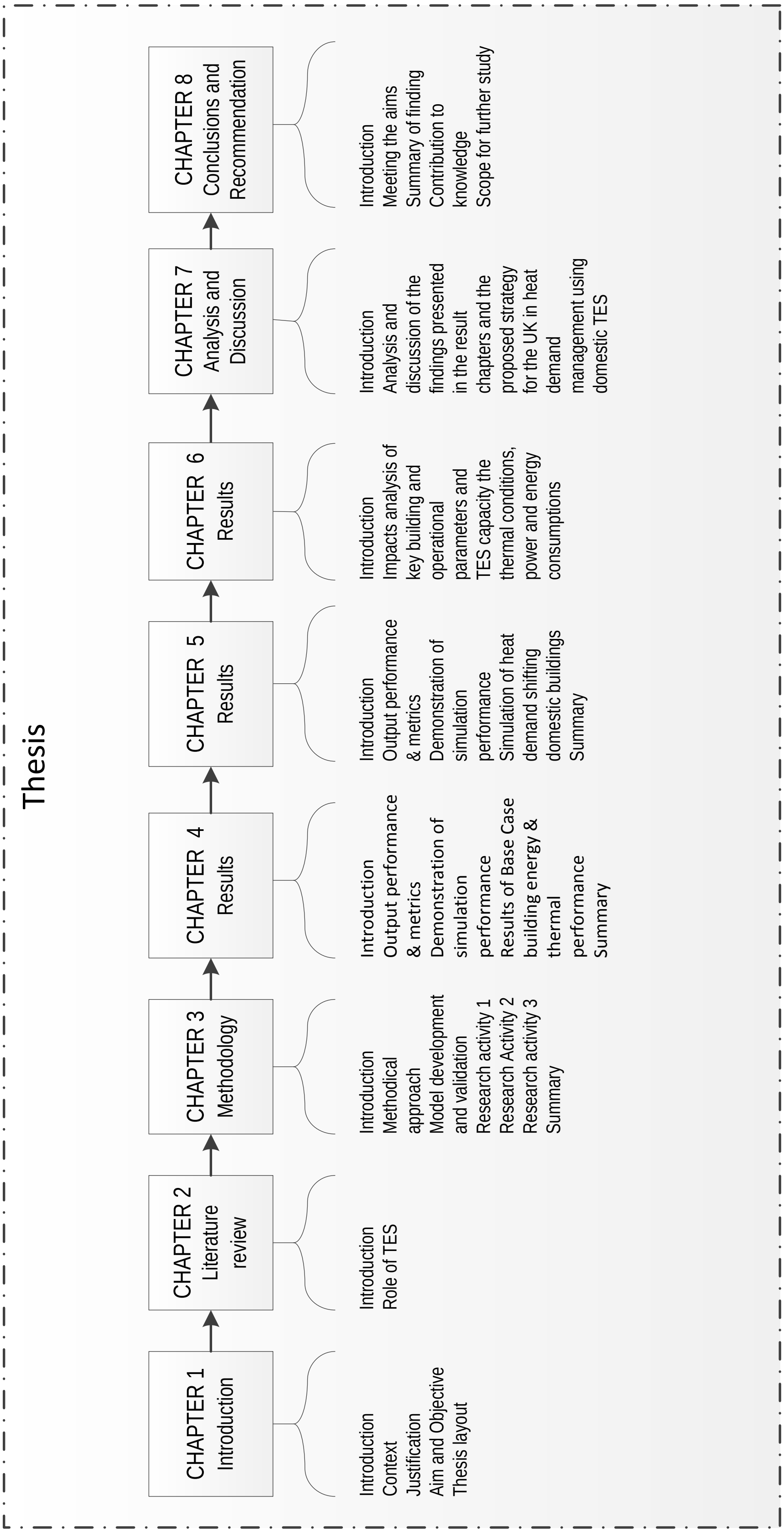


Figure 1-3. Thesis layout block diagram.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter provides details of the literature reviewed during the research programme. It is organised into five sections as described in this section.

A systematic approach to conducting literature review was adopted (Cronin et al., 2008). This approach ensures the use of explicit criteria to identify, critically evaluate and synthesize the findings to meet the requirements of the relevant research questions and objectives. The sources of the literature included books, conference and journal papers, reviews and articles. The literature were analysed and the relevant information extracted and organised according to six categories as described in the following sections:

Section 2.2: Describes the thermal energy storage needs and its role in the current and future energy system covering: Energy storage and its association with the energy system and the electricity generation, supply and distribution systems; Policy and legislative literature relating to energy storage and related technologies.

Section 2.3: Contains details of the review of the UK building stock, thermal performance, heating methods and heat demand characteristics including: Statistics of the UK domestic buildings; thermal and energy performance characteristics of buildings and buildings and the current domestic heating methods

Section 2.4: Contains the findings of the literature review on thermal energy storage for domestic buildings including thermal storage technologies and options available.

Section 2.5: Details the past research on domestic heating energy consumption covering: drivers and descriptors of heat energy in domestic buildings; heating practices in UK domestic buildings and domestic heat energy consumption studies.

Section 2.6: Contains details of the past research on modelling domestic buildings covering: commonly used modelling approaches and previous building modelling studies.

Section 2.7: Contains details of the past research on TES applications in domestic buildings and the modelling studies carried out on using TES in domestic buildings.

Section 2.8: Summarises the content of this chapter:

2.2 UK energy policy and storage

2.2.1 Overview

It is widely accepted that the effects of global warming will continue, and cause increasingly drastic climate change throughout the world. The disasters that follow as a result are no longer issues just for the national governments. Each and every one of us is directly affected by their impacts financially, physically and mentally. It is, therefore, important for us to take actions to mitigate climate change at all levels and capacities.

The United Nations Framework Convention on Climate Change (UNFCCC) has set up the United Nations Conference on Environment and Development (UNCED), which is also known as the Earth Summit. The first of these summits took place on 14th March 1992 in Rio de Janeiro, and the most recent one on the 17th of March 2010 in Cancun Mexico. The most well-known of these summits took place on 3rd of March 1997, in Kyoto Japan, resulting in the Kyoto Protocol. It sets out legally binding obligations for developed countries, specifically for those that have ratified the protocol, to reduce their greenhouse gas emissions. Furthermore, the Kyoto Protocol provides binding agreements for a worldwide reduction in the use of non-renewable energy. Enshrined in these agreements is the need to actively improve efficiency of current energy use and to look to alternative and sustainable energy sources. The latest summit, referred to as COP21, took place in Paris in November and December 2015, and resulted in 195 countries adopting a legally binding agreement, due to come into force in 2020. Some of the main points in the agreement include: *'Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*; *Recognizing the need for an effective and progressive response to the urgent threat of climate change on the basis of the best available scientific knowledge", and "Acknowledging that climate change is a common concern of humankind,……."* (UN, 2015)

Recognising global warming and the future risks of climate change, this agreement legally binds the signatory countries, including the UK, to take necessary actions.

The worldwide demand for energy is set to increase by 49% by the year 2035 (EIA, 2010). Of this, 84% is due to come from non-Organisation for Economic Cooperation and Development (OECD) countries such as India and China. Only 16% of the increase is expected in the OECD countries including Europe and North America. This will lead to greater competition for resources, affecting energy security and reliability of supply. Also, as shown in Figure 2-1, the use of renewables is projected to rise steadily, which may lead to challenges such as ensuring power quality and supply reliability (Hall, 2008).

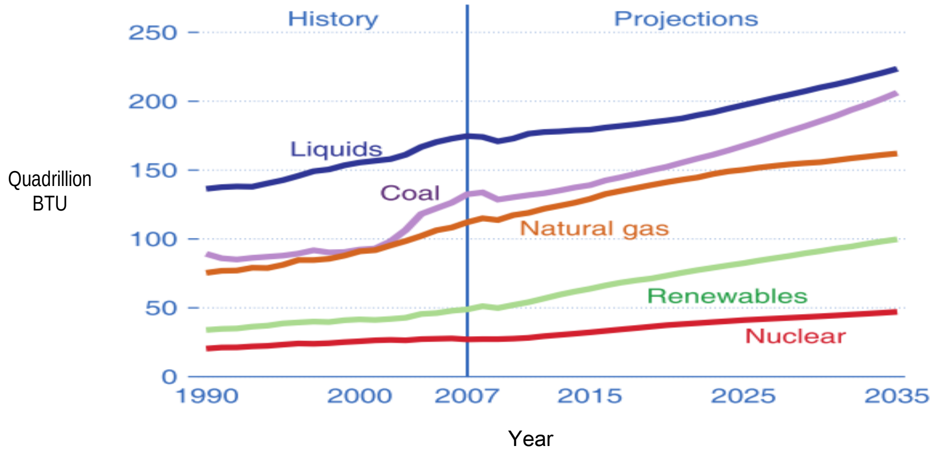


Figure 2-1. World energy demand by fuel type, 1990-2035 (quadrillion Btu) (EIA, 2010)

Over 30GW of electricity could be generated from wind power alone in the UK by 2050 (ERP, 2011). In such a scenario, a few days lull in wind could result in severely low electricity generation compared to the demand and therefore creating power shortage and supply reliability concerns. Also high wind fluctuation could give rise to grid balancing issues, where under or over production of electricity may result compared to the demand. The Energy Research Partnership (ERP) suggests that to mitigate these problems substantial energy storage capacity, higher than 10GW, may be needed (ERP, 2011). Energy storage, therefore, is considered a critical part of a future energy system and an integral part of the decarbonisation challenge facing the UK (Wilson et al., 2013; Wilson et al., 2010). In light of these projections, new energy policies are being developed, of which storage is a significant part, in order to ensure that the future energy security, economic, industrial and environmental targets are achieved (HM Government, 2009). Furthermore, the UK needs to act to ensure compliance with its climate change mitigation obligations, and also for the reasons of minimising the environmental consequences and the future costs of not acting (CCC, 2008; Wicks, 2009).

In the UK, the Climate Change Act 2008 provides the frame work for the relevant authorities to set targets for GHG reduction, energy generation and energy security objectives. The coalition government outlined energy policy in the Annual Energy Statement (DECC, 2010). The key policy theme covered four areas focusing on transforming the UK into a ‘Low Carbon Society’. One of the drivers of this policy objective is the legally binding target to reduce the UK CO_2 emission by 80% against a 1990 baseline. Also, 15% of the primary energy is to be generated from renewable energy sources by 2020, which translates to generating 30% of the electricity from renewable sources (H.M. Government, 2009; DECC, 2011b).

The Climate Change Act 2008 (HM Government, 2008) formally set these targets as legally binding. Essentially, the act provides a framework for the UK to achieve its long-term goals of reducing GHG emissions, and to ensure steps are taken towards adapting to the impacts of climate change and energy security concerns.

The Department of Energy and Climate Change (DECC) has commissioned numerous studies to explore and scrutinise the magnitude and complexity of meeting the targets. In the 2050 Pathway Analysis report (DECC, 2010a) DECC describes 6 potential energy pathways for the UK, which could lead to meeting the 2050 emission and energy targets. The report recognises energy storage as an essential part of majority of the pathways, necessary to provide functionality such as back-up capacity, grid balancing and flexibility for incorporating different generation mix, essentially to mitigate problems associated with large intermittent and distributed generation capacity.

MacKay (MacKay, 2009) illustrates six options covering a range of schemes that could meet the energy needs of the UK. Again storage of energy is a large factor in all of the scenarios with the exception of one which assumes the use of large scale nuclear generation with very little diversity of energy mix.

The UK Energy Research Centre (UKERC) has analysed a number of energy pathway scenarios (UKERC, 2009). Storage is also emphasised by UKERC as crucial to building in resilience to the UK energy system.

The UK Electricity Market Reform (EMR) is a measure to be employed to drive the energy and climate change agenda. It is expected to facilitate greater investment in the UK energy system, drive up the uptake of RET and enable transition to a decarbonised electricity sector (DECC, 2010b). Energy storage is recognised as an integral part of the EMR measures, needed to ensure a more flexible and diverse generation mix.

Although the importance of storage has been recognised in most energy pathway analyses, the exact role it could play and its value has been kept relatively abstract, and often mentioned in 'passing'. Current energy system models do not include energy storage, particularly small scale storage, for the reasons that it is difficult to put a value to the economic or technological benefits storage brings, and also because the models operate over long time scales compared to existing storage facilities (UKERC, 2011). More recently however, storage is being given considerable attention by organising workshops and commissioning specific studies on the role it can play. Experts from industry, government and academia attending a stakeholder workshop on storage recognised that:

> *"…lack of a clear numerical understanding of the value proposition of storage could lead to missed opportunity for the UK, both in terms of the transition towards an efficient low carbon energy system, and a possible export market for storage technologies worldwide.*" (UKERC, 2011).

The literature identifies a need for carrying out in-depth research in storage in the UK, given the potential role it could play in climate change mitigation, ensuring energy security and economic development. This is further highlighted by Wilson et al., (2010) by concluding that:

> *"…..decarbonisation challenge facing the UK electricity sector should be viewed not only as a supply and demand challenge, but also as a storage challenge."* (Wilson et al., 2010)

Energy storage is complex due to its diverse range of applications and scales of use in terms of size and time-scale. Small scale distributed storage systems provide benefits in short time scales and quantities. For these reasons storage cannot be evaluated effectively without some understanding of the energy supply and end-use (Dincer and Rosen, 2011). Therefore the structure and characteristics of the energy supply and demand sectors have been reviewed in this thesis, to establish an appreciation for the relationship and dependence with energy storage. Such storage is not effectively represented in the energy system models due to a lack of high temporal resolution (UKERC, 2011) and uncertainties of cost and performance (ERP, 2011). Experts have called for action to enable better understanding of the technoeconomic conditions under which storage can play a role. Detailed and time resolved modelling approaches which should also provide a framework to assess the cost and CO_2 saving potential of storage for different scenarios, as well as the cost and impact of not providing this storage capacity have been identified as areas where knowledge is lacking and where research effort should be focused (UKERC, 2011).

2.2.2 UK energy system

To fully understand the potential role of residential building scale thermal storage in the UK, it is important to gain an understanding of the energy system components it would interact with both now and in the future. For example, it is important to appreciate the current state of UK electricity supply and demand, and the future challenges which may be imposed upon it due to the forthcoming changes to the way electricity is produced. In turn, the challenges may impact the way electricity can be used in homes in terms of availability, quality and price.

The UK Energy Research Centre's (UKERC) definition of the energy system is as follows:

> *"The set of technologies, physical infrastructure, institutions, policies and practices located in and associated with the UK which enables energy services to be delivered to UK consumers".* (UKERC, 2009a)

Technology sectors such as primary energy sourcing, power generation, conversion and storage are all an integral part of the energy system. In 2013, 86.2% of the overall energy consumed in the UK was sourced from fossil fuels, whilst 12.9% was derived from low carbon sources (ONS, 2014). The low carbon sources included energy production from nuclear and renewables such as wind, hydro and biofuels.

The UK is a net importer of all four of the main fuel types consumed, and in 2013 around 47.1% of the total primary energy demand was met through imports, making the UK a net importer of energy (ONS, 2014). In 2013 natural gas was the dominant fuel type used in the UK, around 50% of which was met through imports. According to the Institution of Mechanical Engineers (IMechE), 80% of our gas demand is projected to be met through imports by 2020 (IMechE, 2011). Given the more recent activities in shale gas discovery and production, this may change. However, numerous uncertainties remain for which the recovery factor, or the quantity of gas which we might be able to realistically extract given the appropriate technology, economics and other factors, is yet to be determined (Andrews, 2013), which may impact our natural gas import projections.

As discussed in Section 2.2.1, greater competition for energy from developing countries and the unstable source of supply being in volatile countries such as the Middle East and Russia, presents the UK with a tough challenge in ensuring energy security (EIA, 2010). The government has identified three elements pertinent to the issue of energy security:

1. **Physical security:** avoiding involuntary physical interruptions to consumption of energy (i.e., the lights going out or gas supplies being cut off);
2. **Price security:** avoiding unnecessary price spike imbalances or poor market operation (e.g. market power); due to supply/demand.
3. **Geopolitical security:** avoiding undue reliance on specific nations so as to maintain maximum degrees of freedom in foreign policy.

(UKERC, 2009a)

The literature indicates that building resilience into the energy system will, to a large extent, address the energy security issues. Energy storage with its potential to enable back-up generation capacity, accommodation and integration of larger quantity of intermittent distributed generation can be used as a means of infusing resilience into the energy system (IMechE, 2014). The 'resilience' of an energy system is defined as follows:

"Resilience is the capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs circumstances." (UKERC, 2009a)

Three key elements of a resilient energy system are (UKERC, 2009a):

1. Lower level of energy demand and import, implying reducing demand and increasing local sourcing;
2. Diversity of supply; and
3. Robust physical infrastructure.

These imply that a resilient energy system will consist of mechanisms which will enable energy demand management and reduction, and integrate a diverse mix of electricity generation technologies, including non-load following and intermittent RET. Also, it will have to withstand the peak demands and a diverse range of energy sources. At the same time, the energy system has to contain mechanisms for the climate change mitigation challenges, such as CO_2 emission reduction, to be addressed.

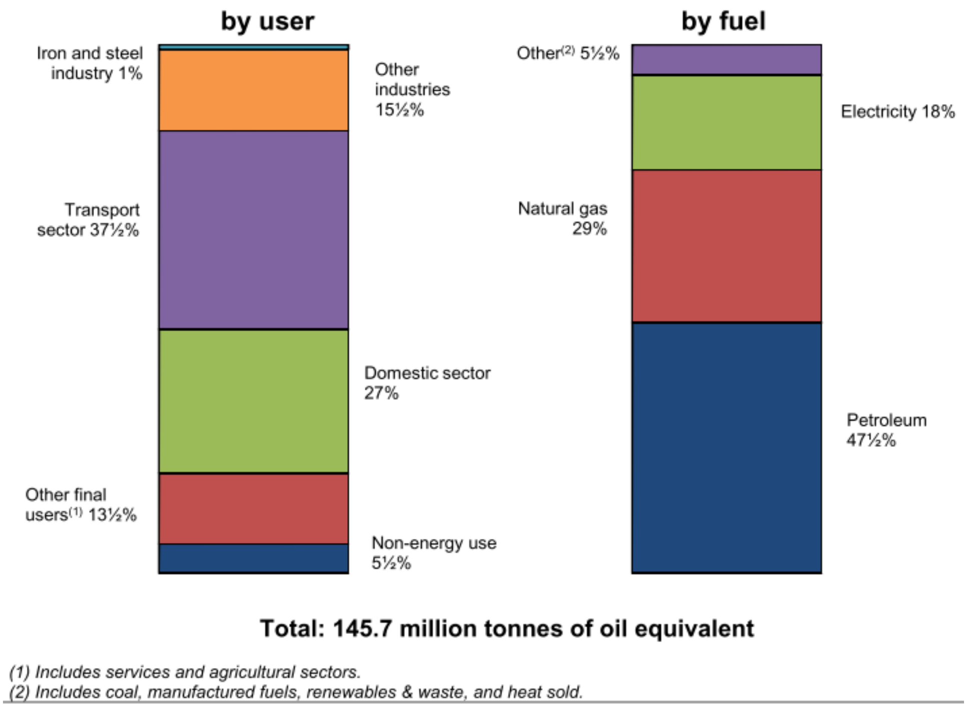


Figure 2-2. Breakdown of overall UK final energy consumption by sector and by fuel type in 2015. (ONS, 2016)

The Digest of United Kingdom Energy Statistics (DUKES) categorises the energy use in the UK into five main sectors; 1) Domestic; 2) Industry; 3) Transport, 4) Other energy users, and 5) Non-energy users, as shown in Figure 2-2. In 2015 the domestic building sector was the second largest consumer at 27.0%, following the transport sector which had 37.5% of the overall final energy consumption. It is estimated that the domestic energy demand will increase by 0.3% per year to 2035 in OECD countries such as the UK (EIA, 2011), and so will remain a significantly large energy consuming sector. Figure 2-2 also shows the final energy consumption in the UK by the main fuel type. It can be seen that Petroleum, which is mainly used in the transportation sector, dominates with a 47.5% share whilst natural gas and electricity comprising of 29.0% and 18% respectively. In 2015, around 82% of the overall primary energy was sourced from fossil fuels whilst only 16.5% was derived from low carbon sources such as nuclear, wind, hydro and biofuels (ONS, 2016). This provides a sense of the magnitude of the challenges for the UK in terms of reducing the overall national carbon emission by 80% by 2050 from the 1990 level, or reducing it from a total emission in 2006 of 695 $MtCO_2e$ to a value of 159$MtCO_2e$ by 2050, as illustrated in Figure 2-3.

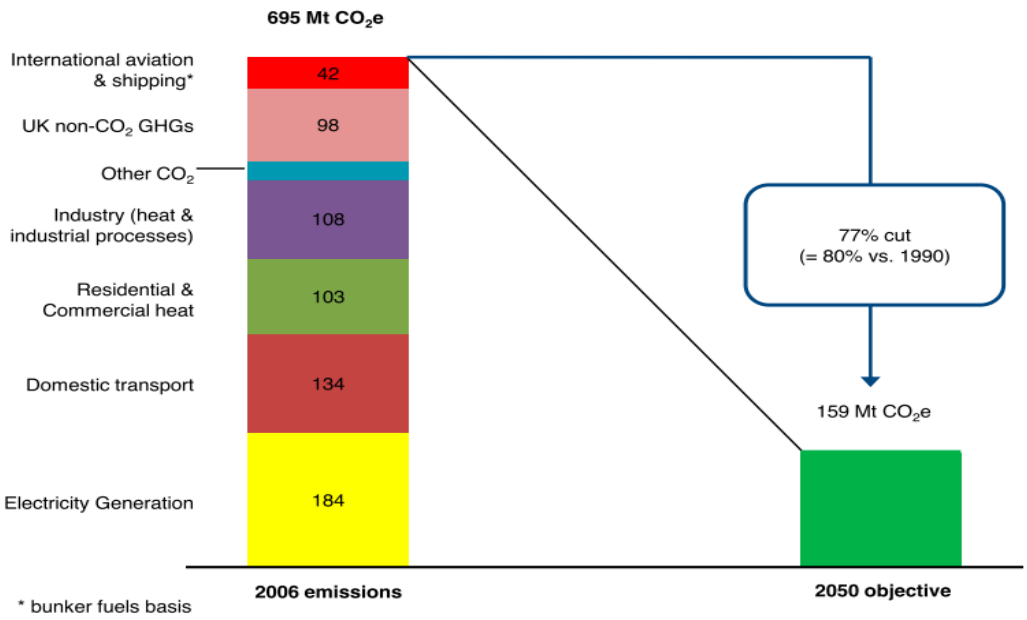


Figure 2-3. The scale of the emission reduction challenge to the year 2050 (CCC, 2008)

Nevertheless, the 2050 emission and energy targets are considered achievable though sustained and intense efforts will be required from all sectors and players within the energy system (DECC, 2010a; Mackay, 2009; UKERC, 2009; CCC, 2008). Fortunately, as has been stated by Grubb (2006), technologies and measures that reduce CO_2 emissions also contribute to energy security and vice versa. Therefore efforts and resources focused on technological measures could address both the CO_2 emissions and energy security issues.

Detailed analysis of the energy use at an individual level is provided in a book by David Mackay (MacKay, 2009). He estimated that the average overall energy consumption per capita in the UK is approximately 125kWh/d. This is broken down into three main categories; 1) Transportation (40kWh/d), 2) Heating (40kWh/d), and 3) Electrical Equipment (18kWh/d). Also, he stated that 27 kWh/d or 21.6% of the energy is lost due to conversion inefficiency from fossil fuel to electricity. Clearly heating is one of the main sources of energy demand at an individual level. Furthermore, in a future energy system with large scale electrification of heating, the energy demand arising from heating could be significantly higher. This is because of the relatively large losses occurring in converting fossil fuels to electricity, and delivery to the end user. This loss factor associated with heating could be reduced by converting and storing locally generated electricity, from PV, micro wind and micro CHP (Combined Heat and Power) systems etc., as heat and using it for heating the building at the time of need. Heat energy captured through the use of solar thermal systems could also be stored and used later for heating. Doing this effectively could reduce the energy losses in centralised generation, which is approximately 65% of the overall primary energy input (Allen et al., 2008). For this to happen, efficient and cost effective heat storage methods will need to be developed, and this is a further reason why research in domestic scale TES is essential and relevant, and called for in the literature.

The UK government categorises the end use of energy into two main categories; 1) Heat and 2) Non-heat (DECC, 2013). These are separated into various final use types falling within the domestic and non-domestic sectors as shown in Table 2-1. In 2011, the total energy used for the heat end use, excluding transport, was 699TWh (76%) whilst for non-heat use it was 218TWh (24%). This indicates that average heat use exceeds the average non-heat use by a factor of approximately 3 (DECC, 2013).

The main fuel types for Heat end use are natural gas, oil, solid fuels and electricity, whilst the main fuel type for the Non-heat end use is electricity. The share of heating provided by electricity was 109TWh (16%) compared to 562TWh (84%) by non-electric means.

As shown in Figure 1.1, there is a large seasonal variation in heat demand compared to electricity, and during the winter season the heat demand can exceed the electricity demand by factors in excess of 100. This could lead to major supply and demand gaps during peak hours if the heat was to be provided mainly by electricity, as is predicted to be the case in the future (Foxon, 2013; ERP, 2011). Ensuring a secure, affordable and environmentally friendly heat supply throughout the year is, therefore, a major supply side challenge for the future UK energy system.

Table 2-1. Categories of energy end uses and types (DECC, 2013).

Heat		Non-heat	
Domestic	Space heating	Domestic	Lighting
	Water heating		Appliances
	Cooking/catering		
Non-domestic	Space heating	Non-domestic	Computing
	Water heating		Cooling and ventilation
	Cooking/catering		Lighting
	High temperature process		Motors
	Low temperature process		Compressed air
	Drying/separation		Lighting
			Refrigeration
			Other

2.2.3 National electricity demand and supply

One of the goals of the research described in this thesis was to investigate the potential of decoupling the temporal link between the heat demand and supply in residential buildings using small scale rechargeable TES. As previously discussed, such application of TES could benefit both supply and demand side stakeholders. However, the benefits could only be of significant value if a large scale electrification of domestic heating takes place, and if the energy input to the TES system was electricity. Therefore, this research assumes that the source of energy to the TES is the mains electricity network. Thus, on the demand side, the impacts and benefits of TES is assumed to be applicable to those households which will satisfy their heating needs using electricity. On the supply side, the impacts and benefits is assumed to be applicable to the electricity generation and supply industry. Consequently, greater understanding and appreciation of the electricity generation, demand and supply characteristics was deemed to be necessary as described in this section.

Heat energy input to the TES systems from non-electric sources, for example natural gas, has not been considered in this research. This method (or the storage of heat converted from natural gas in some TES before the time of use) would simply add an unnecessary and an extra layer of storage, on top of the network scale storage of natural gas. No benefits to the household or the electricity supply sector will be imparted, and the extra layer of storage could, in fact increase energy consumption and cost due to the storage system efficiency losses.

The amount of electrical energy generated in the UK during 2013 was 359TWh from the total generation capacity of 85GW (ONS, 2014). As shown in Figure 2-2, electricity accounted for 18% of the overall final energy use in the same year, which equates to 374TWh. Therefore, the UK was a net importer of electricity in 2013, importing 3.9% of the total demand.

An important point to be noted is that the share of renewable generation increased from 11% in 2012 to 14.9% in 2013, as a result of increased capacity (ONS, 2014). The increase in renewable generation came mainly from the increases in off-shore and on-shore wind generation. The rate at which renewable generation increased in the UK since the year 2000 is shown in Figure 2-4. The rate of increase in renewables is clearly rapid, but the UK still lags significantly behind other European countries, for example Germany where the renewable share of electricity generation in 2013 was 24.9% (Wikipedia, 2014) compared to that of 14.9% in the UK.

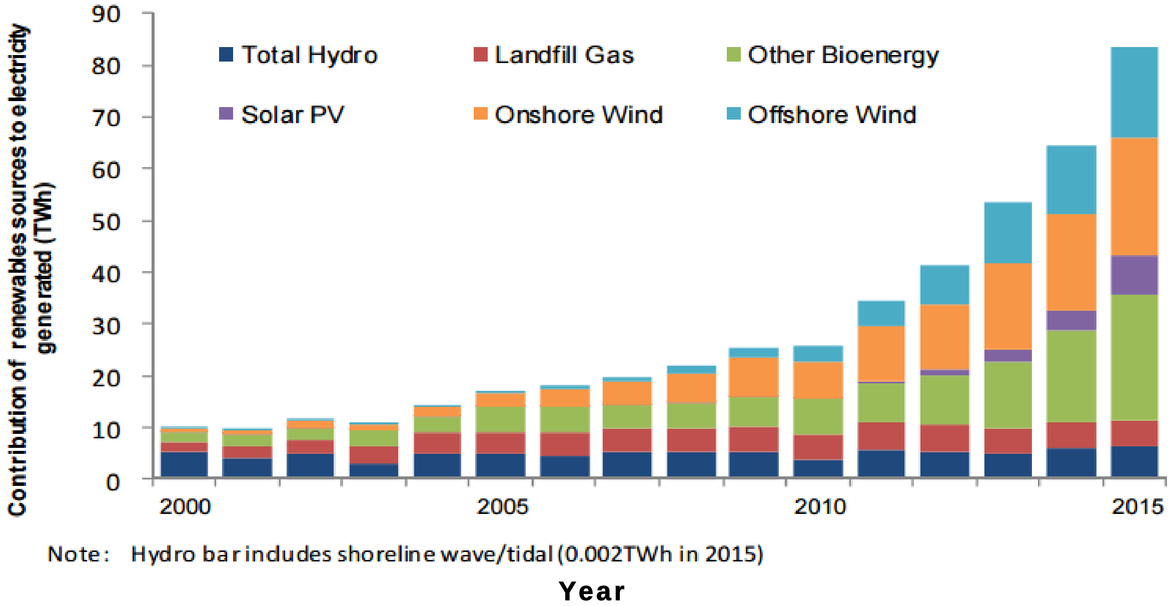


Figure 2-4. Electricity generation by main renewable sources since 2000 (ONS, 2016)

The growth of renewable generation and the demand for electricity are likely to continue. This is given that the CCC's scenarios for achieving the UK's interim energy and carbon budgets and the 2050 energy and emissions targets focus largely on the UK moving to a 'highly-electric' future (Foxon, 2013), on which our energy and climate change policies are largely based. Figure 2-5 shows CCC's projection of the electricity production levels up to 2050 for different emission level trajectories. It can be seen that higher emission constraint results in higher demand for electricity, and based on an 80% emission reduction target the electricity generation projection is around 560TWh per year (CCC, 2008). This represents a 50% increase from the 2013 generation level of 374TWh. Also, it is worth noting that the electricity demand projection remains high even with no emission constraints in place, indicating that the grid balancing problem will not only remain but increase from the current levels.

The projected increase in electricity generation is mainly due to the anticipated increase in electric heating and transport. Both of these have cyclic demand timing and therefore could result in large daily peak and off-peak differences, and demand and supply matching problems. For example, demand for heating would peak during the morning and evening occupied hours whilst the demand for transport could peak during the evenings when electric vehicles are charged up (Strbac et al., 2010).

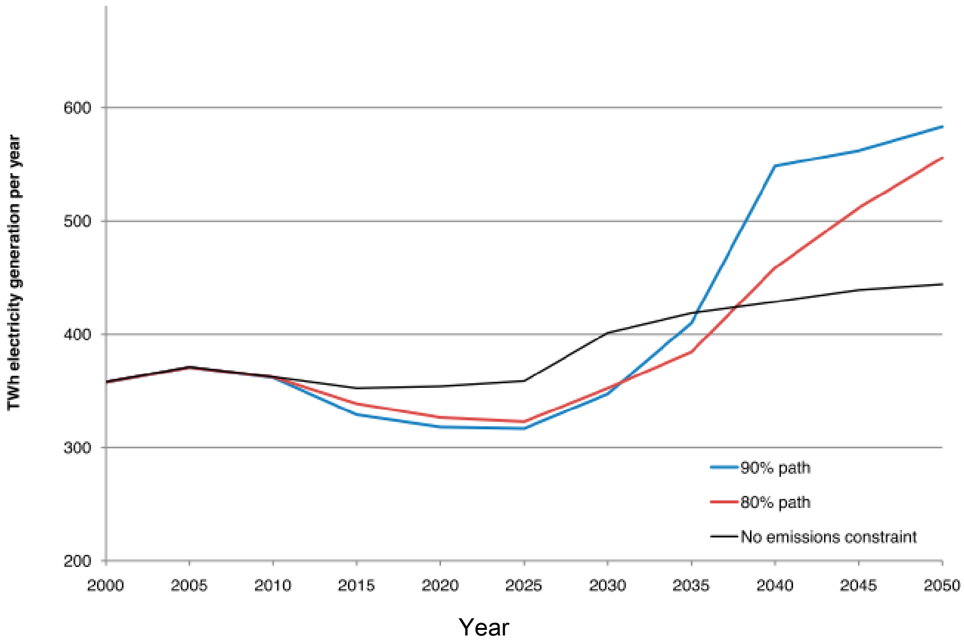


Figure 2-5. Long-term electricity generation for 2000–2050 for 90%, 80% and no emission reduction trajectories (CCC, 2008)

With increasing demand and generation of electricity, the types and sizes of the generators is also expected to diversify, with the deployment of more distributed renewable generation such as wind, biomass and tidal power (CCC, 2008).

The intermittent nature of renewable generation could induce supply and demand matching problems on the energy system if not mitigated by storage (ERP, 2011). Though currently this is manageable given the existing generation capacity, large increase in such renewables in the future could make it more difficult and uneconomical. Furthermore, the problems would be more severe if large scale electrification of heating takes place, and if the intermittent generation drops at peak times, as highlighted by the Energy Research Partnership (ERP, 2011). Conversely, at times of high output from renewables, other electricity generation must be backed-off to avoid 'spilling' or overproduction.

In scenarios such as this, putting in place storage loads could allow management of electricity generation to minimise carbon emissions. As indicated by Energy Research Partnership (ERP, 2011) potential storage based solutions to problems such as these exist at grid-scale, distribution and domestic levels, highlighting research gaps and confirming the need for carrying out research in areas, one of which is the subject of this thesis.

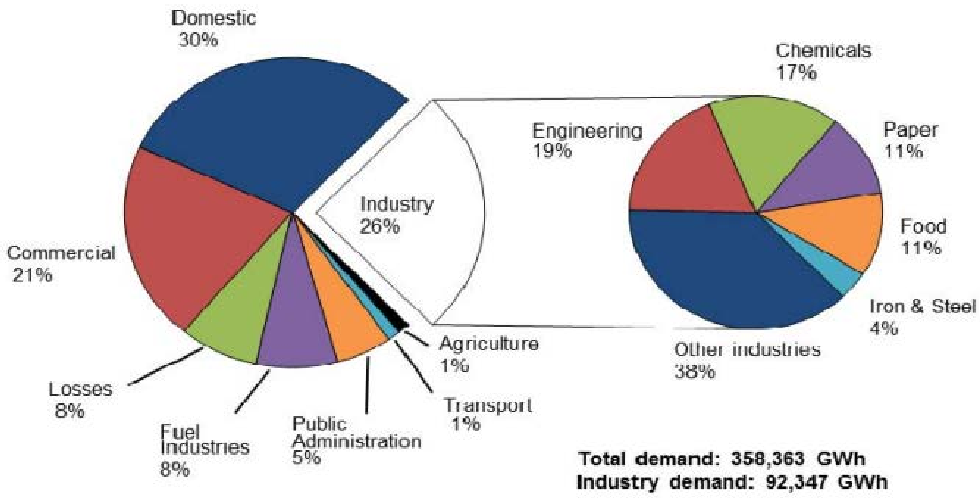


Figure 2-6. Final electricity consumption in 2015 by sector (ONS, 2016)

A breakdown of the electricity demand by sector in 2015 is provided in Figure 2-6. It can be seen that the domestic sector is the largest consumer of electricity at 30% equating to 107.5TWh, followed by Industry at 26% or 92TWh, and commercial sector at 21% or 75TWh. An interesting statistic is that in the same year 20% of the domestic electricity was purchased through some off-peak pricing structure for example Economy 7. This could be considered as an indication that domestic scale rechargeable TES may potentially be acceptable to the end users given that they could facilitate the buying and storing energy (as heat) for heating during cheap and off-peak times. At the supply side, more flexible and financially attractive off-peak electricity pricing structure could be provided to incentivise the uptake of TES, which in the long run could bring considerable economic benefits by way of deferring or removing capital and network investment costs (Ofgem, 2010) as discussed earlier.

The graphs in Figure 2-7 illustrate the national grid electricity demand profiles for four winter days during the month of January 2012. It can be seen that the load peaks on Monday and Wednesday to about 54GW (Peak demand) at approximately 17:30. It drops to the lowest level of around 30GW on these days at around 05:30. The demand is lowest on Sunday, perhaps due to the low demand in the weekends from the industry and commercial sectors. The demand is also low on Friday possibly for a similar reason as the industry sector winds down for the weekend break. The demand remains highest during the period 16.00 to 21.00 in all of the respective days as shown. The peak to off-peak demand variation is at its highest on Monday whilst it is at its lowest on Sunday and Friday at about 25GW and 16GW respectively.

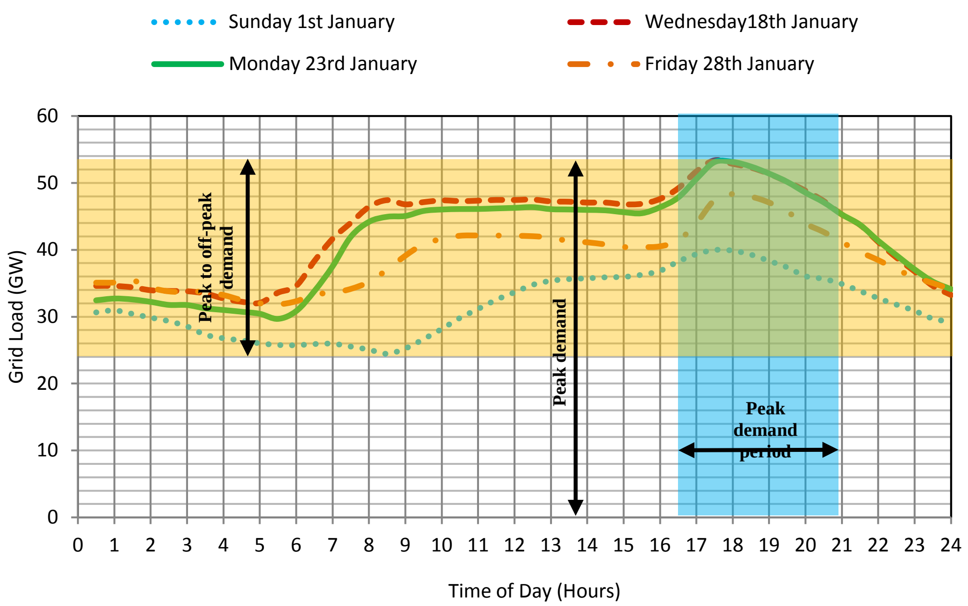


Figure 2-7. National grid electricity load curve for four days in the month of January 2012 (National Grid, 2014)

The grid is obviously able to adjust the supply to match the demand variations with the existing generating capacity and diversity in terms of flexible and quick response peaking plants. In January 2010 the demand variation during the peak period (16.00 to 21:00) was about 7GW and was mainly met through the use of pumped storage (ERP, 2011). However, the demand profile in a future electricity grid is likely to be considerably different, and will be much more challenging to maintain an acceptable match between the demand and supply in terms of quality, quantity and cost (ERP, 2011).

Wilson, et al. (2013) provides a good account of how future electrification of space heating could modify electricity grid load profile. The demand for heat, which is mostly met through the burning of natural gas and which falls within the non-daily metered element of the national gas supply, is several times bigger compared to electricity during the winter days (see Figure 1.1 and Figure 2-8). The seasonal gas demand differences, mainly due to heating, is also considerably large as previously illustrated in Figure 1.1 and also as shown in Figure 2-8. Considering these points, they indicated that even a partial electrification of domestic heating could have '*serious implication for the UK's ageing electrical transmission and distribution networks*'.

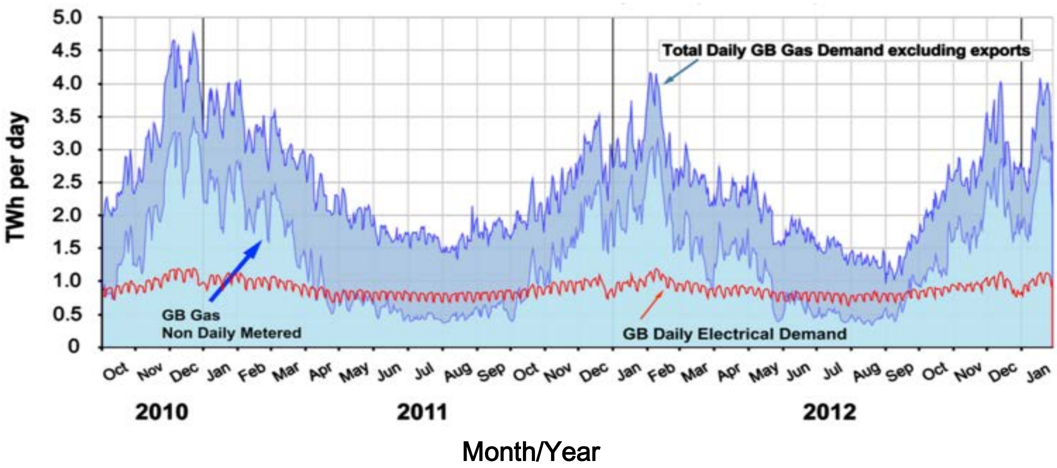


Figure 2-8. Daily GB Gas and Electricity Demands (TWh) (Wilson et al., 2013)

To illustrate the point, they have considered a scenario where 30% of the heating, during the period 2010 and 2011, is transferred over to the electricity grid. They considered heat pumps, with a Coefficient of Performance (COP[11]) value of 3 and resistance element heating with a COP of 1, as the technology for providing the heating services. They demonstrated the impact this would have on the gas and electricity network as shown in Figure 2-9. It can be seen that the demand for gas reduces by 30% due to the shift of heating to electricity. The electricity demand profiles based on the two heating methods are shown. It can be seen that for resistance element heating, the peak demand would be around twice the original value, whilst for heat pumps it would be around 25% more than the original level. This analysis shows that even a 30% penetration of electric heating could have a 25% to 100% peak demand increasing effect depending on the method of electric heating used, and that employing heat pumps with higher COP could minimise the impact.

This analysis does not consider the peak demand levelling impact which could be obtained from the use of thermal storage. Nevertheless, they do state that a *'substantial'* amount of local thermal storage would be necessary to shift some of the extra demand arising from electric heating to off-peak times. Also it is suggested that large amounts of thermal storage could increase the overall energy use for heating, arising due to the parasitic heat losses from the thermal stores and reduced heat pump performance below a COP of 3. This is a valid argument which needs understanding along with the impact local thermal storage could have on energy use

[11] COP is the ratio of the useful heating effect of a technology to the primary energy consumption. In the case of electric resistance heating COP is 1. For ground source heat pumps the COP is approximately 4 and for air source heat pumps the COP is 2 to 3.

and the thermal comfort of the occupants, which this thesis discusses. This work does not include the future impact of electric vehicles which is also likely to increase the load on the future electricity grid, and the transmission infrastructure.

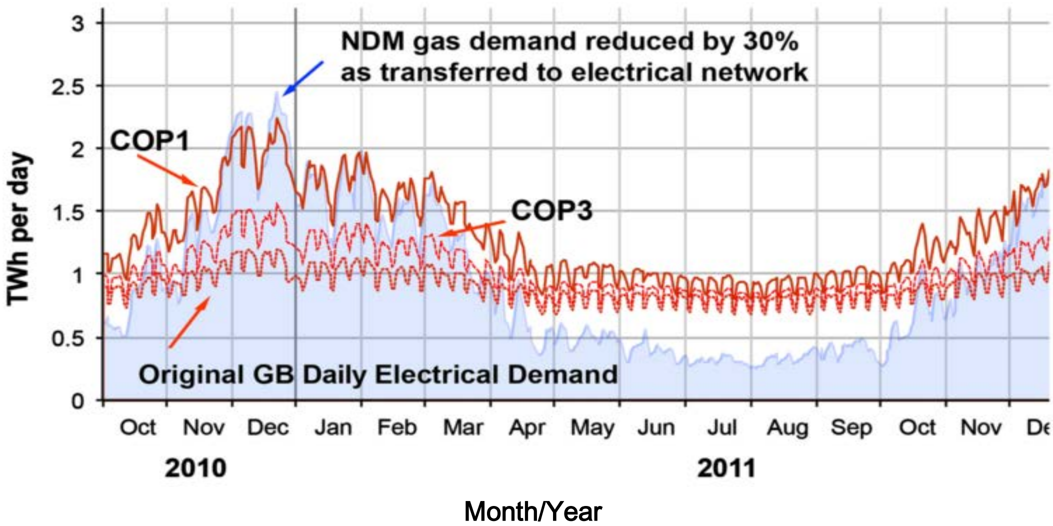


Figure 2-9. Transfer of heat and hot water demand from gas to electrical network using historical data (Wilson et al., 2013).

A study by Strbac et al., (2010) analysed the future daily impact of a large scale use of Heat Pumps (HP) for electric heating and Electric Vehicles (EV) on the national grid. Using data from the National Transport Survey[12], they simulated the EV energy requirement and the corresponding daily electricity demand profile. The daily electricity demand profile which would result from the use of heat pumps for domestic heating was also simulated. The study assumes 26 million dwellings in the building stock, with annual thermal energy demands in the range 10,000-30,000 kWh for the space heating and domestic hot water needs. The dwellings are assumed to have a Grade A energy efficiency rating. The penetration levels of the EVs and the HPs considered were between 10% and 100%. The combined average effect of the EV and the HP on a winter day electricity demand profile was simulated as shown in Figure 2-10. The study predicted a 95% rise in the overall peak electricity load from a 2010 level of 60GW to 117GW. The heating component of the peak load is 36GW which accounted for 60% of the increase from the 2010 level, whilst the EV component is 21GW accounting for the remaining 35% increase from the 2010 level. Despite having numerous assumptions and uncertainties (such as the energy efficiency level of buildings of Grade A which may not be the case in all buildings and

[12] The National Travel Survey (NTS) is the primary source of data on personal travel patterns in Great Britain, monitoring long-term trends in personal travel and to inform the development of policy.

the HPs (the COP used for the HPs are not reported) and the penetration level), this study indicated how the electricity demand could rise in the future, and the challenges of matching the supply and demand.

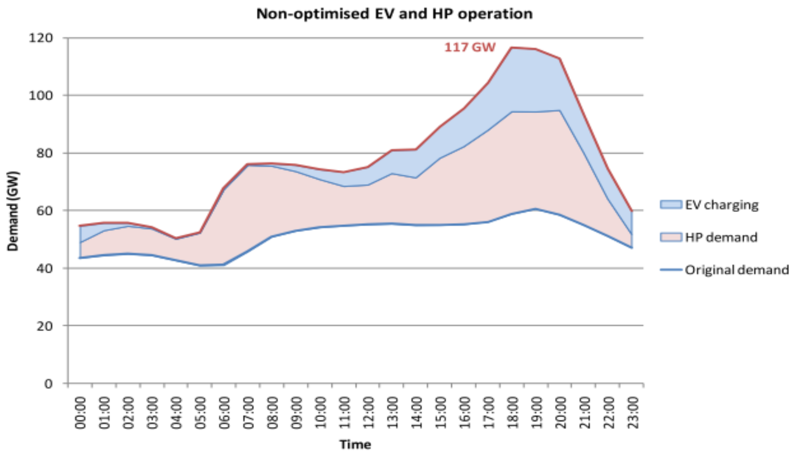


Figure 2-10. Comparison of a simulated winter day average national electricity load profile for EV charging and HP based heating, with an actual 2010 winter day load profile (Strbac et al., 2010).

2.2.4 The role of energy storage

The 2050 carbon emission and energy targets are largely focused around a highly electrified future (Foxon, T.J., 2013). These are made legally binding by the Climate Change Act 2008 (HM Government, 2008) and are designed to transform the UK into a low carbon economy. Transitioning to a low carbon economy will require an energy system consisting of a significantly increased and diverse electricity generation mix. A large amount of renewable generation, from sources such as wind, solar, tidal and wave power, is expected to be installed in a future electricity system. Fossil fuels will be replaced with electricity to provide the seasonal space heating services, increasing the demand for electricity (Wilson et al., 2013; CCC, 2008; ERP, 2011). Such a future electricity system will face various challenges due to undesirable 'side-effects'. The undesirable effects will occur over different timescales as detailed in Table 2-2.

Table 2-2. Challenges for the electricity system over different timescales (Hall, 2008; ERP, 2011).

Timescale	Challenges
Seconds	Aggregation of multiple renewable sources introducing harmonics, thus affecting power quality
Minutes	Rapid change in supply from wind generation affecting power frequency characteristics
Hours	large daily peak to off-peak electricity demand variation due to heating by electricity
Hours-days	variability in electricity supply due to intermittency in renewable generation needs backup supply or demand response
Months	Increased use of electricity for heating leads to strong seasonal demand variation.

Ultimately, the resultant challenge to the future electricity system will be to ensure delivery of a reliable electricity supply, cost effectively, which also meets the climate change mitigation targets. One way of overcoming these challenges is through the use of effective energy storage (CCC, 2016; Eames et al., 2014; ERP, 2011; UKERC, 2011; Hall, 2008; Arteconi et al., 2013; IMechE, 2014) as described in Chapter 1. Energy storage could be viewed as the ability to store energy for use at a later time to shift the demand in time. There are many ways in which energy could be stored, for example as electricity, heat, potential (pumped hydro), kinetic (flywheel), compressed gas and chemical (battery) as discussed in section 2.4. This thesis only considers heat or thermal energy storage as a potential method of storing heat for use in residential buildings, for the purpose of shifting DHW and space heating energy demand in time. Storage is referred to as an 'enabling' technology which, as well as providing energy backup functionality, also allows other technologies to be better integrated into the energy system by enabling the unwanted side effects to be alleviated (Dincer and Rosen, 2011). In this context, the roles storage could play can be categorised as follows (Eames et al., 2014; ERP, 2011):

1. Daily demand levelling: To enable time shifting of demand through demand side management via storage, to aid grid balancing and reduce the capacity needed to meet the daily peak demands.
2. Backup supply for reliability: To counter variable, reduced or absent wind generation over a few hours to a few days.
3. Seasonal demand levelling: In this role storage could be used in reducing the differences between the peak seasonal demands, in order to reduce the capacity needed to meet the winter peaks.
4. Power quality improvement: Counter frequency and noise (harmonics) impacts on the supply due to aggregation of a large number of intermittent and highly distributed renewable generators.

The technology and methods of energy storage which can be used in these roles, as discussed in Section 2.4, depends on a number of factors including energy storage capacity, charge and discharge rates and the storage efficiency. For example, a system with a large storage capacity with low intrinsic losses would be required for use in a seasonal demand levelling role, whilst a storage system with a highly responsive charging and discharging characteristics would be needed for use in a power quality improvement role. The aim of this work is to investigate the demand for thermal energy in domestic buildings, and the impacts of shifting this demand in time through the use of thermal energy storage and demand side management. Therefore the energy storage method suitable for investigation during this work was one that is appropriate for the relatively small size of UK domestic buildings, and one that is unlikely to pose health and safety hazards to the occupants of the buildings. If we consider that heating dominates domestic energy use, and that large scale shift to electric heating is predicted in the future, we can conclude that a heat or TES system which can be recharged using electricity is the more relevant form of energy storage method for this study. Therefore the main focus of this thesis is electrically rechargeable TES which will be suitable for typical UK residential buildings. The appropriate use for such a TES system, due to the small nature of the building where it will be located, is likely to be one in which it plays a daily electricity demand levelling role where excessively large storage capacity is not necessary. This thesis explores in detail the supply and demand side impact such a TES system could have when subjected to the mentioned environment, and in the role described.

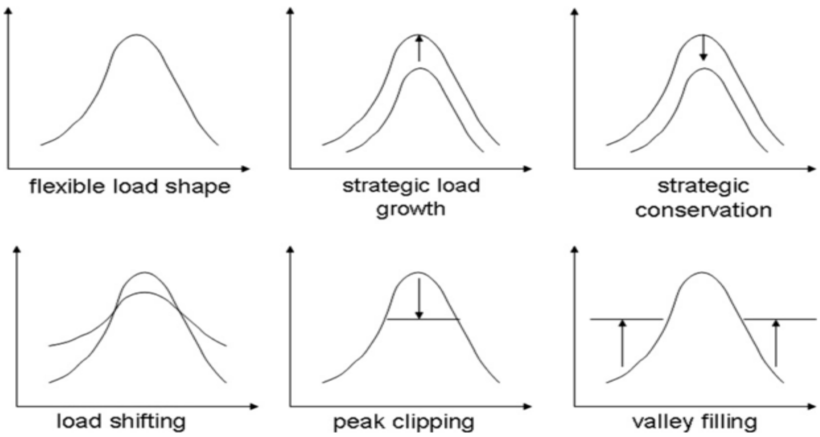


Figure 2-11. Demand side management categories (Arteconi et al., 2012)

As discussed in Chapter 1, rechargeable TES systems can be used as tools for DSM. Demand side response, which is a DSM technique, is usually associated with influencing energy use by electrical goods and appliances, in terms of magnitude and timings, to improve energy efficiency and better match the supply with the demand. Using electric heating in conjunction with rechargeable TES could enable the heating system to be treated similar to an electrical appliance, and allow DSM techniques to be applied to make the heating load response flexible in terms of timing. Arteconi et al. (2012) discusses five DSM techniques (see Figure 2-11) some of which could be used to make the heating load flexible and enable the load response to be modified and matched to the grid. For example, rechargeable TES could enable load shifting by decoupling the heat demand and supply, allow peak clipping by releasing stored heat during the peak times and allow valley filling by recharging the store during the off-peak times. Overall, the daily household level electricity load response could be modified in a way that provides a grid level load balancing impact, thereby fulfilling a daily grid level demand levelling role.

There are several competing options with storage which can be used to mitigate the challenges mentioned, and these include (ERP, 2011):

1. **Flexible plants** – new and existing plants with greater power up and power down flexibility of generation to counter extra or a lack of demand.
2. **Interconnection with other countries** – providing flexibility through additional imported or exported capacity or load.
3. **Hydrogen** – for use as an energy vector and storage medium.
4. **Demand side response** – providing incentives and mechanisms to reduce energy consumption and shift electricity demand to off-peak times.

These are outside the scope of this research, except for demand side response, which is considered as a tool for making effective use of energy storage.

2.2.5 Current energy storage in the UK

Electrical and thermal rechargeable energy storage exists in the UK as detailed below (ERP, 2011). The majority of these are large scale systems and inappropriate for domestic buildings. Hot water storage tanks and electrical storage heaters are suitable domestic building options and will only be considered beyond this section of the thesis.

Pumped hydro storage (PHS)

The UK has a grid scale PHS based electricity storage capacity of 27.6GWh. There are four PHS facilities, the largest being Dinorwig in Wales having a storage capacity of 10GWh. At a maximum output of 1.7GW it can store approximately 5 hours' worth of electricity (Mackay, 2009). The other PHS facilities are Ffestiniog, Ben Cruachan and Foyers, each having a smaller maximum output (360, 440 and 405 MW respectively) and storage capacity of approximately 1.3, 10 and 6.3 GWh respectively. Altogether PHS provides approximately 1.1% of the total grid electricity and mostly used for arbitrage over a daily cycle (Wilson et al., 2010).

Hot water

Domestic Hot water (DHW) storage using cylinders are present in 11 million UK households. A 100 litre cylinder can store 6kWh of energy when the water is heated to 50°C. Average DHW demand is approximately 122 litres/day with an energy content of 4.7kWh. When aggregated across the UK, it comes to about 65GWh/day (CCC, 2016; ERP, 2011; EST, 2008). Opportunities exist for more effective use of this readily available infrastructure, which is considered as one of the cheapest options. However, combination boilers which do not use HW storage tanks are increasing therefore reducing the opportunities.

The Pimlico District Heating scheme in London stores 2500m^3 of water just below boiling point, and serves over 3,000 dwellings and nearly 50 businesses. The storage capacity of this scheme is 3.4MWth. A smaller 1.6MWth scheme exists in Woking, Surrey, and stores 163m^3 of water. In total, CHP based heating capacity for buildings is 472MWth, but there are no figures for the total thermal storage involved (ERP, 2011). However, there is an opportunity for thermal storage to make a place for itself in the market by enabling CHP systems to operate at higher efficiencies, through effective storage and use of heat at different times.

<u>Electrical storage heaters</u>

Electric storage heaters provide the primary heating service in 7% (1.55 million) of the UK housing stock which are mainly flats. Economy 7 accounts for 23% of the GB domestic space heating electricity used, which is based on the time-of-use tariff, with average annual domestic consumption 5.7MWh (ERP, 2011).

<u>Fossil fuel storage</u>

The UK has 47TWh of gas storage capacity. Approximately 30% of this is used for power generation, equating to 7TWh electric output at 50% conversion efficiency, and 30TWh for coal in terms of electrical power generation (ERP, 2011).

2.3 Domestic buildings in the UK

2.3.1 Overview

The UK housing stock comprised of over 27 million homes in 2014 (DCLG, 2014). Of these, 22.77 million are located in England, 1.38 million in Wales, 2.45 million in Scotland and 0.74 million in Northern Ireland. The stock is projected to rise at an annual rate of just less than 1% a year, to 24.31 million in England and 29.19 million in the UK by 2021. Housing stock in the UK is closely monitored. The English Housing Survey (EHS) published by the Department of Communities and Local Government (DCLG) provides a summary of the state of the English housing stock and its occupancy, covering parameters such as the dwelling type, age, size, demography, occupancy, energy efficiency and thermal performance[13] ratings. The EHS categorised the English housing stock in 2011 by construction period, dwelling type, floor area size and sub-national location as quantities, and as percentages of the total of 22.754 million as shown in Table 2-3. It can be seen that 62.6% of the buildings are post 1945 when the thermal performance standards were raised (Wright, 2008). This also implies that a significant percentage (37.4%) of the buildings was built before 1945. These have low thermal performance and are difficult and costly to insulate, often due to thicker and solid wall construction, and have a higher rate of heat loss. Consequently they consume more heat to ensure the preferred indoor temperature. Wright (2008) suggested that 74% of UK building stocks present in 2008 will still exist in 2050, and this suggests that the higher energy use for heating will continue to exist as well. The EHS (DCLG, 2013) breaks down the building stock into seven built-forms[14] categories (see Table 2-3). The percentage dwellings falling in each of these categories in 2011 are as shown in Table 2-3. The terrace houses are sub-divided into end terrace and mid terrace. There are more mid-terrace dwellings (18.9%) than end-terrace dwellings in the building stock. The detached, Semi-detached, Mid-terrace and the purpose built flats represented 75.8% of the building stock in England, and these four categories are often used to represent the building stock in research investigations (Yeo et al., 2005; Yohanis, et al., 2010). The dwellings are further categorized in terms of sizes (or floor space) as shown in Table 2-3. The average floor area of the dwellings in 2011 was

[13] Thermal performance of buildings is their ability to retain heat within them and is dependent on the technical parameters of the building fabric such as the external wall and window U-value, and not on the behavioral aspects of the occupants
[14] Built-form refers to the physical building form for example detached, semi-detached, terrace etc.

91m^2 and around 63.8% of them had a floor area less than 89m^2 (DCLG, 2013). Another important category is the sub national location of the housing stock. Around 29.3% of the housing stock is located in the north, 30% in the south and 40.7% in the middle.

Table 2-3. English dwelling stock summary for 2011 (DCLG, 2013)

Dwellings in England			
	Floor area (m^2)	**Dwellings in group (000s)**	**% of all dwellings**
Dwelling age			
Pre-1919	102	4,739	20.8%
1919-44	94	3,762	16.5%
1945-64	87	4,502	19.8%
1965-80	85	4,782	21.0%
1981-90	84	1,918	8.4%
Post 1990	91	3,052	13.4%
Dwelling type			
All terrace	83	6,428	28.2%
Semi-detached	93	5,917	26.0%
Detached	152	3,786	16.6%
Bungalow	78	1,996	8.8%
Converted flat	63	949	4.2%
Purpose built flat, low rise	55	3,247	14.3%
Purpose built flat, high rise	60	432	1.9%
Size			
Less than 50m^2	41	2,674	11.8%
50-69m^2	61	5,522	24.3%
70-89m^2	79	6,309	27.7%
90-109m^2	99	3,205	14.1%
110m^2 or more	161	5,044	22.2%
Sub-national area			
North	90	6,675	29.3%
South east	89	6,822	30.0%
Rest of England	94	9,257	40.7%
All dwellings	**91**	22,754	100.0%


a) Detached


b) Semi detached


c) Mid terrace


d) Purpose built flats

Figure 2-12. Residential buildings in the UK by built form: a) detached; b) Semi-detached; c) Mid terrace, and d) Purpose built flats.

A large variety of building typologies or built forms are present in the UK because of the long period over which the buildings have been built. Figure 2-12 shows examples of the variety of buildings present by built form. Numerous differences exist between the buildings, the way they are constructed and the materials used which can affect their thermal performance characteristics. Some of these differences are visible such as the building type, external wall construction material used, window type, link to adjacent buildings or outbuildings, and added extensions and conservatories. Many of the differences are not easily observable such as solid and cavity walls, whether the wall cavity is insulated and the level of thermal bridging between the inside and the outside. Complex interaction of these with other factors such as occupier demographics, the way the buildings are operated the climatic conditions and the affordability of fuels drives the energy use in buildings for water and space heating (Wright, 2008; Famuyibo et al., 2012).

2.3.2 Energy efficiency rating of UK buildings

The Standard Assessment Procedure (SAP) is the main measure of Energy Efficiency Rating (EER) of domestic buildings in the UK. SAP considers heating, domestic hot water and lighting but not appliances, and is a rating of energy costs and carbon emission normalised by total floor area (Wright, 2008). The SAP EER values range from 1 to 100. Dwellings are also categorised into seven EER bands, from A to G. Table 2-4 illustrates the SAP EER of the domestic English housing stock for the year 2011. Large variation between EER of buildings can be seen. The reasons for this include the long period of time over which the buildings has been built, and the different building materials and techniques used, from stone and solid brick walls to the contemporary insulated cavity wall construction (Firth et al., 2010; Famuyibo et al., 2012).

Table 2-4. SAP Energy Efficiency Rating bands, values and the EER rating of the housing stock (DCLG, 2013).

EER of all dwellings			
EER Bands	SAP EER by band	No. of dwellings in EER bands (000s)	% of dwellings by EER band
Bands A/B	(92-100)/(81-91)	38	0.2%
Band C	69-90	3311	14.6%
Band D	55-68	11199	49.2%
Band E	39-54	6454	28.4%
Band F	21-38	1363	6.0%
Band G	1-20	389	1.7%
Total		22754	100.0%

The average EER of the English housing stock in 2011 was 56.7 (DCLG, 2013). Only 14.8% of the housing stock had an EER rating of 69 or higher whilst 85.2% had less than 69 (Table 2-4). This is in sharp contrast to a typical Scandinavian house having an EER rating of 90-100 (Martiskanen, 2007), confirming the widely accepted notion that the UK housing stock is one of the least thermally efficient in Europe (DECC, 2012a; Martiskanen, 2007). The low EER is prevalent throughout all the dwelling types except the purpose built flats, approximately 55% of which have a rating of over 60.

One of the key determinants of thermal performance of dwellings is the level of heat loss. There are two ways by which heat loss occurs in buildings: 1) Ventilation heat loss and 2) heat loss through the building fabric. Ventilation heat loss (which can be deliberate for exchanging stale air with fresh air or uncontrolled infiltration caused by inadequate draught proofing etc.) occurs due to exchange of warm air from the inside with cold or 'fresh' air from the outside. Under steady state condition the heat loss from ventilation can be calculated using the equation:

$$Q = 0.33\ N\ V\ \Delta t \qquad \textbf{Equation 2-1}$$

Where *Q = rate of ventilation heat loss (W)*
V = Volume of room (m^3)
N = rate of air infiltration (number of air change per hour)
Δt = Difference between the indoor and outdoor temperature

Building fabric heat loss is the result of the transfer of heat through the building fabric and depends on the thermal insulation present. The thermal transmittance (U-value) dictates the heat transfer rate through the building fabric (DCLG, 2013; Kane, 2013; Lowe et al., 1996). Heat transfer through the fabric is a function of the U-value, the area of the building envelope and the difference between the indoor and the outdoor temperatures, and so increasing the insulation level reduces the U-value and therefore the heat loss. Some of the main building fabric elements through which heat loss occurs are the external walls, external windows and doors, ground floor and the roof. (Famuyibo et al., 2012). Under steady state condition the building fabric heat loss can be calculated using the equation (Kane, 2013):

$$Q = U\ A\ \Delta t \qquad \textbf{Equation 2-2}$$

Where *Q = rate of fabric heat loss (W)*
U = U-value (W/m^2K)
A = Area (m^2)
Δt = Difference between the indoor and outdoor temperature

At the whole house level the Heat Loss Coefficient (HLC) is used to describe the total heat loss from the building and is the sum of the fabric and ventilation losses. The Heat Loss Parameter (HLP) is the standardised measure of the building heat loss per unit floor area and can be useful for comparing the heat loss characteristics of different buildings (Kane, 2013).

$$HLC\ (W/K) = \text{Ventilation heat loss } (Pv) + \text{Fabric heat loss } (Pt) \qquad \text{Equation 2-3}$$

$$HLP = \frac{HLC}{A} \qquad \text{Equation 2-4}$$

Where A = total floor area (m^2)

Building regulation standards have been systematically upgraded over the last thirty years to influence improvement. The U-value of the key elements through which heat loss occurs was tightened as illustrated in Table 2-5. Whilst it has been possible to ensure compliance to these standards in new developments, through building control, the existing building stock is lagging behind. For example in 2011, whole house double glazing is only present in 76.3% of the existing dwellings in England whilst 11.9% had less than half or no double glazing at all. Also, 41.9% of the existing building stock had less than 200mm of loft insulation in comparison with the 2010 Building Regulation guideline being 250mm (HM Government (2010_PL1B)). Only 38.4% of the dwellings in England have cavity wall insulation out of the possible 69% with cavity wall construction (DCLG, 2013). These suggest that a significant number of the existing buildings are lagging behind the latest building regulation and just barely conforming to the 1990s edition.

Table 2-5. U-value of the main building fabrics and the air infiltration level by building regulation standards (HM Government, 2010_PL1A; HM Government, 2010_PL1B).

	Floor	Infiltration	Ext. Wall	Windows & Doors	Loft/Roof
	$W/m^2.K$	ACH	$W/m^2.K$	$W/m^2.K$	$W/m^2.K$
1981 Regulation	0.74	2.00	0.60	5.70	0.40
1990 Regulation	0.45	1.75	0.45	3.30	0.25
2002 Regulation	0.25	0.75	0.35	2.00	0.16
2010 Regulation	0.17	0.40	0.22	0.96	0.14

2.3.3 The Occupiers of the buildings

One of the main drivers of energy consumption in buildings is the occupants (Wright, 2008; Yeo et.al, 2005; Kane, 2013). Some of the main factors linking the occupants and energy consumption are the household composition (number of people in the household, their ages, and their occupancy patterns), family income, cultural background, and human factors (yeo et al., 2005). Of these, the human factors or the energy use behaviour element plays a significant part in driving energy consumption (CCC, 2008). This includes variables such as the general behaviour towards energy use and awareness of the effect of climate change on the environment. The impacts of these are difficult to quantify and are compounded by the number of occupiers, their age and their occupancy patterns, which makes energy consumption complex to predict and simulate. Nevertheless, any study analysing domestic energy consumption must include the influences of occupancy and the behavioural aspects of the occupiers for the results to be of value, for example in policy formation (Firth et al., 2010).

The EHS monitors occupancy demographic and economic characteristics of the households in England, including data on age, economic status and ethnicity related to the Household Reference Person (HRP). The HRP is defined as the “householder” in whose name the accommodation is owned or rented (DCLG, 2013). Some of the key information which usually impact energy consumption in terms of both quantity and timing are:

- The age of the HRP; which are fairly evenly spread between the 24 year to over 65 years, with the exception that less than 4% of the HRP were under 24 years old.
- The employment status of the HRP: (50.6%) were working full-time whilst 27.8% were retired.
- The ethnicity of 89.5% of the HRP was white and 10.5% being from all other ethnicities.
- Family demography: couples without dependent children constituted 35.1% of the HRPs whilst couples with dependent children accounted for 21.4% of the HRP.
- Household size: the average size of the households was estimated as 2.3 persons whilst 28.7%, 36.0% and 16.4% were one, two and three person households respectively.

2.3.4 The building location

The heating energy consumption in buildings has a large dependence on its geographical location. This is because the ventilation and infiltration heat loss in buildings is proportional to the difference between the indoor and the outdoor temperatures as previously described (see Equation 2-1 and Equation 2-2). The outdoor temperature can vary considerably in the UK depending on the location as shown in Figure 2-13. For example, the variation in the outdoor temperature between the north and the south of the country on a winter month of December can be up to 10˚C during the cold periods (or days of snow) and as little as 6 ˚C during the milder December months. For buildings with identical physical construction, occupancy and operational conditions the HLP could still be different due to the different outdoor temperatures, requiring different amounts of heat to ensure similar indoor thermal conditions. Therefore understanding this variation is essential to enable the development of appropriate heating systems and heat demand management strategies that are suitable for the location of the dwellings.

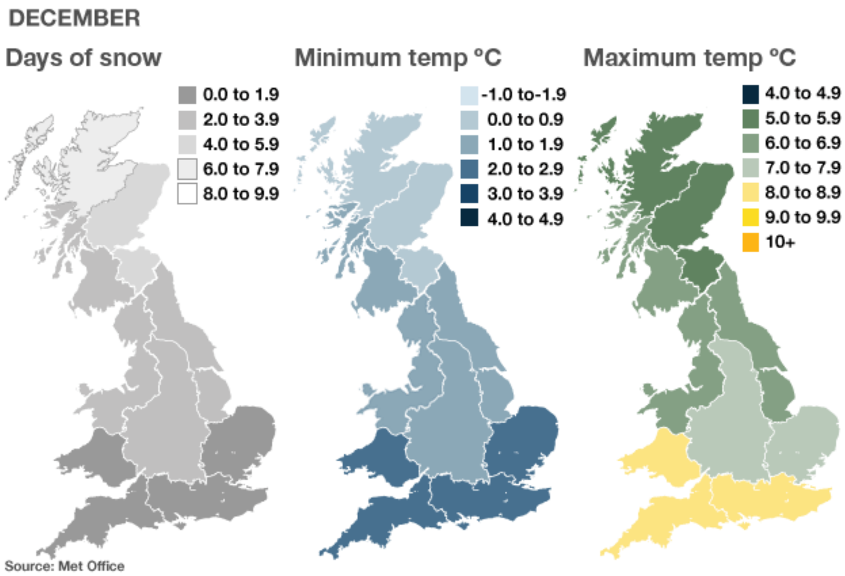


Figure 2-13. Illustration of the outdoor temperature variation in Great Britain during the month of December (Source: Met. Office).

2.3.5 Heat energy use in buildings

Domestic energy consumption is driven by four basic needs: 1) space heating, 2) water heating, 3) cooking, and 4) lighting and appliance. The first three needs are for heat and the last one is normally referred to as a non-heat need (DECC, 2013). As shown in Figure 2-14, in 2011 space heating accounted for 280TWh (62%), Water heating 83TWh (18%), Lighting and appliances 77TWh (17%), and Cooking 13TWh (3%). Space and water heating combined accounted for 363TWh (80%) of the total domestic energy consumption of 453TWh (DECC, 2013). Energy use for lighting and appliances will not be given further consideration in this thesis as it is not within the scope of this research. Cooking will be considered for comparison purposes only.

Energy supplies to domestic buildings are mainly provided in the form of electricity and natural gas. Other forms of energy are also used, though they are relatively small in comparison (see Figure 2-15). The water and space heating is predominantly met through the burning of natural gas (79%) and oil (9%), compared to electricity accounting for only 8% based on the national energy consumption data for 2011 (DECC, 2013).

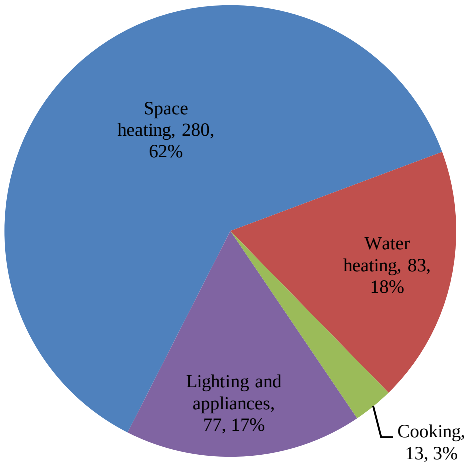


Figure 2-14. Breakdown of the domestic final energy consumption by use type in 2011 (DECC, 2013)

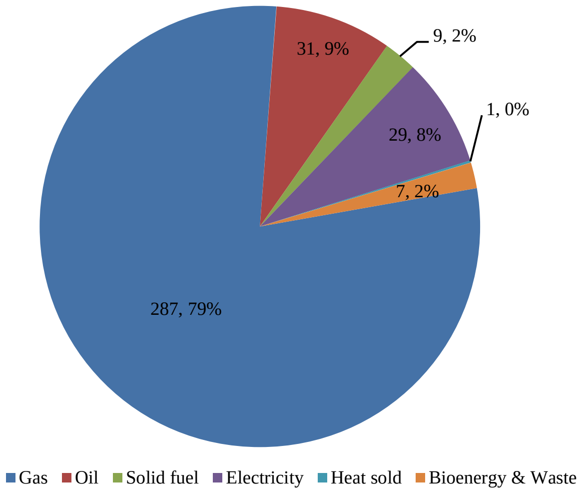


Figure 2-15. Domestic energy consumption for heating by fuel (DECC, 2013)

The graphs in Figure 2-16 show the historic energy consumption for domestic space heating from 1970 to 2012 (DECC, 2013; DECC, 2013a). There is a clear falling trend in the energy use for hot water. If the energy demand for hot water declined at the same rate as in Figure 2-16, then the energy demand in 2050 would be approximately 50% of the 2011 level of 3133kWh per year. It is unlikely that this will happen as it could be argued that the expected rise in population and external temperature forcing people, for example to have showers more frequently, will increase DHW demand in 2050. The overall trend in domestic space heating energy use since 1970 to 2012 shows a steady rise. If the data from 1990 to 2012 is only considered, during which the effort to make dwelling more energy efficient has been much more intense and that the winter seasons have been relatively milder, then the rate of rise in energy demand for space heating looks relatively modest. According some research space heating energy use could fall in the future. Isaac et al., (2009) in a paper described modelled scenarios where the heating demand reduces by 34% by 2100 due to the ambient temperature increasing as an effect of climate change. Collins et al., (2010) looked at the existing buildings and their future energy consumption. Their study showed that existing buildings will dominate the building stock in 2050 where heating will still dominate cooling, though a 20% reduction in heating energy demand will result due to the energy efficiency improvement of buildings and the climate change impact. A decline in space heating energy consumption from the year 2005 to 2012 can be seen in Figure 2-16. It would be speculation to suggest that this is due to the improving energy efficiency of the buildings or is due to the climate change effect. One possible explanation for this could be the recent economic downturn and the volatile energy markets, which has increased cost and fuel poverty level, and therefore could have forced the affected consumers to use less energy for heating.

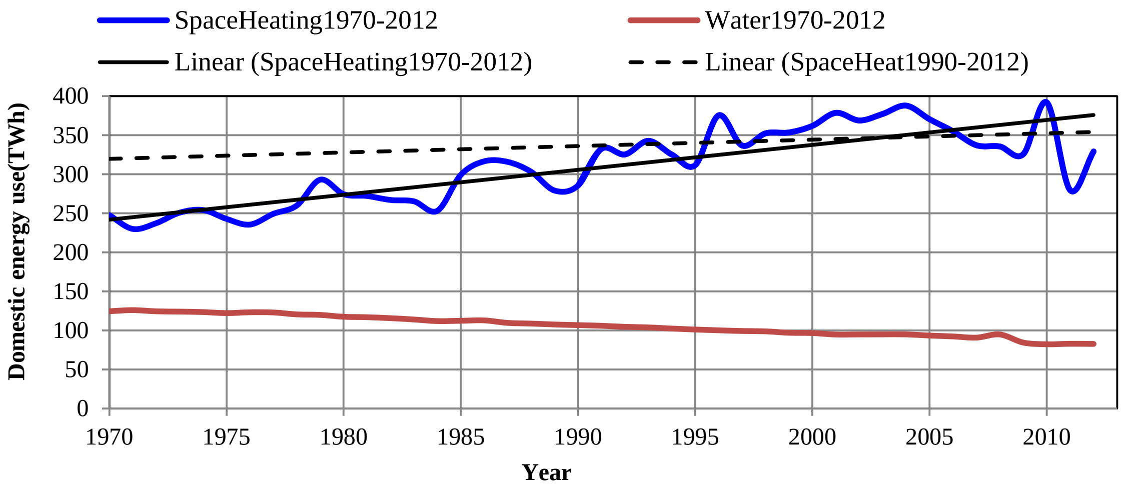


Figure 2-16. Historic domestic energy consumption by space and water heating from 1970 to 2012 (DECC, 2013).

A breakdown of the average domestic heat energy consumption at the household level in 2011 is provided in Table 2-6. This is based on an estimated UK building stock size of 26.53Million homes. In 2011 the mean space heating energy consumption per dwelling was 10,544kWh per year. This was 74.4% of the total domestic heat consumption whilst water heating accounted for 22.1%. The heat demand for cooking was considerably lower at 3.4%.

Table 2-6. Mean domestic heat energy consumption in 2011 per dwelling per year, by fuel type (DECC, 2013)

	Gas (kWh)	Oil (kWh)	Solid fuel (kWh)	Electricity (kWh)	Heat sold (kWh)	Bio energy (KWh)	Total (KWh)	Percentage (%)
Space heating	8214	959	309	780	23	260	10544	74.4%
Water heating	2586	211	23	310	0	0	3130	22.1%
Cooking/catering	262	0	0	226	0	0	488	3.4%

The space heating demand figure would be much higher (18,750kWh/year) in 2050 if it increased as per the historic (1972-2012) trend line. But it would be 14,538kWh/year if the rate of increase was as per the 1990-2012 trend line (see Figure 2-16). However, if the demand reduces by 20% from the 2010 level as stated by Collins et al. (2010), then the annual demand would be 8,435kWh.

2.3.6 Domestic space heating

The vast majority of the UK space heating needs are met through using water based central heating systems. In 2007 boiler driven central heating systems with radiators dominated, with 87% of the English housing stock comprising of this type of heating system, accounting for 19.3 million dwellings (BRE, 2009b). Some form of central heating systems are reported to have been present in 91% of the UK dwellings, compared to 36% in 1970 (BRE, 2008).

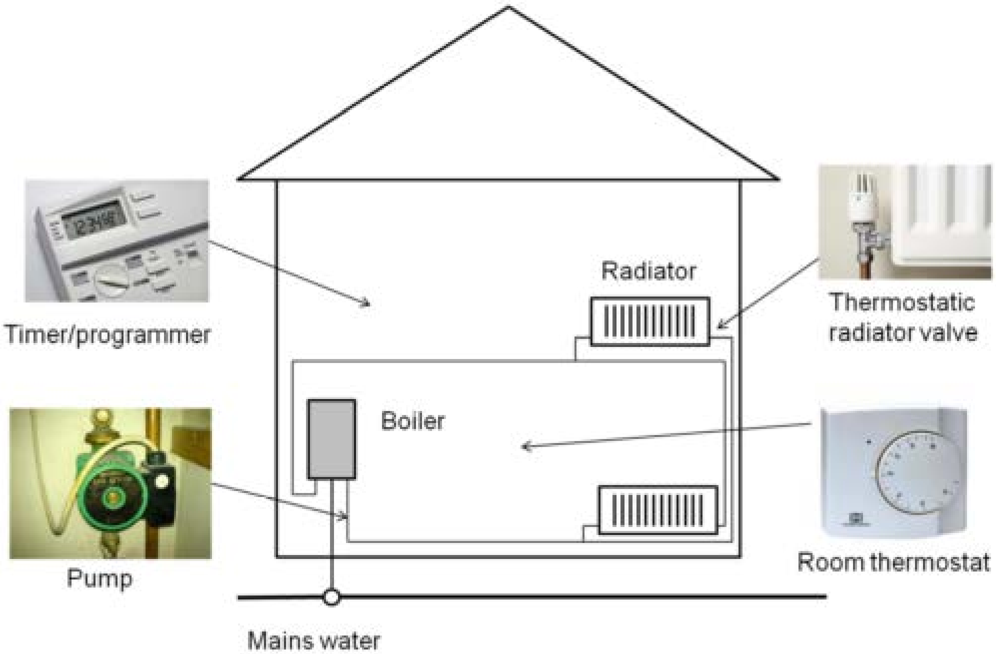


Figure 2-17. Typical components in a central heating system used in a UK dwelling (Source: Kane, 2013)

Typical components of a central heating system and their arrangement are shown in Figure 2-17 (Kane, 2013). The boiler heats the water to the required temperature which is circulated around the radiators by the water pump. There are three main types of boilers: 1) Combination boilers, 2) Convention boilers, and 3) System boilers (British Gas, 2014). Combination boilers supply hot water for the central heating system and the DHW directly from the boilers on demand. They are more popular with households as they take less space and can be economical as no hot water storage cylinders are required. However, they are more suitable for smaller houses for example ones with a single bathroom. Conventional boilers supply hot water for the central heating system and a hot water storage tank. They are suitable for larger homes. Water from the storage tank serves the DWH needs but the quantity is limited to the capacity of the storage tank. They are not as popular due to the space required for housing the hot water cylinder and a cold feed water tank. System boilers are similar to the conventional boilers but some components, such as the cold feed tank and expansion tanks, are incorporated into the boiler. An external hot water storage tank is still required to service the DHW need.

The timer/programmer controls the system turn on and off times, and the duration of the heating periods. Room thermostat monitors the space temperature and the operation of the boiler. Thermostatic radiator valves are installed at the feed to the radiators to enable the temperature of the individual heated spaces to be controlled. Since July 2003, BS EN442 requires manufacturers to specify radiator outputs for ΔT or difference between the air 20°C and the radiator surface temperature difference of 50°C (BSI, 1996). This ensures radiator design flow and return temperatures of 75°C and 65°C respectively, giving an average radiator surface temperature of 70°C. ΔT is calculated using Equation 2-5.

$$\Delta T = \frac{Flow\_T + Return\_T}{2} - Room\_T \qquad \text{Equation 2-5}$$

Where ΔT = Indoor air and radiator surface temperature difference (°C)
Flow_T = Water Flow temperature (°C)
Return_T = Water Return temperature (°C)
Room_T = Room air temperature (°C)

A large number of existing dwellings (11million) have hot water storage tanks connected to the central heating systems and have dedicated space where they are fitted (ERP, 2011; EST, 2008). The water tanks are primarily used for storing DHW for activities such as washing and bathing. However, there is a growing shift towards the use of instant combination boilers, which do not require water tanks.

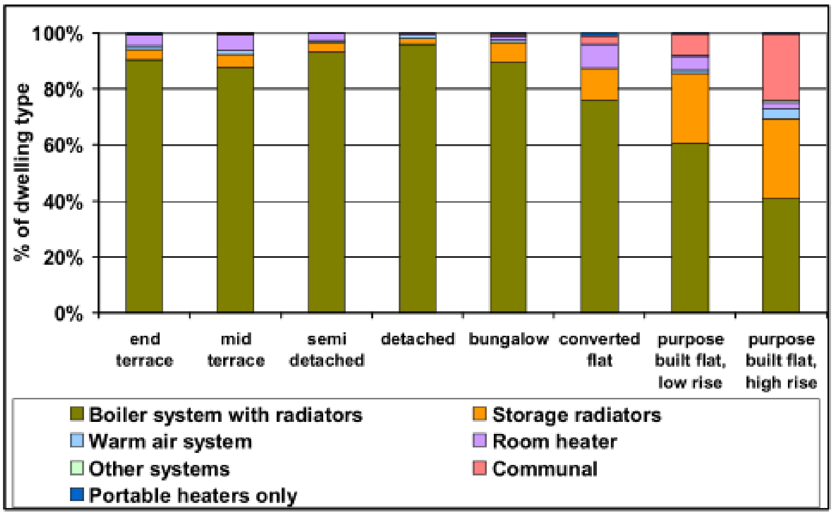


Figure 2-18. Comparison of storage system and dwelling type (BRE, 2007)

Dwelling type has a significant impact on the type of heating system installed (see Figure 2-18). It can be seen that over 90% of all types of dwellings have a central heating system, except for flats for which it varies from about 40% to 75%. Communal and storage heating provides a relatively large proportion of the heating needs in flats.

Most central heating systems are fuelled by gas, accounting for 84% of the systems in 2007 (BRE, 2009b). In rural areas, central heating systems are fired by oil due to a lack of gas supply. Electric and solid fuel central heating systems also exist but are in decline (BRE, 2009b). The standard boiler is most commonly used (40%), followed by combination boilers (37%) including condensing combination boilers. Twelve percent of the stock does not have a boiler, and 3% of the stock has standard condensing boilers (BRE, 2009b).

Other methods of space heating also exist in UK dwellings though the numbers are comparatively less. These methods include: 1) warm air systems which involves pumping hot air into the space; 2) electric storage heaters which electrically heat up bricks to high temperature during off-peak times and later release the heat into the space; 3) room heaters which can be fixed or portable electric fan driven or convective heaters that directly heat the air in the room; 4) communal heating where a heating system (air or water based) supplies heat to more than one dwelling; 5) heat pumps which use electricity to draw heat from cooler external air or ground and pump into to the living space, utilising an inverse refrigeration cycle, and 5) micro Combined Heat and Power systems (CHP) where a fuel such as natural gas is used to operate a heat engine to simultaneously generate electricity and useful heat.

The sizes of the heating systems used in buildings depend on many factor including, the size of the occupied space, external temperature and thermal insulation level. Environmental Design: CIBSE Guide A illustrates how the heating plant sizes could be calculated. Residential buildings in UK are mostly subjected to intermittent heating where the plant is switched off at the end of a period of building occupancy and turned on again at maximum output prior to the next period of occupancy to return the building to the required temperature (CIBSE, 2006). The heating plant size for building with intermittent operation can be determined by multiplying the heat loss parameter by an intermittency correction factor that takes into account factors like thermal response and heating operation times. The lowest intermittency correction factor used usually is 1.2 that adds a 20% contingency over the heat loss parameter.

2.3.7 Domestic hot water

The most common method of water heating in the English housing stock is through the same system as space heating which is central heating, and accounts for 86.9% of the UK DHW needs (BRE, 2007). This is expected given the dominance of central heating in the housing stock, where the boiler is used to heat water for both direct use and for circulating through radiators in order to provided space heating. Currently combination boilers are the most popular DHW providing option due to the convenience they offer as previously discussed. Nevertheless hot water storage tanks are present in a significant number of dwellings (13.7 million) in the UK though this is declining as households switch to the combination boiler based heating systems.

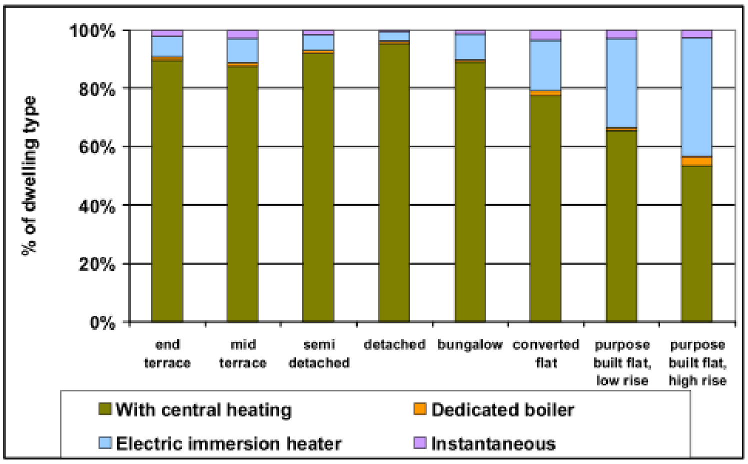


Figure 2-19. Comparison of DHW system with dwelling type (BRE,2007)

As with space heating, dwelling type has a significant impact on the type of DHW system used as shown in Figure 2-19. DHW is primarily provided by the central heating systems in all dwelling types except flats where a significant proportion is provided by electric immersion heaters. In 2007 immersion heaters accounted for 9.9% of the water heating. A small fraction of the DHW demand is met through the use of dedicated boilers and instantaneous water heaters.

DHW is used for various purposes in the home, and the main uses and the respective water temperatures according to a study by Yao et al., (2005) are: 1) Bath/Shower 40℃; 2) Wash & basin 35℃; 3) Dish washing 55℃; 4) Cloth washing (50%) 60℃; and 5) Cloth washing (50%) 10℃. The delivery temperature of DHW varies from 10℃ to 60℃. Temperature of the water handled by the occupants and used in buildings is mostly around 45℃ for uses such as baths, showers and sinks (Yeo et al., 2005; EST, 2008). A study by the Energy Saving Trust (EST) provided statistical analysis of DHW use in 119 UK dwellings based on monitored data (EST, 2008). The distribution of the hot water delivery temperature is shown in Figure 2-20 for 112 of these dwellings. The study indicates an average DHW delivery temperature of 51.9℃ with a 95% confidence interval of ±1.3℃. This study also indicated that a significant proportion (over 50%) of the DHW is directed to the bath and shower, and the temperature of the water for this use is around 45℃.

Although most of the DHW draw off temperature is lower than 60℃, the recommended minimum hot water storage temperature is 60℃ (HSE, 2000). This is to prevent the growth of Legionella bacteria which favour temperatures of between 20℃ and 45℃ but do not survive above 60℃. Legionella bacteria if inhaled can cause Legionnaires' disease which can be fatal, therefore preventing growth of Legionella bacteria in any hot water systems such as central heating and DHW storage is essential. The Health and Safety Executive guideline (HSE, 2000) is that the DHW systems should ensure the hot taps reaching 50°C within 1 minute of being turned on. The guideline for central heating systems is that the water circulating loop design should ensure a return temperature of at least 50°C.

The EST study showed an average DHW consumption of 122litres/dwelling/day with a 95% confidence interval of ±18 litres. As indicated by EST, DHW demand is linked to the number of occupiers residing in the building. The average household size in the UK is 2.3 persons (DECC, 2013), and this implies that the mean DHW consumption per person is about 53litres/day. This is relatively low compared to the DHW consumption per capita 67.4litres/day used by Yao. et al. (2005).

The distribution of the DHW use over a day for the 119 dwellings monitored is shown in Figure 2-21. Due to the nature of the uses of hot water in domestic buildings, their timings are largely concentrated during the morning period from 07:00 to 11:00 and the evening period from 18:00 to 23:00. The morning time average peak demand was about 11lt for one hour from 08:00, whilst the evening time average peak demand was about 9lt, for one hour from 19:00. This form of distribution of DHW consumption could be problematic in the future if both the DHW and the space heating needs are met using electricity. The electricity load during these periods could be much higher due to the concentration of DHW demand in this relatively narrow time period.

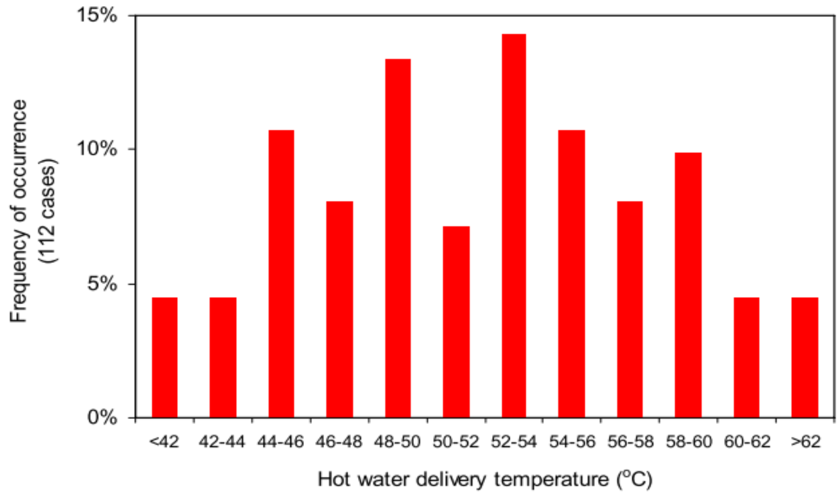


Figure 2-20. Distribution of DHW delivery temperature in 112 dwellings (EST, 2008)

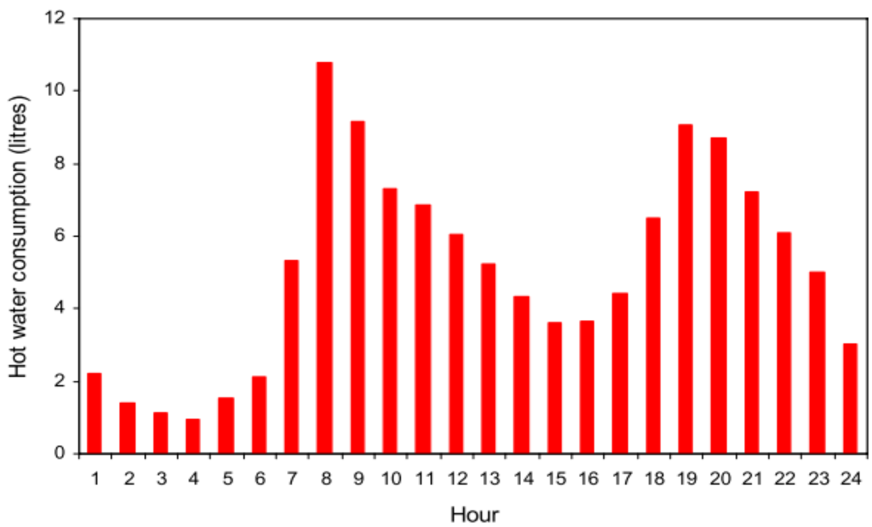


Figure 2-21. Daily DHW consumption profile for 119 dwellings in the UK (EST, 2008)

2.4 Energy storage options for domestic buildings

The majority of final energy use is in the form of heat or electricity. Supplying these reliably, securely and cost-effectively in the future are the main supply side challenges. Rechargeable energy storage in the form of heat or electricity is a way of overcoming these challenges. Heat or Thermal Energy Storage (TES) involves accumulating heat energy in a storage medium. Both the input and output of such a store is heat. Electrical Energy Storage (EES) involves using technologies to store energy in several forms, the common ones being electrochemical, potential and mechanical. Both the input and output of an EES system is electricity.

We have been using heat energy for purposes as basic as our survival, as well as for enabling us to live more comfortable lives. People have been collecting and burning wood for thousands of years, and converting it into heat energy for cooking and keeping warm. Often, people gathered more wood than their immediate need so that it could be used during the times when it was not available. This can be described as the most primitive and simplest form of energy storage. In the modern age, we can store and harness energy nature has provided for us in the form of hydrocarbon based fossil fuels, such as coal, oil and natural gas. Other modern energy vectors such as uranium, plutonium and hydrogen can be converted to other useful forms of energy. These are referred to as energy carriers (Huggins, 2011). In this context, the fundamental function of energy storage is to provide mechanisms that ensure reliable energy supply for use at a later time, at a different place or for a different purpose (Huggins, 2011).

2.4.1 Conventional and rechargeable energy storage

Rechargeable energy storage involves capturing and storing energy when its real-time availability is high and demand is low, so that it could be used at a later time. An energy storage system can be used as a store or a source depending on the supply and demand timing. Application of energy storage in this way makes it 'rechargeable'. It is the 'rechargeable' feature of energy storage and its ability to de-couple the supply from demand, in time and location, particularly for heating, that is of interest and is the focus of this research.

Ibrahim et al. (2008) describes three economic advantages of rechargeable electricity storage; **1) Energy Transfer** – referring to the ability to store during low demand and cost, and supplying during high demand and high price, **2) Network Savings** – referring to the savings in infrastructure cost due to the storage providing additional supply during peak hours, enabling generators with smaller capacity to meet the peak demand, and **3) Kinetic advantage** – referring to having the flexibility to respond to demand and load levelling with less generation capacity. It is the view of the author that these advantages also apply equally to thermal storage now, and even more in the future. This is because of the expected increase in electrification of heating as projected in most of the 2050 energy system pathway analyses (DECC, 2010a; Mackay, 2009; UKERC, 2009a; ERP, 2011).

2.4.2 Electrical energy storage

EES is outside the scope of this research and shall not be covered in detail. However, for completeness and context, a brief summary of EES is provided in this section.

EES involves the use of a wide range of systems and technologies providing electricity as an output directly or indirectly. The end use is also primarily electricity, at domestic level used in lighting and appliances, and at industrial scale used in providing back-up, grid load balancing and power quality improvement. A thorough review of EES technologies and their applications are provided in numerous articles (Ibrahim et al., 2008; Coppez, 2010; Wagner, 2007; Styczynski et al., 2010; Hall et al., 2008; Beaudin et al., 2010; Wilson et al., 2010; Nair et al., 2010)

The use of electrochemical technologies is the most common form of EES. Examples of these technologies include various batteries such as the 'one time use' primary cells, and the 'rechargeable' (lead-acid or flow battery) secondary cells. Their use has been limited mainly to small and medium scale applications such as consumer electronics and short term electricity back-up storage. The reasons for this are the inherent low storage capacity, high cost and low power to physical foot print ratio. However, there is a significant scope for advancement, particularly in Lithium based technology (Wagner, 2007; Baker, 2008; Hall et al., 2008), which could make it cost effective for application in domestic buildings in the future, for both electricity and heat end uses.

Mechanical and potential storage technologies such as Compressed Air Energy Storage (CAES), flywheel and Pumped Hydroelectric Storage (PHS) are used for indirect storage and supply of electricity. Direct storage and supply of electricity is possible using capacitors, super-capacitors and Superconducting Magnetic Energy Storage (SMES). These are used in power systems for supporting base-load generation, to even out peak and off-peak demand, and improving the power quality (Baker, 2008; Hall et al., 2008).

At present, EES for heating is not very widespread, and so will not be a cost effective or an efficient way of shifting the peak heating energy demand. However, it is worth noting that in a future UK energy system, with a decarbonised national grid, heating will need to be provided by electricity in order to reduce the heating related CO_2 emission. Also, as the uptake of RET increases, the role of EES in ensuring power quality and combatting intermittency will become critical (Hall, 2008). Therefore, it is vital that research in EES continues, though this is not within the scope of this research.

2.4.3 Thermal energy storage

The principle behind the use of a rechargeable TES system is the same as any other rechargeable storage device. During energy storage, heat energy is supplied to the TES system (charging) whilst during discharging heat is removed from it for other use (discharging). Application of TES can be split into two temperature categories (Fernandes et al., 2012):

1. Low temperature TES – below 200°C. Application examples include building heating & cooling, cooking, water & air heating and in solar green houses.
2. High temperature TES – any safely usable temperature higher than 200°C. Application examples include waste heat recovery from brick & cement kilns, solar thermal power plants and metallurgical industries.

It is the low temperature heat that is of value in domestic heating, although it may be necessary to store high temperature heat for increasing the storage capacity.

A TES system can be described as a device that can store thermal energy by cooling, heating, melting, solidifying or vaporizing a material or medium. Its operational principle can be classified into three categories; 1) Sensible, 2) Latent and 3) thermochemical energy storage as illustrated in Figure 2-22. Also, there are two concepts of energy removal and deposition within a TES system and the associated components; a) Active and b) Passive (Pinel et al., 2011). These are extensively described in various literatures (Khartechenko, V. N., 98; Pinel et al., 2011; Arteconi et al., 2012; Sharma et al., 2009; Ibrahim et al., 2008; Parameshwaran et al., 2012). An overview of these is given in the following sections.

The fundamental difference between the TES techniques (see Figure 2-22) is their energy storage capacity. Pinel et al. (2011) cited research which approximated the volume of storage medium required to store 6.7MJ (or 1861kWh) of energy for the three storage principles as shown in Figure 2-23. As can be seen, chemical storage has considerably greater storage capacity compared to water, which makes it potentially very useful for the relatively small domestic buildings in the UK. Other factors also need consideration prior to selecting a TES method as discussed in the following sections.

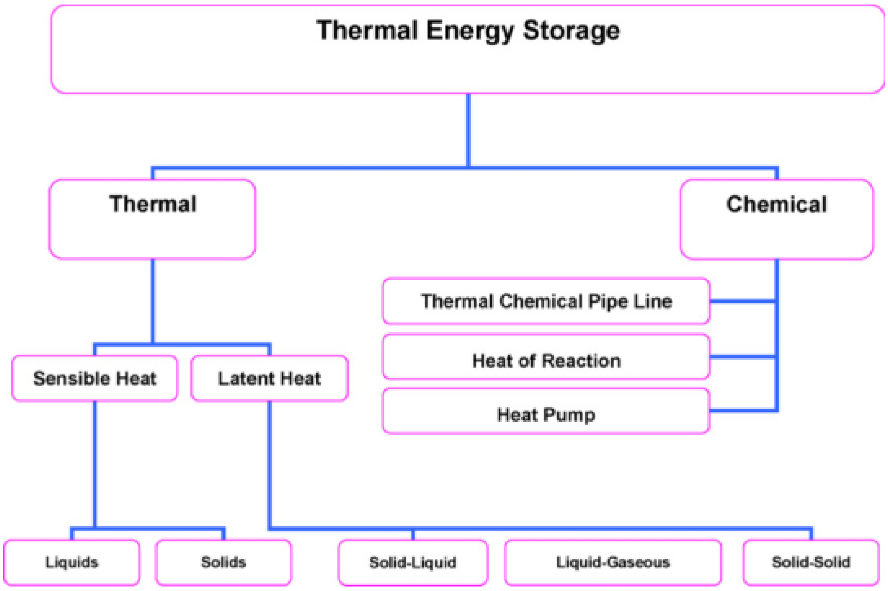


Figure 2-22. Different types of thermal energy storage (Sharma et al., 2009).

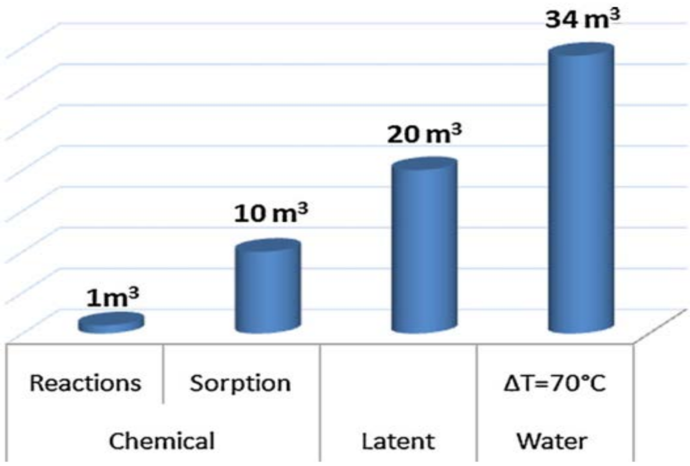


Figure 2-23. Volume required to store 6.7 MJ of thermal energy. (Pinel et al., 2011).

2.4.4 Sensible TES

Sensible heat storage involves heating or cooling materials without reaching the temperature extremes that result in their physical state being changed, for example from solid to liquid or liquid to gas. Low temperature sensible TES, in the range 20℃ to 80℃, have been used for centuries with water as the storage medium (Hadorn, J. 2007). An example of sensible TES in residential buildings is hot water storage at temperatures between 0 to <100℃, through the use of solar thermal systems for Solar Domestic Hot Water (SDHW). These are systems where solar thermal energy is used to heat up the water and then stored into some TES device such as cylindrical storage tanks. As Pinel et al., (2011) points out, sensible TES is proven, well understood and used successfully for decades and will remain the method of choice for the foreseeable future due to its low complexity and cost. The material for any TES application must have an adequate thermal storage capacity. The amount of heat which can be stored in a mass of material can be determined using Equation 2-6 (Khartechenko, V. N., 1998; Sharma et al., 2009).

$$Q = \int_{T_i}^{T_f} mC_p \, dT = mC_{ap}(T_f - T_i)$$

Equation 2-6

Where: *Q=quantity of heat stored (J)*
M=mass of material
C_p=Specific heat (J/kg K)
T_f= Final Temperature
T_i=initial temperature
C_{ap}= Average specific heat between Ti and Tf (J/kg K)

Table 2-7 shows a list of materials suitable for sensible TES, though water, oil, molten salts, molten metals, bricks, sand and soil are considered as more appropriate for short-term storage. For long term or seasonal storage large aquifers, rock beds, solar ponds and large storage tanks are considered suitable (Dincer, 2002; Pinel et al., 2011). Water is a comparatively good material in terms of its high specific heat, low cost and chemical stability. However, there are other important factors such as the freezing and boiling temperature, and the system operating temperature, which also needs to be taken into account. Synthetic and organic oils can be substituted for water where high storage temperature is needed, though they have roughly half the specific heat capacity of water, in addition to the other disadvantages such as the risks associated with handling high temperature materials (Dincer, 2002). Molten salts are also an option for sensible TES, where higher temperatures are needed. Again, the disadvantages are the lower specific heat and the high temperature material handling.

Table 2-7. Thermal capacities of some common TES materials at 20°C (Sharma et al., 2009)

Medium	Fluid type	Temperature range (°C)	Density (kg/m^3)	Specific heat (J/kg K)
Rock		20	2560	879
Brick		20	1600	840
Concrete		20	1900–2300	880
Water		0–100	1000	4190
Caloriea HT43	Oil	12–260	867	2200
Engine oil	Oil	Up to 160	888	1880
Ethanol	Organic liquid	Up to 78	790	2400
Proponal	Organic liquid	Up to 97	800	2500
Butanol	Organic liquid	Up to 118	809	2400
Isotunaol	Organic liquid	Up to 100	808	3000
Isopentanol	Organic liquid	Up to 148	831	2200
Octane	Organic liquid	Up to 126	704	2400

2.4.5 Latent TES

Sharma et al. (2009) provides a detailed analysis of Latent TES, the materials used and how it can be applied in energy storage. Basically, latent TES involves using heating and cooling materials such that a physical phase or state change occurs. Materials which provide good thermal storage capability when used in this way are referred to as Phase Change Materials (PCMs). The energy storage capacity of a latent TES system with a PCM can be calculated using Equation 2-7 (Sharma et al., 2009).

Equation 2-7

$$Q = \int_{T_i}^{T_m} mC_p \, dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p \, dT$$

$$Q = m[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)]$$

Where: *Q=quantity of heat stored (J)*
m=mass of material
a_m=fraction melted
Δh_m=heat of fusion per unit mass (J/kg)
C_{sp}=average specific heat between Ti and Tm (kJ/kg K)
C_p=Specific heat (J/kg K)
C_{lp}= average specific heat between Tm and Tf (kJ/kg K)
T_m=Melting temperature (°C)
T_f= Final Temperature (°C)
T_i=initial temperature (°C)
C_{ap}= Average specific heat between Ti and Tf (J/kg K)

Typically, a PCM can store 5-14 times more heat per unit volume compared to a sensible storage medium. Figure 2-24 illustrates the heat energy storage capacity of water, rock and a PCM, based on an experimental and theoretical research cited by Sharma et al. (2009). The superiority of a PCM can be clearly seen, which is considerably greater than water, which itself is considered as a good material for TES (Pinel et al., 2011).

PCMs are generally classified into three categories (Arteconi et al., 2012):

1) Organic compounds (such as paraffins and fatty acids)
2) Inorganic compounds (such as salt hydrates and metallics), and

3) Eutetics (where for example, transition from one liquid phase results in more than one solid phases upon cooling)

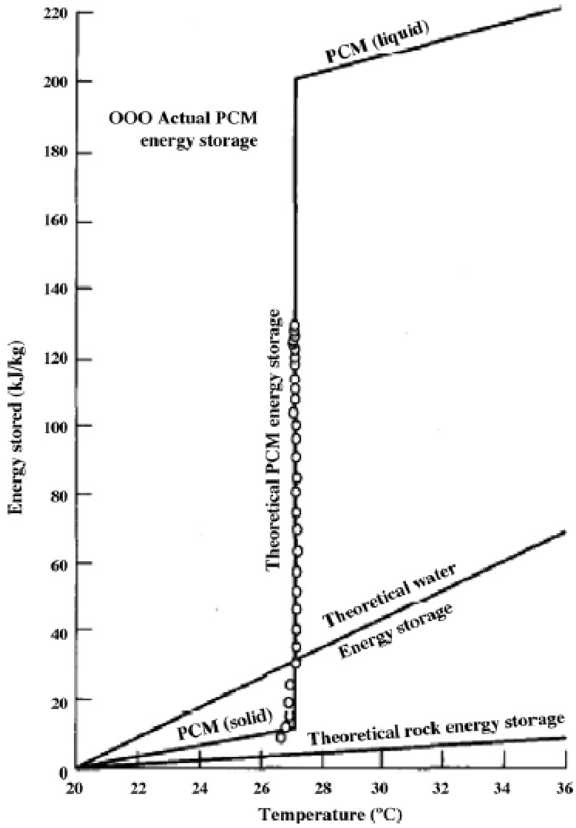


Figure 2-24. Performance comparison of PCM, water and rock storage system (Sharma et al., 2009)

Table 2-8. Comparison of PCM types (Arteconi et al., 2012)

Classification	Advantages	Disadvantages
Organic PCMs	1. Availability in a large temperature range 2. High heat of fusion 3. No supercooling 4. Chemically stable and recyclable 5. Good compatibility with other materials	1. Low thermal conductivity (around 0.2 W/m K) 2. Relative large volume change 3. Flammability
Inorganic PCMs	1. High heat of fusion 2. High thermal conductivity (around 0.5 W/m K) 3. Low volume change 4. Availability at low cost	1. Supercooling 2. Corrosion
Eutectics	1. Sharp melting temperature 2. High volumetric storage density	Lack of currently available test data of thermophysical properties

The pros and cons of these PCM types are provided in Table 2-8, whilst Table 2-9 provides the thermo-physical properties of some of the common commercially available PCMs for building comfort applications. A more comprehensive list of materials and their thermal properties, ranging from various paraffins, non-paraffins, fatty acids, salt hydrates, metallics and eutectics that are suitable for latent TES are available in the paper by Sharma et al. (2009). Latent TES using PCMs can be more effective than sensible TES in residential applications, due to its high energy storage density (see Figure 2-23 & Figure 2-24). Also, PCMs are able to provide heat at a constant temperature, corresponding to the phase-transition temperature of the material, which would be useful in both water and space heating. However, the technology comes with its own disadvantages as shown in Table 2-8 which must be overcome. In addition, there are other factors affecting the choice of PCMs such as cost and availability, thermal, physical, kinetic and chemical properties. These are extensively explored by Huggins, (2011) and Dincer and Rosen (2011).

Table 2-9. Thermo-physical properties of commercial PCMs for comfort applications in building (Arteconi et al., 2012)

Product	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Source
RT 20	Paraffin	22	172	0.88	Rubitherm GmbH
Climsel C23	Salt hydrate	23	148	–	Climator
E23	Salt hydrate	23	155	0.43	EPS Ltd
Climsel C24	Salt hydrate	24	108	1.48	Climator
TH 24	Salt hydrate	24	45.5	0.8	TEAP
RT 26	Paraffin	25	131	0.88	Rubitherm GmbH
RT25	Paraffin	26	232	–	Rubitherm GmbH
STL 27	Salt hydrate	27	213	1.09	Mitsubishi Chemical
S27	Salt hydrate	27	207	–	Cristopia
AC 27	Salt hydrate	27	207	1.47	Cristopia
RT 27	Paraffin	28	179	0.87	Rubitherm GmbH
RT 30	Paraffin	28	206	–	Rubitherm GmbH
E28	Salt hydrate	28	193	0.21	EPS Ltd

2.4.6 Thermochemical TES

Thermochemical TES systems rely on absorbing and releasing energy in two ways (Pinel et al., 2011):

1) Chemical reaction process: consisting of using heat to excite a reversible endothermic chemical reaction (charging). Recuperation of the heat is done by reversing the reaction by adding a catalyst (discharging).

2) Thermo-chemical process (Sorption): consisting of using heat to break up the bonding of water with another substance and evaporating one of the products (charging). Recuperation of the heat is done by condensing the product and re-bonding it with the other substance (discharging). The amount of heat stored depends on the amount of storage material, the endothermic heat of reaction and the extent of conversion, and can be calculated using Equation 2-8 (Sharma et al., 2009):

$$Q = a_r m \Delta h_r \qquad \text{Equation 2-8}$$

Where: *Q=quantity of heat stored (J)*
m=mass of material
a_r=fraction reacted
Δhr=endothermic heat of reaction

Table 2-10. Potential materials for chemical reaction storage identified during IEA SHC Task 42 (Pinel et al., 2011).

Material	Dissociation reaction	Storage density (GJ/m^3)	Turnover temperature (°C)
Magnesium sulphate	$MgSO_4{\cdot}7H_2O \Rightarrow MgSO_4(s) + 7H_2O$	2.8	122
Silicon oxide	$Sio_2 \Rightarrow S_i + O_2$	37.9	4065 +HF: 150
Iron carbonate	$FeCo_3 \Rightarrow FeO + CO_2$	2.6	180
Iron hydroxide	$Fe(OH)_2 \Rightarrow FeO + H_2O$	2.2	150
Calcium sulphate	$CaSO_4{\cdot}2H_2O \Rightarrow CaSO_4 + 2H_2O$	1.4	89

Chemical TES has advantages where much greater heat storage density per unit volume can be achieved (see Figure 2-23), which would be desirable in residential environments. Also the storage reaction products can be stored at ambient room temperature, thus not resulting in energy loss due to self-discharge. This makes chemical TES attractive for seasonal storage, though this is not within the scope of this research. However, there are disadvantages to be overcome, as cited by Pinel et al. (2011), from the research carried out by the International Energy Agency (IEA) under the SHC Task 32 Programme, and the European NNE5-2000-00385 & SOLARSTORE projects, highlighting the need for much more research and development of materials with better properties, and making them more economical.

2.4.7 Benefits of TES

TES has many potentially useful applications, providing benefits which are essential to achieving a resilient energy system as discussed previously. Potential benefits for domestic households have also been identified including reduced energy use, taking advantage of varying energy tariffs and reducing energy bills (Dincer, 2011; Pinel et al., 2011; Sharma et al., 2009; Arce et al., 2011; Arteconi et al., 2012; Parameshwaran et al., 2012). An example of the benefits is the potential energy bill saving ability for the households through storing heat generated during the off-peak times through the use of reduced ‘time-of-use’ electricity tariffs such as Economy7 and Economy10. The savings could be significant given that around 80% of the energy demand in buildings is for space and water heating and, as suggested by a study, that under an Economy 10 tariff, 70-90% of heat load for a domestic property could be generated during off-peak times (ERP, 2011). An example of the electricity prices based on standard and economy7 tariff in June 2014, from Npower (one of the main electricity suppliers in the UK), are 16.72p/kWh and 6.44p/kWh respectively (Npower, 2014). The economy7 rate represents a 61.5% reduction from the standard tariff, though more energy than normal will need to be purchased to compensate for the intrinsic storage losses occurring outside of the occupied hours, assuming that the TES is located inside the building, reducing the savings. The literature (ERP, 2011; Pinel et al., 2011) emphasises the potential ability of TES providing electrical load management through DSM if it can be coupled with electrically driven heating and cooling systems.

2.4.8 TES selection criteria for optimum performance

The suitability of TES, like other storage techniques, is dependent on the end use, which defines the performance characteristic requirements. Typically, the performance characteristics are described in terms of such factors as energy density (Wh/kg), power density (W/kg), cycle efficiency, self-discharge characteristics and cycle life (cycles). Other factors such as cost, size and environmental impact are also relevant to its successful application. Dincer & Rosen (2011) have identified eight criteria by which TES can be evaluated:

1. **Technical Criteria:** covering parameters such as storage capacity, lifetime, size, cost, resource use, efficiency, commercial viability, safety, installation and environmental standard.
2. **Environmental Criteria:** considering the design, material and operational practices which could affect public health, natural ecology and the environment.
3. **Economic Criteria**: providing justification for the application of TES in terms of upfront/operational cost versus benefit analysis, payback periods and availability of financial incentives.
4. **Energy saving criteria**: investigating the potential impact in terms of shifting the energy demand from peak to off-peak hours, and analysing the indirect and direct energy savings
5. **Sizing Criteria**: to ensure under or over sizing which could impact indoor comfort and cost, thereby reducing satisfaction levels.
6. **Feasibility criteria**: to eliminate unknown factors preventing implementation or optimum operation.
7. **Integration criteria**: involving evaluating the potential interaction between existing thermal infrastructure and TES.

8. **Storage duration criteria:** covering; a) short-term or diurnal (used to address peak power loads lasting a few hours to a day), b) medium-term (used where waste heat or seasonal energy loads can be transferred over a few weeks to a few months), and c) long-term or annual/seasonal (used to take advantage of seasonal climatic variations).

These are all important factors relating to the uptake of TES, which need critical evaluation with a UK domestic building perspective. This could be done through theoretical, modelling, experimental testing or a combination of these research methods.

2.5 Previous research on domestic heating

This section contains details of the previous academic research on heating domestic buildings. Research addressing the drivers of space heating energy consumption such as thermal comfort, and the descriptors of heat energy consumption are first reviewed. Research into the winter time heating practices in the UK are analysed, followed by a review of the past research projects on domestic heat energy demand studies.

2.5.1 Thermal comfort – the driver of domestic heat demand

Thermal energy in domestic buildings is mainly used for ensuring a living environment that minimises the potential health risks and for ensuring the buildings are comfortable for occupation (DECC, 2012a; Yohanis et al., 2010). The air temperature in the living spaces is considered as the most important parameter for defining comfort and can be used as a measure of thermal comfort. The UK government uses 21℃ as an acceptable temperature for the living room and 18℃ for the other rooms (DECC, 2012a; Yohanis et al., 2010). The Chartered Institute of Building Services Engineers provide design guidelines of 19-20℃ for continuous occupancy and 18℃ for transient occupancy of dwellings. The BRE guideline for achieving satisfactory winter thermal comfort is a temperature range of 18℃ to 21℃ for the living room (Yohanis et al., 2010). In reality thermal comfort is a subjective phenomenon and can vary with occupant demographics, geographical location, type and size of dwellings, and seasonal and climatic conditions (Hewitt, 2012; Peeters et al., 2009). Therefore the energy needed to attain thermal comfort will vary depending on these parameters as well as the building energy and thermal performance.

2.5.2 Descriptors of domestic energy use

Kane (2013) categorised the major factors or descriptors that influence heat energy use in domestic buildings in the winter days into two categories: 1) Technical descriptors and 2) Social descriptors:

Social descriptors:

Social descriptors relate to the occupants and household composition. These are broken down into six descriptors which directly or indirectly influence domestic energy use for heating (Kane, 2013):

1. **The tenure of a dwelling**: whether it is owned by the occupier or rented, and relates to energy use by indirect means.
2. **The employment status of household**: this can influence the heating pattern used in the household and therefore the indoor temperature.
3. **Age of household occupants**: is related to the indoor temperature levels and the duration of heating periods.
4. **The number of children in the dwelling**: influences the occupancy of the dwelling and therefore the heating practices that are used by occupants.
5. **Household size:** is the number of occupants that live in a dwelling. A higher number of occupants living in a dwelling have been found to increase the energy use.
6. **Household income:** Income has been found to have a direct relationship with energy expenditure with higher income groups using more energy. However, Kane (2013) cited research which indicates that much of this higher energy use is related to households with higher incomes owning more appliances; therefore income is a less significant driver of energy use for space heating.

Technical descriptors:

Technical descriptors relates to building characteristics such as the size or age of the dwelling. There are numerous technical descriptors, however Kane (2013) describes five of the main descriptors and how they influence energy use and indoor temperature (Kane, 2013):

1. **House type:** is the term used to describe the built form of a dwelling.
2. **House size or floor area:** relates to energy use as larger dwellings require more energy to increase indoor temperatures to the occupant’s expectation.
3. **House age**: is related to indoor temperature as changes in building standards and techniques have influenced both the heat loss and the infiltration through the building fabric.
4. **Wall type**: describes how a dwelling is constructed, for example before 1930 UK dwellings were predominantly built without a cavity between bricks. Wall type has a direct link to the heat loss through the walls.

5. **Heating type**: is related to whether dwellings are heated by central heating systems or fixed heaters.

Yao et al. (2005) identified two main determinants of domestic heating and non-heating energy demands:

1. **Behavioural determinants**: These relate to behavioural and habitual characteristics of the occupants such as sense of thermal comfort, frequency of use of appliances and general view of energy use and the environment. These are less dependent on factors such as the climate and building design. Behavioural determinants result in energy use and load profiles based on relatively 'flexible' decisions which occur on an hourly/daily/weekly time scale
2. **Physical determinants**: These relate to the physical and building physics aspects of energy consumption such as dwelling size and the U-values of the building fabrics. These have low correlation to the occupant's habits. Physical determinants result in energy use and load profiles based on relatively 'fixed' decisions

These correspond with the social and technical descriptors described by Kane (2013). The parameters which are common to both the behavioural and the physical determinants which can influence domestic energy are the occupancy patterns and the household income (Yao et al., 2005). For example, the occupancy patterns can decide how often and for how long the heating systems are used. The household income could also dictate the heating duration and the indoor temperature setting, although it is considered to be less significant (Kane, 2013). Wright (2008) concludes that the actual energy usage in homes results from a complex interaction between factors such as its built form, its location, the energy using equipment it contains, its occupants and the affordability of fuel, and that households have a stronger influence on energy use than built form.

2.5.3 Heating practices in the UK

Heating practices, which include factors such as the temperature homes are heated to, the heating duration and heating patterns, can play a vital role in determining the heating energy consumption and the heating load patterns. It is therefore essential to appreciate the heating practices in the UK, so that they are taken into account in any heat demand management activities to maximise their effects.

Kane (2013) carried out a thorough examination of the heating practices of domestic buildings in the UK during the winter periods using heating monitoring data of 249 dwellings in Leicester, UK. He categorised the heating practices into two categories: 1) Timing related heating practices and 2) Temperature related heating practices, and identified different metrics for each of these heating practices. Information corresponding to the metrics was extracted and disaggregated according to the different elements within the social and technical heating energy influencing descriptors as described in Section 2.5.2. The information was analysed to identify and highlight heating practices employed in the dwellings. It was concluded that households employ a variety of heating practices to maintain the preferred indoor temperature during the winter period. Table 2-11 illustrates seven heating metrics identified by Kane (2013) which are relevant to this study. These metrics and the corresponding findings are useful in that they could determine the operational characteristics of domestic TES systems.

Table 2-11. Timing and temperature related heating practice metrics and their findings relevant to this thesis (adapted from Kane, 2013).

Heating practice category	Heating practice metric	Definition	Findings (which are relevant to this study)
Timing	Heating pattern	The number of times when heating is predominantly used	Double (51%) and Single (31%) heating periods dominated the sample
	Start and end times of heating	The first and last time when heat is regularly delivered by the heating system	Single heating period: start and stop times are predominantly 07:00 and 23:00 Double heating period: morning start and stop times are predominantly 07:00 and 09:00; Evening start and stop times are mainly 15:00 and 22:00
	Daily heating period	The average number of hours the heating is used per day during the heating season	Average daily heating period was 12.6 hours (standard deviation 3.4 hours). Longest and the shortest daily heating period was 22 hours and 4 hours respectively
Temper-ature	Average maximum temperature	The average of the daily maximum temperature measure in the living rooms.	Average maximum temperature for all 249 dwellings was 20.9°C (standard deviation 3.2°C)
	Average temperature when heated	The average temperature between the start and end times of heating	For single heating period: the average temperature 18.2°C (standard deviation 3.2°C) in living rooms and 17.6°C (standard deviation 3.4°C) in bedrooms. For double heating period: average temperature was 17.5°C (standard deviation 2.8°C) in living rooms and 17.0°C (standard deviation 2.7°C) in bedrooms in the first heating period and 19.0°C (standard deviation 3.0°C) and 17.8°C (standard deviation 2.8°C) in the second heating period in living rooms and bedrooms respectively
	Time to reach peak temperature	The time between the start of each heating period and the time when the peak temperature (in that heating period) is reached.	Double heating pattern: the median time to reach peak temperature was 3 hours for the first heating period and 7 hours for the second heating period. The shortest times to reach peak temperature were 1 hours and 3 hours for the first and second heating periods respectively. For single heating period: longest times to reach peak temperature were found in the dwellings with single heating periods
	ΔT_{room}	The average temperature difference between the living room and the bedroom	The mean ΔT_{room} was 1.0°C (standard deviation 2.5°C) for all dwellings. The mean ΔT_{room} 0.9°C in dwellings with central heating but 2.8°C with no central heating.

The BREDEM model (See section 2.6), which is the most commonly used building energy model, and on which SAP is based, assumes that the living room is heated to 21℃ for 9 hours on weekdays (07.00 to 09.00 and 16.00 to 23.00) and for 16 hours on weekends (07.00 to 23.00) (Shipworth et al., 2010). In the real-world, this varies for different conditions and occupants as demonstrated by Kane (2013) and as described in Table 2-11.

Shipworth et al. (2010) presented empirical data on central heating demand temperatures and use durations, based on the national survey of energy use in English homes. The data was collected from buildings of various demographics, through interviews and direct measurement of living room and bedroom temperatures, for a six month period from 22 July 2007 to 3 February 2008. The mean thermostat setting, according to 164 respondents, was 19℃. The thermostat setting, estimated from the temperature measurement from 195 dwellings was 21.1℃. The heating duration, based on the responses from 344 dwellings, was 9.4, 9.8 and 9.5 hours per day, for weekdays, weekends and average over the week respectively. The estimated use duration of the systems, based on the recorded temperatures from 196 dwellings, was 8.2, 8.4 and 8.3 hours per day, for weekdays, weekends and average over the week respectively. There is an obvious difference in the mean thermostat setting reported by the respondents and the estimated value based on temperature measurement. However, the estimated values have an inherent margin of error, which could have been reduced by direct measurement. The weekday heating duration figures are marginally lower than the BREDEM model assumption. Overall, the BREDEM model assumptions for thermostat setting and system use duration match reasonably well with the findings of this research, with the exception that in the weekends BREDEM assumes 16 hours of heating compared to approximately 9 hours indicated by this research. This paper does not provide 24 hour indoor temperature profiles for the different household demographics and building size and location variants. Information in this regard would be useful, in that it would enable analysis of the suitability of heating using electricity and shifting the heat demand in time.

Kane (2013) presented findings of the internal space temperature measurements carried out on 249 dwellings in the city of Leicester, UK, during the winter months of December 2009 and January 2010. Figure 2-25 shows the frequency distribution of the mean internal temperature of these dwellings separated by dwelling types. Clearly, there is a significant variation in the temperatures observed. He identified ten energy use descriptors which have significant impact in the mean winter temperature. Four of these were technical descriptors namely: house type, house age, central heating or not and wall type; four were social descriptors namely: employment status, tenure, age of oldest occupant and household size; and two were heating practice related namely the preferred indoor temperature (thermostat setting) and the daily heating period.

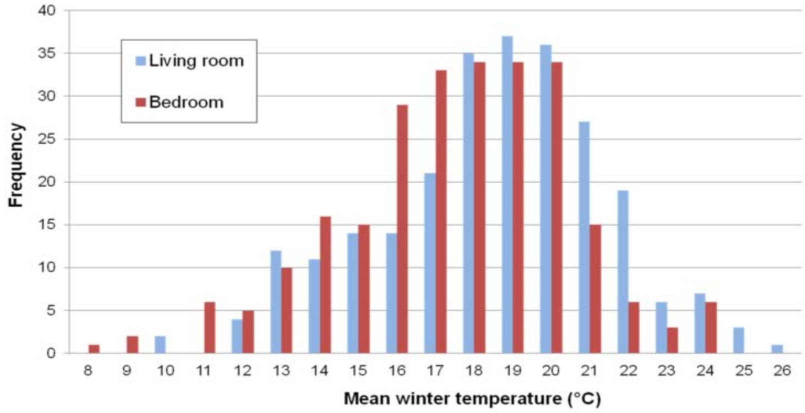


Figure 2-25. Frequency distribution of the measured living room and bedroom temperature of 249 dwelling in Leicester, measured during the December 2009 and January 2010 (Kane, 2013).

The temperature in the occupied space can vary considerably over a day due to the variation in the external temperature and the heating and occupancy cycle (Kane, 2011; Kane, 2013). Also, the temperature in a room, at a point in time, can also vary depending on the position of the room where it is measured. As demonstrated by Kane (2013) (see Figure 2-26), temperature monitors placed near the ceiling can record higher values compared to those placed away from the ceiling, most probably due to the thermal stratification effect in the room. This could affect the occupants' perceived thermal comfort in the room and influence the heating practice, and therefore the heating energy consumption. The temperature effect of the on/off cycling of the heating system can be seen in Figure 2-26, though it appears much more pronounced near the ceiling.

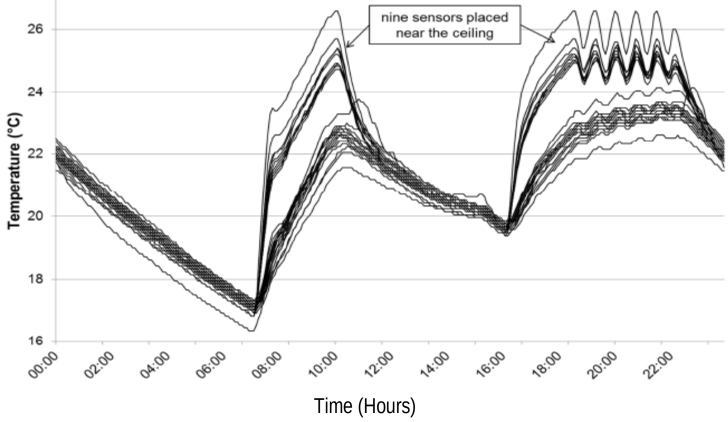


Figure 2-26. Temperature measurements taken in 27 positions in a single room at five minute intervals for one winter day (Kane, 2013).

2.5.4 Domestic heating energy consumption studies

Numerous studies and reports exist, which discuss and provide energy consumption data in the different demand sectors including the domestic building sector (BEIS, 2016; SDECC, 2013; DECC, 2013a; ERP, 2011; BRE, 2007; BRE, 2008; BRE, 2009b). The United Kingdom Housing Energy Fact File (UKHEFF) (DECC, 2013a) provides detailed data on domestic energy use and other related areas. This, like most others, provides space heating and DHW energy consumption at the individual household level. However, the values are specified on an annual basis, and derived from low resolution models particularly Cambridge Housing Model (CHM) and BREHOME (See Section 2.6). For example, the data provided does not specify how energy consumption varies during different days of the month and different times of the day. This is important especially as heat demand mainly occurs during specific occupied hours, and in cold winter days, and so will not be the same every day of the year. The data available from most sources, such as DUKES and UKHEFF, do not provide this information and therefore are not particularly useful in short term heat demand management studies.

Understanding and appreciating the energy consumption patterns in domestic buildings at short time intervals is essential, so that they are taken into account in any short term heat demand management activities, to maximise their effects. This requires high resolution energy consumption data, for example measured on a one minutely up to a one hourly interval, during the times when energy use for heating is widespread for example during the winter days. The data has to reflect the diversity of buildings, occupancy and operational conditions found in the UK housing sector. As noted by Lomas et al., (2006), there has been a 'chronic' shortage of such data which has prevented the production of transparent and valid models for understanding and predicting energy use.

One study which produced data that could be useful in short term heat demand management studies, and appropriate to this research, is the Milton Keynes Energy Park (MKEP) longitudinal study of 1989 to 1991. It involved hourly energy consumption for a range of houses, for example varying in built form and size (UKERC-EDC, 1991; Summerfield et al., 2010a). A total of 160 dwellings covering 35 different designs were used, each constructed in the late 80s to a higher energy performance than the required building regulation of that time. The construction features included floor and wall insulation, double glazing, and condensing boilers, complying with the requirements of the 1995 Building Regulations for England and Wales. Various occupied room temperatures were also monitored in 29 of these dwellings. A follow up study was carried out in 2005 on a sub sample consisting of 14 dwellings. Summerfield et al. (2007), in a paper, analysed the data from the follow up study and reported an average gas derived heat energy consumption of 71.5kWh/day under standardised winter condition with an external temperature of 5°C, and a mean floor area of 108.6m^2. The mean living room space temperature was reported as 20.1°C. The same dwellings in 1990 had an average heating energy consumption of 65.2kWh/day which is an increase of around 10%. The authors however stated that the evidence relating to this increase is 'weak', and therefore cannot be taken as indication of a general heating energy consumption rise over time in the UK. The reason for this, most probably, is the very small sample of buildings used and that they all have the same geographical location. Also, the mean floor area was slightly lower in 1990 at 104.8m^2, which did not include some extensions made by the occupants before 2005. Summerfield et al. (2010a) in another paper analysed the energy consumption data for a sample of 36 dwellings of MKEP, made up from a further follow up study of 24 dwellings carried out in 2007, and combined with the 14 dwellings used during the 2005 follow up study. The dwellings this time had a mean heated occupied floor size of 98m^2. He reported an average heat energy consumption of 67kWh/day under standardised winter condition with an external temperature of 5°C. This indicates that the mean gas consumption in buildings over a period of the 17 years remained relatively static. However, as noted by the authors, the sample sizes in the follow up studies discussed above are small, and so the results cannot be taken as representative of the UK housing stock.

Neither paper provided details on the exact composition of the buildings in the samples in terms of, for example, the U-values of the critical fabric elements and the floor size. A closer examination of an 'information file' and some of the data files for the individual dwellings in the MKEP, available from UKERC-EDC, (1991), indicated that the U-value for the floor and the external walls varied from 0.22W/m^{2}K to 0.45W/m^{2}K and 0.30W/m^{2}K to 0.44W/m^{2}K respectively. Also, the external widows mostly had double glazing with some triple glazing, taking the U-values more close to the 2002s Building regulation recommendations, as discussed in Section 2.3.2. It is reasonable, therefore, to suggest that these dwellings will have lower energy consumption than those that are insulated according to the 1990s building regulation standard. The MKEP study, as analysed by Summerfield et al. (2007; 2010a), provides a good indication of the heat energy consumption that can be expected in dwellings of varying physical and thermal characteristics, which heat demand management models could be validated against. This is especially so given that the MKEP data was used to develop and refine the BREDEM model (Summerfield et al. (2007) on which SAP is based, as discussed in Section 2.3.2 and Section 2.6.

Buswell et al. (2013) reported some early results from a whole house monitoring trial in the East Midlands, England. The heat use was disaggregated from a high resolution measurement of gas, hot water and power consumption during the month of January for a sample of two dwellings. The first was a detached dwelling built between 1950 and 1965 with cavity walls (uninsulated) and an extension built in the 70s. There was no loft insulation present and the external windows were double glazed. Heating was provided by a gas central heating system. The household comprised of a mother and child aged 11. The second was a semi-detached dwelling constructed between 1966 and 1974 with cavity walls, and had an extension added in 2000s. The dwelling including the conservatory was heated by a gas central heating system. The cavity walls were insulated and the loft had over 250mm of insulation. The property was fully double glazed. The household comprised of 4 adults and two children between 11 and 16 years of age. Both dwellings had an approximately internal heated floor area of 100m^2 over two floors. The disaggregated heat and DHW energy consumption measured for the detached dwelling were 56.5kWh/day and 13.0kWh/day respectively (total of 69.5kWh), and for the semi-detached they were 58.6kWh/day and 14.7kWh/day respectively (total of 73.3kWh). Based on the building fabrics (those that are mentioned in the paper) present in the detached dwelling, it’s thermal insulation level could be assumed to be somewhere in between the 1990 and 2002 building regulations, and the semi-detached building could be considered more in line with the 2002 building regulations. Under similar occupancy and operational condition the detached dwelling would be expected to consume more energy compared to the Semi–detached (DECC, 2013a; BRE, 2008). However, it can be seen that the measured energy demand in the semi-detached dwelling is higher compared to the detached. The explanation could be the semi-detached having twice as many occupants compared to the detached, possibly resulting in a higher heating duration and/or higher thermostat set-point. The extra occupants in the semi-detached use marginally more (1.7kWh) energy for DHW which increased the overall energy use. Unfortunately, the paper does not state what the external ambient temperature was when the measurements were taken or whether the measurements were taken on the same day. It could be that the measurements for the detached dwelling were taken on a relatively warm day for which the demand for heat was less. Without this information the results cannot be compared or verified with other measured data.

2.6 Previous research on modelling domestic buildings

This section details the methods and practices employed in modelling domestic building energy and thermal performance. The two main modelling methods (Top-down and Bottom-up), the methods used in representing the buildings and the environment in which they operate are discussed. The tools available for modelling domestic energy and thermal performance of buildings are analysed.

2.6.1 Top-down modelling approach

Numerous papers and books discuss the top-down modelling approach (Swan et al., 2009; Kannan et al., 2009; Kane, 2013). In the energy domain, top-down modelling methods are used to inform policy makers concerning the impacts of the economic and social drivers of energy consumption. For example, they are used to gain a better understanding of how factors such as geographic, economic, demographic and technological affect energy consumption based on historic data. Given these factors and certain policy instruments, top-down models are used to generate trends of energy use impacts in different population categories. However, they cannot be used to determine the impact of the heating practices at the household level. Instead, households are grouped into categories and attributes assigned reflecting the behaviour of the key members such as social descriptors, for example income and age. As such, little details of the actual energy consumption habits of the households are required, and do not distinguish energy consumption from different end-uses. Treating the residential building sector as an energy sink, this method applies the above mentioned factors to determine trends (Swan et al., 2009). Therefore it is not possible to predict the impact of energy consumption influencing interventions such as behaviour of households (e.g. thermostat setting and heating duration) and thermal insulation upgrades. However as mentioned above, top-down energy models have the advantage of being able to predict the impacts of economic changes, and for this reason are extensively used by policy makers.

The most commonly used top-down model in the UK is the UK MARKAL. It has been extensively used as a policy tool by the UK government, and has been used to generate the pathways that could lead to the UK meeting the 2050 emission reduction and energy targets (Kannan et al., 2009; Kane, 2013).

As documented by Kane (2013), a number of other top down models are in use in the UK including:

1) Annual delivered energy and temperature (ADEPT) model – uses linear regression on data available since 1970
2) Seasonal temperature energy price (STEP) model – uses polynomial regression with quarterly energy data since 1998
3) Local Area Resource Analysis (LARA) – determines the CO_2 emission at national and regional levels using a four stage calculation: 1) using Expenditure and Food Survey (of around 7000 households) to determine expenditure on fuel; 2) converting household expenditure into energy use by using price information for fuel types; 3) CO_2 emission estimated by using the emission factor for the fuel type, and 4) CO_2 emissions are scaled up according to the household characteristics of: household income, house type, tenure, age and economic status of the oldest member of the household, based on the 2001 census.

2.6.2 Bottom-up modelling approach

The bottom-up modelling approach is also extensively discussed in the literature (Kavgic et al., 2010; Swan et al., 2009; Kannan et al., 2009; Kane, 2013). In the energy use domain, this approach accounts for the energy consumption of individual end-uses, individual houses or groups of houses. The results are then extrapolated to represent regions or the UK.

Swan et al., (2009) describes two methods that can be used in bottom-up modelling of domestic energy use:

1) **Statistical Method (SM):** using historical information and regression analysis to determine the relationship between the end-use and energy consumption.
2) **Engineering method (EM)**: determines the relationship between the energy consumption and end-use based on the explicitly defined power ratings, heat transfer and thermodynamic characteristics of the equipment and systems that make up the buildings.

Input data into EM method of bottom-up models include dwelling properties such as geometry, envelope fabric, equipment and appliances, climate properties, as well as indoor temperatures, occupancy schedules and equipment use. This gives it the ability to model the impacts of technological and behavioural changes, and identify areas of improvement or concerns. Furthermore, bottom-up EM modelling enables the impacts of “free energy” to be taken into account, such as solar gains. These are historically neglected, but are now an integral part of building design, focused around energy consumption and thermal comfort. These are major strengths of EM method of bottom-up modelling approach, which are, therefore, considered to be an appropriate tool for use in this work.

2.6.3 Modelling of domestic buildings and their operation

As discussed by Firth et al. (2008), heat demand research through housing stock modelling can provide various advantages, for example models can be relatively easily, quickly and cheaply configured to obtain answers that correspond with the research questions of a particular time. Data gathered through the conventional empirical means can relatively easily become out of date (Firth et al., 2008; Famuyibo et al., 2012). This is particularly true in the area of domestic heat energy consumption where various dynamic factors such as energy security, energy price, and weather conditions drive the heat demand. Furthermore, modelling can help drive the development of technology and market uptake (Pinel et al., 2011). For these reasons, researchers and stakeholders have called for much more detailed and high resolution modelling of domestic heating demands, domestic application of TES and energy storage in general (Arteconi et al., 2012; ERP, 2011; UKERC, 2011; Zhang et al., 2005; Pinel et al., 2011).

The thermal properties of the building materials used and the physical form of the buildings are two of the main factors within the domestic building energy system which directly affects energy consumption, and dictates the form of the heating load profile. The size of the housing stock and the presence of a large number of variables, and how they can combine to form a diverse range of differently performing systems make the energy consumption analysis of dwellings complex (Famuyibo et al., 2012; Firth et al., 2010). Therefore researchers often categorise the dwellings into various archetypes to enable easier analysis. As explained by Taylor et al., (2013), an archetype does not match any specific real building but have behaviour, in terms of for example energy consumption, which matches an average behaviour of a group of dwellings. When the behaviour of different archetypes is combined in proportion to the population in the region of interest, the total becomes an accurate reflection of the housing stock. An alternative to archetype method is Actual Building Sample (ABS). This involves creating a large number of models of actual sample buildings, which could be grouped and combined in correct proportions, to reflect the housing stock. The other main factors that affect energy use include the occupant demographics, location and the weather conditions (Wright, 2008; Yohanis et al., 2010; Hewitt, 2012; Peeters et al., 2009).

As discussed by Kane (2013), the building stock models mainly used in the UK are based on the Building Research Establishment Domestic Energy Model (BREDEM). This is also the model on which SAP is based as previously discussed in Section 2.3.2 (Shorrock & Anderson, 1995). A number of BREDEM versions exist including the monthly version (BREDEM-8), annual version (BREDEM-12) and a simplified version of the monthly version (BREDEM-9) which forms the basis of the SAP (Kavgic et al., 2010; Kane, 2013). BREDEM uses building physics and empirical data to calculate domestic energy consumption by four end-use categories; space heating, hot water consumption, cooking and lights and appliances.

The housing stock models used for research purposes in the UK include BREHOMES (Shorrock & Dunster, 1997), the Johnston model (Johnston et al., 2005), the UK domestic carbon model (UKDCM) (Boardman, 2007), deCARB (Natarajan & Levermore, 2007), the Energy and Environmental Protection model (EEP) (Jones et al., 2007), the Community Domestic Energy Model (CDEM) (Firth & Lomas, 2009: Firth et al., 2010), the Domestic Energy and Carbon Model (DECM) (Cheng & Steemers, 2011) and The Cambridge Housing Model (DECC, 2012b). The differentiating factor in these models is predominantly the number of building archetypes use to model the housing stock. They vary from 2 archetypes (in the Johnson model) to 20,000 archetypes (in the UKDCM model), and based on parameters such as built form, age, insulation levels, window type and central heating ownership. Archetypes are created by combining these parameters based on statistical analysis. The energy performance of the archetype is then scaled up according to the number of houses or floor area in that archetype to represent the housing stock (Famuyibo et al., 2012; Firth et al., 2010). The advantages of this approach are highlighted by Firth et al. (2010) and Famuyibo et al. (2012) and include for example: easier evaluation of energy performance and economic interventions; enable impact analyses of future energy retrofit measures; conduct 'what-if' analyses to enable policy makers to optimise regulations and market incentives to achieve specific targets.

Famuyibo et al. (2012) presented 13 building archetypes based on information from literature and a sample of detailed energy-related housing data. The main variables within the 13 archetypes are the dwelling built form (comprising of detached, Semi-detached/end terrace and mid-terrace/apartments), Wall U-value, Roof U-value, Window U-value, Floor U-value, Floor Area, Heating Systems, Air Change Rate, and DWH Cylinder Insulation.

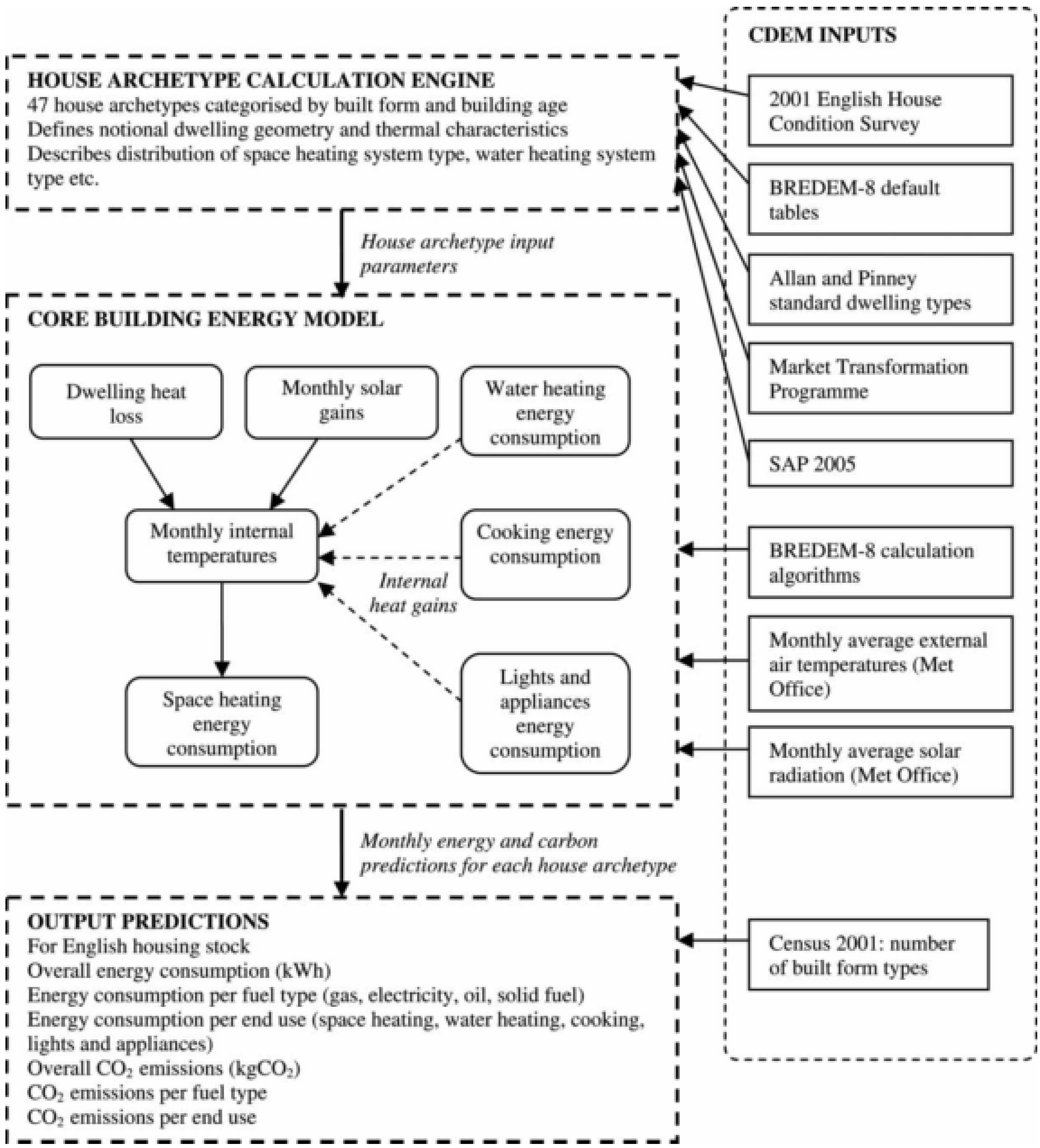


Figure 2-27. Block diagram of the CDEM developed by Firth et al. (2010), used to make prediction of the energy consumption and CO_2 emission of the UK housing stock.

Firth et al. (2010) presented the Community Domestic Energy Model (CDEM), which explores the potential routes to reduce the CO_2 emissions, and to predict the CO_2 emissions and energy consumption of the existing English housing stock. The model consisted of two components: 1) a building archetype calculation engine defining 47 individual building archetypes based on the categories of built form and age bands, and 2) a core building energy calculation model based on the BREDEM energy model (see Figure 2-27). The built forms comprised of: end terrace, mid-terrace, semi-detached, detached, purpose built flats and other flats (e.g. converted flats). The age categories included: pre 1850, 1851-1899, 1900-1918, 1919-1944, 1945-1964, 1965-1974, 1975-1980, 1980-1990 and 1991-2001.

The inputs to the CDEM model consisted of parameters relating to location, geometry, construction, services, and occupancy, for example wall U-values, roof U-values, floor area, thermostat set-point and average number of occupants. The 47 dwellings were created with parameter values such that each was an average example of its archetype. The CO_2 emission and the energy consumption level by built form type were calculated for the whole housing stock by scaling up according to the number of dwellings in each of the built form types. Some of the model outputs reported which are relevant to this thesis include: a) annual average gas based energy consumption for all dwellings of 17449kWh or 73% of the overall energy consumption; b) detached house had the largest gas based energy consumption at 24175kWh, followed by end terrace at 18788kWh, followed by semi-detached houses at 17727kWh, and then by mid-terrace at 15531kWh from gas; c) purpose built flats had the lowest energy consumption at 9416kWh. The annual average of all dwelling electricity consumption was predicted at 4574kWh, with the consumption by dwelling built form type following a similar pattern to the gas consumption. The figures quoted in the paper are annual averages only. Energy use for heating is dominant in the winter and therefore, daily winter time values of energy consumption and CO_2 emission, showing the concentration of demand by time, would have been more useful for the work described in this thesis. A sensitivity analysis highlighted the eight most sensitive parameters to be: heat demand temperature, length of daily heating period, external air temperature, storey height, boiler efficiency, floor area, wall U-value and window U-value.

Yao et al. (2005) presented methods for generating the energy consumption load profiles for dwellings broken down by space heating, hot water and appliance uses.

They use cluster analysis method on the energy demand affecting factors to model the energy load profile for the three uses. These are aggregated to generate the overall energy load profile. Five household occupancy scenarios were used in the model, covering occupied and un-occupied hours depending on peoples' work and childcare requirements. The appliance, hot water and space heating load profile for these scenarios were created separately for a winter weekday case. The overall load profile for each of these uses was obtained by aggregating the profiles for the 5 occupancy scenarios. This was carried out for four dwelling types (Flat, Semi-detached, Detached & Mid-terrace). They validated the model output by comparing it with a statistical profile created by the UK Electricity Associate Load Research (UKEALR), based on 1300 households, and indicated a correlation of 0.84. The method presented in their paper is a good starting point for approximating the energy load profiles. The fact that the model breaks down the load profile for DHW and space heating makes it particularly relevant to this research. However, it is lacking in accuracy and detail. For example, only the load profile for electrical appliances has been validated with UKEALR data, leaving questions as to how well the heating load profile would correlate with real data. Load profile for space heating will be dependent on the thermal performance of the building. For this, thermal resistance method based on the energy balance was used, and verified using the ESP-r building simulation tool. However, greater insight into the thermal model and the associated parameters and boundary conditions used is required, which is lacking. The five occupancy scenarios used do not entirely cover all the possible occupancy scenarios. Households with people working night shifts or rotating shifts are not accounted for. The scenarios do not differentiate between weekends and weekdays. Integrating this model with a more robust occupancy model may produce more accurate occupancy data.

Richardson et al. (2008) developed a household occupancy model that can be used to generate high-resolution domestic building occupancy profiles. This model is based on Time-Use Survey (TUS) carried out in 2000, which contains detailed 24-hour diaries, in 10 minute resolution, indicating location and activities of occupants. Energy use typically happens when the occupants are in an active state in the homes, except in space heating where automated heating systems with temperature set points are used. The model presented in this paper takes into account the active and inactive states of the occupants in determining the occupancy profile. DHW energy load profile based on this occupancy profile could yield more accurate results. The model could be customised to cover more occupancy scenarios than the five occupancy scenarios used by Yao et al., (2005). Combining the two models could enable generation of heat energy load profiles of greater accuracy. A combined model will provide flexibility to generate load profiles to cover a wider range of household characteristics, including different socio-economic, region and tenure types, which is available within the TUS data (Richardson et al., 2008). This model does not take into account children as it is based on occupant diaries, most probably of adults. The occupancy behaviour of children, which also results in water heating, is unaccounted for in the model.

2.6.4 Domestic buildings and energy performance modelling tools

Connolly et al., (2010) provides a review of modelling tools available for model energy systems. These are predominantly whole energy system modelling tools, over long time periods. The nature of this work requires a more bottom up approach, covering short time-scales. Diurnal individual building thermal performance modelling is required with diurnal operational scenarios.

Crawley et al. (2005) provided an overview of twenty major computer simulation tools which are more appropriate for this research. The tools are compared based on feedback from developers on factors such as modelling features, validation, reporting and user interface. Four of the commonly used tools are:

1) IES (Integrated Environmental Systems): a commercially available software package used for whole building performance modelling. It has good graphical user interface, providing high quality visual representation of the model and the output parameters. However, being a commercial package, it provides limited access to the parameter files, limiting the dynamic modelling capabilities.

2) ESP-r: an open source software package developed by Strathclyde University. Full access to the parameter files is possible enabling dynamic modelling. Easier integration of TES models into the ESP-r package may be possible. The package however, is difficult to use and support is limited in terms of documentation and application.

3) EnergyPlus: a modular, structured software tool based on the most popular features and capabilities of Building Load and System Thermodynamics (BLAST) and DOE-2.1E (Crawley et al., 2005). It is primarily a simulation engine and has accessible input and output files enabling dynamic modelling. EnergyPlus has a much wider user community and support base.

4) TRNSYS: a transient system simulation program with a modular structure. It solves complex energy system problems by breaking the problem down into series of smaller components. The modular nature of TRNSYS facilitates quicker addition of new mathematical models.

2.7 Previous research on TES application in domestic buildings

This section contains a review of the past research carried out on TES and its application in domestic buildings that are considered to be relevant to this work.

2.7.1 TES application in domestic buildings

The most widely used and simplest form of TES is sensible heat storage, which has been in use for centuries as discussed earlier in Section 2.4 (Hadorn, J. 2007; Pinel, et al., 2011). Arteconi et al. (2012) explored the potential application of TES in Demand Side Management (DSM) in residential buildings. DSM in residential energy use context is used to describe the methods of matching electricity generation with the demand for electricity in homes. They explore the characteristics of DSM and discuss their relationship to different TES system options. TES has considerable potential in domestic DSM. Six categories of DSM roles for domestic TES have been identified as previously discussed in Section 2.2.4. The TES technologies and their potential DSM role in application areas including heating, air conditioning, heat pumps and micro-CHP are discussed by Arteconi et al. (2012). Their work does not cover detailed analysis of the benefits or the impacts of domestic TES. However, they highlight the likely benefits based on various case studies and researches, and conclude that interests in TES systems for DSM management is growing due to greater renewable energy generation, and peak to off-peak demand variation. Their recommendations include the following to ensure proper understanding of the potential of TES:

- a comprehensive model to simulate TES application in building in different dynamic configurations;
- a demonstration project with heating and cooling TES for residential buildings;
- technical evaluations to improve performance and reduce costs in order to decrease the payback period;
- further studies on some thermal storage media, particularly PCMs, for application in this field;
- agreement with utilities and governments to introduce proper electricity rates and incentives.

It can be concluded from this that there is a research gap in this area, in which this work aims to make a significant contribution.

In domestic buildings cylindrical hot water storage tanks are predominantly used for storing sensible heat (at temperatures below the boiling point of water) and primarily for storing DHW. More recently hot water storage tanks have been used in Solar Domestic Hot Water Systems (SDHW) where solar thermal systems gather and store sensible heat for later use. SDHW systems are extensively analysed and reported in the literature (Han et al., 2009; Karim, M A. 2011; Rodríguez et al., 2012; Pinel, et al., 2011). They have certain disadvantages, one of which is that large increase in the storage material is necessary to increase the stored energy. It can also be difficult to transfer heat to the storage system when it is close to being fully charged, and difficult to make use of the lower quality heat available when the system is close to a state of full discharge (Pinel, et al., 2011). Use of stratified TES tanks can somewhat reduce these problems.

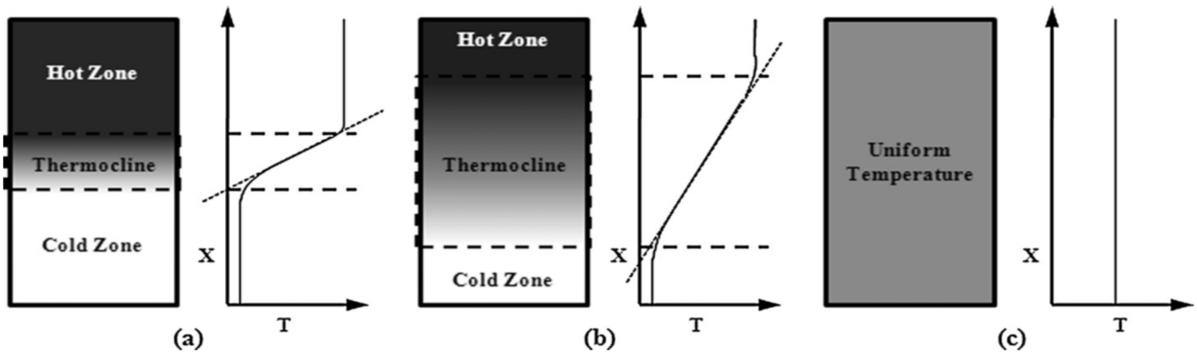


Figure 2-28. Demonstration of differing levels of stratification within a storage tank with equivalent stored energy; a) highly stratified, (b) moderately stratified, and (c) fully mixed (or unstratified) (Source: Arteconi et al., 2012)

When hot water is stored in a storage tank, it naturally stratifies forming a temperature gradient. A uniform temperature or a fully mixed tank can be maintained by continuously mixing the water as illustrated in Figure 2-28. Stratified water tanks provide greater energy storage capacity, and enable efficient use of renewable energy technologies such as SDHW. Sharp and Loehrke, (1979) showed that stratified TES tanks can increase the system efficiency of solar thermal systems by 5% to 15% compared to a fully mixed. Hollands and Lightstone, (1989) reported that a perfectly stratified tank could produce 38% more heat in a solar thermal system compared to a fully mixed tank. These suggest that stratified TES tanks could be appropriate in domestic heat demand management scenarios where large amounts of heat are required, to maximise the energy storage capacity. Arteconi et al. (2012) suggest that heat storage of less than 100kWh is sufficient for residential building application. They further state that, for a dwelling in Northern Ireland with a 100m^2 floor space, built to the 1990's building regulations, 7kWh of heating energy is sufficient per hour, to ensure a 21℃ indoor temperature when the outside ambient temperature is -3℃. This means that a 21kWh of thermal energy will be sufficient to achieve a 3 hour demand shift. These parameters will vary with factors such as building occupancy, type, orientation and household demographics. The impact of such parameters, for example on the heat demand management ability and the thermal comfort in the occupied space, is thus far unexplored. Research is lacking in this area, which is what this thesis addresses, the better understanding of which could enable the development of more effective alternative heating methods.

As discussed previously in Section 2.4, latent heat storage could be used to increase the energy storage capacity. Latent TES can be applied in many ways in residential buildings, for applications including air conditioning, space and water heating, heat pumps and micro CHP. Sharma et al. (2009) provides a good account of these, and others that could be directly integrated into the building fabric. Examples of these are PCM impregnated building material such as plasterboards, trombe walls, ceiling boards, shutters and under-floor heating.

The potential benefit of passive TES is demonstrated by Qureshi et al., (2011). Their paper presents the impact assessment of using PCM in an office to explore the thermal energy storage capability in New Zealand. The benefits in terms of peak demand shifting and heating energy demand reduction are analysed. This is done by studying two identical offices over twelve days, one having internal finishing with an ordinary gypsum board with the other having a PCM impregnated gypsum board. Controlled heating systems provided temperature control within 18-22℃ in both offices. A heat demand shifting of approximately 2.5 hours was demonstrated in one day, whilst no heating was necessary at all in the PCM applied office on another day. Over the test period, an average heating energy conservation of 31.3% was demonstrated, leading to heating cost saving. The research showed that energy conservation gains and demand shifting are sensitive to the minimum and maximum external ambient temperature during the day. The paper does not specify the main wall, roof and the floor construction of the offices which could affect the results. Also, the impacts occupants can have on the results are not taken into account. Nevertheless, these results are encouraging given that the UK domestic buildings can be relatively easily retrofitted with PCM impregnated gypsum boards, although could be the major issue. Such a study in the UK is certainly needed to shed light on the possible benefits and drawbacks when operated within the UK environment.

Arce et al. (2011) analysed the potential benefits of TES use in Spain, Germany and the EU. When applied to the residential buildings and industry sectors for heating and cooling, he estimated that the potential annual energy savings in the EU would be 7.5%. Also, he estimated a potential CO_2 emissions reduction in the EU to be on average 5.5% (based on average of 1990 and 2005 levels). The results may not apply directly to UK buildings due to the assumptions made that are more appropriate for European countries with different building type, construction and weather condition. The methods could be used to assess the potential impact of TES in the UK.

The potential of PCM for domestic TES applications have been highlighted by several researchers. Canbazoglu et al. (2005) demonstrated that the thermal storage capacity of solar hot water storage systems could be increased by a factor of up to 3.45 using salt hydrate based PCM, compared to a non PCM system. Zhang et al. (2005) carried out a detailed study of PCMs from a thermal comfort application viewpoint. Detailed analysis of the PCM thermo-physical properties and the ways of measuring them are discussed. Examples of PCM use in domestic buildings are provided which includes passive solar heating, solar and electricity based active heating and night cooling. The melting temperature of the PCM should be close to the thermal comfort temperature range i.e. 18-21℃ for space heating. Methods of incorporating PCM into the building fabric are also discussed, covering direct incorporation, immersion and encapsulation. Application of PCM in building wall, ceiling, floor and solar shading are discussed, citing literature which indicates the various benefits achievable, such as energy conservation, better control of indoor temperature, energy demand reduction and improved thermal energy storage capacity of building materials. A similar study and a review of PCMs and their potential benefits and drawbacks with regards to domestic building applications are carried out by Sharma et al. (2009). Both of these studies lacked analysis of the potential impact of the building performance and occupant behaviours on the overall performance of a home as a complete system.

Enhancement of the thermal conductivity is considered particularly important, and seen as a barrier to effective application and a wide scale uptake. Thermal conductivity of PCMs drops as they change state from liquid to solid and vice-versa, limiting the rate of charge and discharge. Huang et al. (2011) investigated the use of Phase Change Slurry (PCS) to improve the thermal conductivity of a PCM based heat storage system. The PCS comprised of micro-encapsulated PCM particles (paraffin wax with 65℃ melting temperature) suspended in a carrier fluid (water) at 50%, 35% and 25% PCM to water ratios. A test system was developed to observe and characterise the thermal process within the thermal store which consisted of a helical heat exchanger placed inside a 1m high and 0.27m diameter hot water storage cylinder. It was concluded from the study that the slurry with less PCM concentration performed better, and that the 50% volume concentration slurry is not suitable for thermal storage applications, due to the low heat transfer rate. Different heat exchanger design and placement are recommended for further investigation to ensure better performance. This study demonstrated that simply having high theoretical thermal storage density and capacity is not sufficient, and that adequate measures must be in place to enable quicker transfer of heat to and from the storage medium. Further research in PCM, particularly the heat transfer aspects during charging and discharging, is therefore considered an integral part of developing an effective TES system for domestic or any other application.

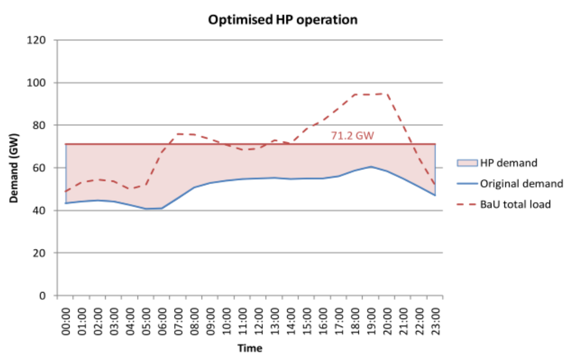
2.7.2 Modelling studies of domestic scale TES

Buildings can be relatively easily modelled using the tools as described in Section 2.3.4. The difficulty lies in integrating the building model with the TES system model and its operational transients, and the dynamics of the occupant's energy use behaviour. Various studies have described the modelling of individual TES systems, for example, Pinel et al. (2011) explored the methods employed in modelling free-standing and buried hot water storage tanks. Simple models of water tanks are based on the assumption that the store is a single temperature heat capacity node. These were used in the 80's and 90's when computing resources were limited. More recently, whole building simulation tools such as TRNSYS, ESP-r and EnergyPlus are used, which allow the models to capture the transient dynamic interactions between the systems and their surroundings. Plug-flow models, which only assume flow direction and velocity, are commonly used and shown to adequately represent stratified thermal storage tanks, especially where the charge and discharge flow rate is low. These models only require the resolution of an energy balance equation and are based on one-dimensional numerical formulations which incorporate basic models of tank heat loss, thermal diffusion, flow, and buoyancy induced mixing. The one-dimensional approach assumes that a temperature gradient exists in the virtical direction only, and is negligible in the radial direction, i.e. that no heat escapes through the tank wall (Pinel et al., 2011). Badescu (2003) describes a TES model where it is considered as an unsteady heat exchanger i.e. it is either charging or discharging at any given time. The form of the storage medium is a solid block with holes for the heat transfer fluid (air) to pass through. The TES device is represented as two differential equations which could be programmed into some of the building simulation tools mentioned above.

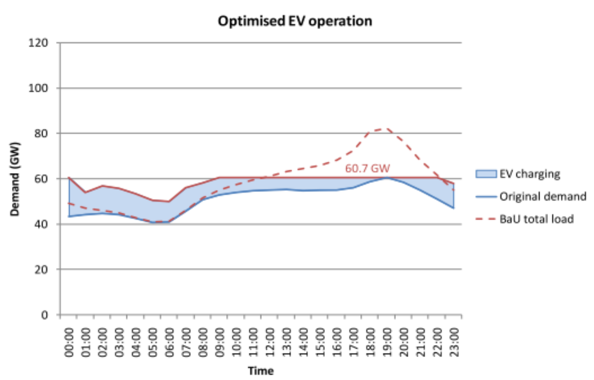
Ihm et al. (2005) created a model of a cold TES system which was integrated into a three zone simple building model using EnergyPlus. The TES system is included as part of the EnergyPlus cooling plant components. The charge and discharge rates are provided as input data. The results indicated that cooling energy and cost savings are possible with advanced thermal control systems. No building construction details or the occupancy characteristics are provided in the paper which could impact the outcome. The research demonstrated that it is possible to integrate TES and building models into EnergyPlus and analyse the energy performance and benefits.

Hewitt (2012) describes how domestic buildings could be used as an energy store using active and passive heat storage methods. A passive system would involve storage of heat in the actual thermal comfort temperature range, for example using the thermal mass of the building fabric. An active system would require storing heat outside of the thermal comfort range, for example using water tanks, and using it to ensure thermal comfort at different times. The extent of the storage capacity (active or passive) has not been researched in detail, but he suggested that 3 hours' worth of passive heat storage is reasonable. This will vary with building type, occupancy type, orientation etc., and greater research to determine their influence is necessary. Understanding this is important as it will directly impact the effectiveness of an alternative heating system. Clearly, there is a research gap in this area, in which this thesis intended to contribute.

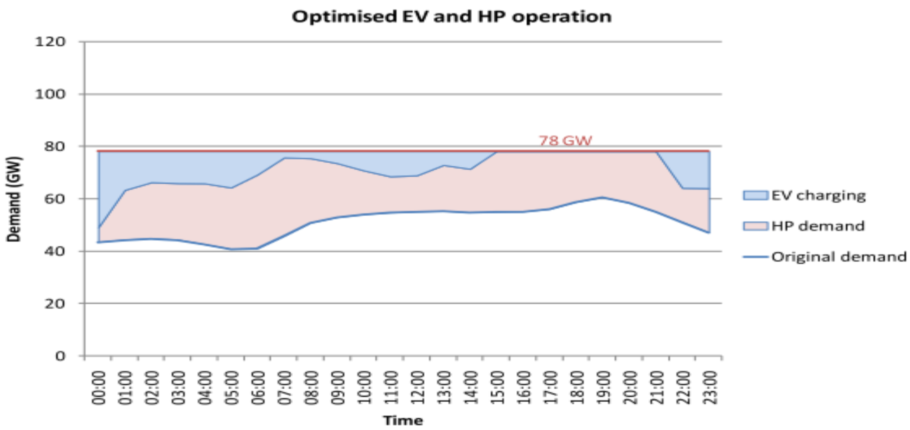
Strbac et al., (2010) simulated the future increase in winter time electricity demand due to the electrification of domestic heating (through the use of HPs) and transportation (via EVs), and the levelling effect of the overall demand response achievable through the use of thermal energy storage and the charging time flexibility for the HP and EV respectively as discussed earlier in Section 2.2.3. Their work predicted an un-optimised winter time electricity demand increase from the current level of about 60GW to around 117GW (See Figure 2-10). The simulation optimised the HP induced load profile to one having a flat load of 71.2GW as opposed to a peak load of about 96GW as shown in Figure 2-29(a), achieved by allowing lower power rated HPs to operate more continuously, and spreading the load over the off peak times. This was made possible by utilising thermal storage to store heat during off peak times and using the stored heat during the peak times to meet the heating needs of the households. The simulation optimised the EV induced load response to one having a flat load of 60.2GW as opposed to a peak load of about 81GW as shown in Figure 2-29(b), achieved by spreading the charging over the off peak times. This is due to the simulated flexibility in the EV charging arising from the assumptions that EVs have modest energy requirement, short driving times, stationary on average for 90% of the time, small passenger vehicles and batteries having relatively high power ratings. The overall combined HP and EV induced load response was optimised to have a flat load of 78GW as opposed to a peak load without optimisation of 117GW, which represents a 33% reduction from the peak as shown in Figure 2-29(c). This analysis showed that with optimisation of the load profile in this way could accommodate an additional 57GW (36GW heating and 21GW EV) worth of demand with the peak load increasing by only 18GW from the current winter day level.



(a)



(b)



(c)

Figure 2-29. Comparison of simulated average national load profile with; a) optimised EV charging; b) optimised HP operation, and c) jointly optimised EVs and HPs (Source: Strbac et al., 2010).

This study has identified (and also quantified as discussed above) the electricity demand levelling and generating capacity reducing opportunities as *'very significant'* through demand response optimisation using domestic building scale thermal storage. However, the authors have acknowledged that the actual optimum demand response would be highly dependent on factors such as location, time, building fabric thermal properties and thermal storage types, and suggested further research to account for these variables which this thesis tries to address. One aspect which Strbac et al., (2010) have not considered is the impacts which may result as a consequence of TES deployment is residential buildings. For example, using TES to modify the demand response could lower thermal comfort level within the occupied space. The level of energy bill saving benefit achievable may not be sufficient to encourage investment by the households. Exploring these issues, which may or may not affect the uptake of TES and therefore may or may not affect the electricity load levelling and generating capacity reducing potential are also important, some of which are addressed in this thesis.

2.8 Summary

The literature demonstrated a need for storage, which has to play a significant role in overcoming some of the current and forthcoming challenges of the energy system. The challenges are categorised in terms of timescales, namely seconds, minutes, hours, days and months.

Heating accounts for over 80% of the domestic energy consumption, presenting a vast opportunity to apply TES. Nearly 14 million UK homes already have domestic hot water storage tanks, providing scope for applying advanced TES methods for both DHW and space heating.

Research shows that uptake of electric heating and electric vehicles in the future could double the winter day peak electricity demand from around 60GW to around 117GW. This could present major challenges in terms of matching the short term real-time electricity supply with demand. Domestic TES could make significant impact in the minutes, hours and days challenge categories, in a daily demand levelling role, to decouple the heating energy demand and supply timings. TES could enable better heating energy demand management, through demand shifting and allowing more effective use of the locally generated renewable energy, minimising the variation between peak and off-peak electricity demand.

Rechargeable TES could be an effective tool in decoupling the heating energy demand and supply. Sensible, latent and thermochemical heat storage methods are usually used in thermal storage. Sensible TES using water is a well proven, cheap and widely used technology, but it has relatively low storage capacity per unit volume. Therefore, sensible TES may not provide sufficient storage capacity, for both water and space heating, in the space restricted domestic buildings. Passive and active latent TES using PCMs have been shown to possess great potential for domestic applications, offering various technical and economic benefits. However, further research is needed to develop more effective PCMs and to understand the wider impacts in terms of the occupied dwelling as a system. Thermochemical TES provides the best storage capacity per unit volume, and may be the most suitable option for domestic buildings, in terms of capacity. But much more research is needed in order to develop technically, economically and environmentally acceptable systems.

Domestic heating load profiles are mainly dependent on the occupancy characteristics of the households and the thermal performance of the buildings. Both of these parameters determine the indoor temperature profile and DHW consumption, which should be well represented in a domestic heating and thermal storage model. A thermal store capable of storing 100kWh is considered sufficient to heat a domestic building for one day. Also, it is considered feasible to achieve a 3 hour heat demand shift with a thermal store capacity of 21kWh, in a 1990's dwelling of 100m^2 floor space, and with an outside ambient temperature of -3℃.

The literature indicated that domestic application of active and passive TES can provide a wide range of benefits, including energy demand reduction, heating cost saving and energy demand levelling. However, a holistic study of TES in domestic settings with the interaction of the occupants is needed to understand the wider impacts, and this is where a research gap exists.

The literature review highlighted a lack of in-depth and higher time resolution modelling of small scale TES, within the domestic built environment and the operational surroundings. The potential economic, energy security and environmental benefits which could be gained from domestic TES needs to be quantified to encourage quicker technology development and uptake.

A wide scale adaptation of domestic TES can provide considerable benefit for the electricity supply side stakeholder community, by deferring construction and upgrades of generation, transmission and distribution facilities (Nair et al., 2010). This would be possible by enabling better heating peak load management for residential customers. The benefits available to this group of stakeholders need to be quantified and demonstrated, in order to encourage rapid investment in TES and other technologies that are needed to make domestic TES effective, such as smart electricity grid and variable electricity price tariffs. Research literature is lacking in this area indicating a research gap.

3 CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter discusses the methodology employed during the research programme. The methods used and the logical approach followed to ensure that the aim and objectives are achieved are outlined. The modelling tools used and the real world buildings and their constituent parts are presented, highlighting the assumptions and constraints. The validation of the models is described, followed by two investigations conducted to satisfy the research objectives. The chapter is arranged as described below:

Section 3.2: Describes the research questions derived from the literature review which the subsequent chapters of this thesis attempts to answer.

Section 3.3: Defines the context of Heat Demand Shift as considered in this work.

Section 3.4: Describes the research activities carried out and how they relate to the overall aims and objectives of the research programme.

Section 3.5: Describes the general modelling approach followed, the construction of the building models, the modelling tools utilised, thermal and physical parameters of the buildings and the heating systems considered in creating and simulating the models. Also provides details of the model validation exercises carried out to ensure validity of the results.

Section 3.6: Describes the methodology used to analyse the energy consumption, heating energy cost and the thermal performance characteristic of most common building, occupancy and operational options found in the UK housing sector, without Thermal Energy Storage (TES) and heat demand shifting.

Section 3.7: Describes the methodology used to generate predictions of heat energy demand shift using active sensible TES, from the grid peak times to the grid off-peak times by three fixed durations (2 hours, 3 hours and 4 hours), and the related impacts and benefits.

Section 3.8: The methodology used to simulate how the effectiveness of TES and its impacts change with varying parameters such as TES capacity, building thermal insulation, physical, occupancy and operational conditions are also described.

Section 3.9: Provides a summary of this chapter.

3.2 Research Questions

The literature review has shown that the challenges and opportunities in decarbonising domestic buildings in the UK and overcoming the undesirable consequences of a highly electrified future are widely studied by the relevant scientific, political and business communities (Foxon, 2013; Wilson et al., 2013; ERP, 2011). This thesis contributes to this study, particularly in the area of short-term matching of the future electricity supply and demand, by shifting the DHW and space heating from the grid peak times to grid off-peak times through the use of residential building scale TES. The need for further research in this area is echoed in many recent reviews of energy storage in the UK, and calls have been made for deeper and better understanding of the scope, impacts and benefits of thermal storage in buildings through modelling and simulation, as discussed in the literature review (Hall, 2008; Wilson et al., 2013; Arteconi et. al., 2013; Wilson et al., 2010; Hewitt, 2012; UKERC, 2011; ERP, 2011; Strbac et al., 2010; IMechE, 2014). Based on these findings, the following three research questions have been formulated and addressed in the subsequent chapters of this thesis, to allow the previously stated objectives to be met:

1. ***What are the dynamics of heat demand in buildings and how do they vary with building typologies, their thermal characteristics, and the variation in occupancy and operational conditions?***

   This will prompt exploration of the heating characteristics of domestic buildings and how it changes with factors such as different build-forms, size, thermal performance, occupant behaviour, household demography, and weather conditions. Good understanding of the heating characteristics of the buildings is necessary as it will dictate the suitability and the functional requirements of the TES.

2. ***What is the scope of heat demand shifting in time by using residential building scale TES, and what are the potential benefits and impacts of using residential building scale TES?***

   The extent to which heat demand management could be achieved in existing buildings is a critical factor in their successful deployment. This research question looks into the heat demand shift achievable in the most common buildings found in the UK housing stock using TES systems that can be relatively easily deployed. This research question also looks into the impacts of the heat demand shift on the occupied space temperature, the heating power and energy consumption, and the potential energy bill savings for the households which may or may not incentivise uptake.

3. ***What are the key building, occupancy, operational and TES parameters which could affect the effectiveness of heat demand shifting in domestic buildings using TES?***

   This research question assesses the impact of parameters such as the building fabric construction details, building use and occupant behaviour, household demographics and weather conditions, on the sensitivity and effectiveness of the TES in shifting energy to off-peak times and thermal condition in the occupied space. This is necessary to enable informed decision making to encourage/discourage uptake of TES and/or the development of alternative grid balancing solutions.

3.3 Definition and context of Heat Demand Shift (HDS)

This section describes the context of HDS and the top level assumptions made. Also, the context in which the 'Impacts' of HDS is considered in this thesis is described.

This work only considers the mains electricity grid as the primary energy source. The thermal energy used in the simulations is derived using resistance element water heater models, with a COP of 1, converting electrical energy into heat with 100% conversion efficiency.

The impacts of HDS as considered in this works refer to: 1) the thermal condition or the thermal comfort of the occupied space; 2) the power demand resulting from the heat requirement during the occupied heated hours or when the TES is charged up; 3) the energy consumption for providing the space heating and DHW needs; 4) the quantity of heat energy shifted from the mains grid peak time to an off-peak time, and 5) the heating energy bill savings possible if the energy is bought at an off-peak discounted electricity price, based on the time-of-use Economy7 electricity price currently available, facilitated by the heat demand shifting function as discussed below. In this work, the occupied space temperature has been considered as a good indication of thermal comfort as has been assumed in other studies as discussed earlier in Section 2.5.1. A space temperature of 18℃ or higher is regarded acceptable for ensuring thermal comfort.

HDS in domestic buildings can have many meanings, the main one being to displace the DHW and space heating energy use from a certain time period to an earlier or a later one. This is so that no energy consumption occurs during that period. In essence, HDS as considered in this work, refers to the act of separating the times when energy is drawn from the mains supply and when it is actually used in the home as heat for meeting the DHW and space heating needs.

Usually, heat energy consumption and building occupation overlap each other in time, for example heating systems are operated to heat the homes during the occupied hours to ensure thermal comfort. Also, the draw time of energy from the mains grid is the same as the heat demand time in the buildings. It is commonly accepted that homes are most actively occupied during the morning hours of around 07:00 to 09:00 and during the evening hours of around 16:00 to 23:00. It is therefore reasonable to assume that the energy demand on the mains electricity grid for heating could centre around and accumulate to large levels during these times, especially in a future scenario where electric heating is widespread. This could create daily grid load balancing problems.

One solution to this could be utilising HDS in the buildings that can shift and/or spread the mains grid peak time energy demand to periods where the demand for electricity is low, for example to the night or early morning periods as previously discussed in Section 1.1 and 2.2. It can be realised that this form of HDS can be achieved in three ways: 1) by moving the time periods when people occupy their homes so that the associated heat demand also moves with them; 2) by preheating the buildings before occupying them and rely on the thermal inertia to maintain thermal comfort during the occupied hours, and 3) by drawing and storing energy from the mains grid in some independent active rechargeable Thermal Energy Storage (TES) device, and to use the stored energy later during the time of occupation.

The first method, which would involve people occupying building at different times, is unrealistic and unlikely to be acceptable to the households. This is due to the impracticality of changing daily routines of society as a whole, such as when the normal working hours start and finish and the start and end times of schools, which largely define the occupied hours. The second method is also unlikely to be effective for reasons including that the demand time at the grid could remain too close to the peak; the thermal comfort level would be dependent on the thermal insulation of the buildings which can vary significantly (see Section 2.2), and therefore could have detrimental impact on the thermal comfort making this option unattractive. The third method is one that could potentially have a more significant impact, due to having independent storage, thereby enabling the TES to be recharged at any time (when grid load is low) and use the stored heat later as and when the DHW and space heating need arises.

The overall effectiveness of HDS in grid load balancing will be dependent on the TES capacity and functional characteristics, and also on the scale of uptake in the housing stock. Therefore, the focus of this thesis, in addition to exploring the ability to achieve HDS as described above, is also to explore the benefits which could be available for the households, which could encourage or discourage uptake.

In summary, the HDS as considered in this thesis is one that uses rechargeable active TES, to explore and determine:

1) It's ability to decouple the temporal link between energy demand at the mains grid and the demand for heat in the building.
2) It's effectiveness in displacing the energy demand at the mains grid to different times without altering the occupied hours
3) The effects of displacing the heat demand on the occupied space temperature and therefore the thermal comfort.
4) The participating household's ability to benefit from financial incentive schemes such as Economy7 time-of-use electricity price tariffs, which may or may not encourage uptake and utilisation.

3.4 Research tasks

This section describes the activities carried out to fulfil the objectives of this work. Four research tasks have been carried out as described below, to explore answers to the research questions set out in Section 3.2 and to satisfy the research objectives defined in Section 1.3:

Research Task 1: Model development and validation:

Aim: achieving research Objective 3

This focused on developing models to represent the UK housing stock, and the associated HVAC and TES system components. Representation of the thermal, physical, occupancy and operational variable to be applied in simulating predictions of the heat energy demand, demand response, thermal comfort impact and the benefits of domestic building scale TES were created. Three subsequent research activities as described below utilised appropriate combinations of the building archetype models and the operational and occupancy options.

Research Task 2: Understanding the thermal performance characteristics of domestic buildings

Aim: achieving research Objective 4

This research activity focused on simulating common domestic buildings with typical occupancy and operational conditions, represented by 12 Base Case scenarios as discussed later in section 3.4.2, to create predictions of the heat energy demand and the daily heating load profiles during the winter period of January and February. Predictions of the thermal comfort parameters within the occupied spaces are simulated. Predictions of how the thermal comfort and energy performances are affected by changes in the thermal insulation, physical size, location, occupancy and operational conditions are also produced. No TES was applied during this research activity. Heating energy cost predictions are generated based on the energy consumption figures and the currently available electricity price tariffs. The aim of this activity was to gain better understanding of the thermal and energy performance characteristics of the housing stock, and the likely heating energy cost impacts for the households. The findings could be used to determine the most suitable TES options given the variability in the housing stock thermal performance, physical, occupancy and operational conditions.

Research Task 3: Impacts and benefits of fixed period heat demand shifting using active sensible TES

Aim: achieving research Objective 5

This research task focused on investigating the thermal condition, heating load and energy demand impact of three heat Demand Shift Periods (DSP), 2 hour, 3 hours and 4 hours, during the evening occupied hours, in 12 building archetypes with a common set of occupancy and operational scenario options. The physical size and the thermal storage capacity of the TES is selected such that it could be relatively easily retrofitted into existing dwellings which may and often contain hot water tanks as part of the heating system. The thermal comfort level in the occupied space is allowed to degrade as the stored heat is depleted during the demand shift period. Potential heating energy cost impacts are explored based on the currently available Time-of-Use Economy 7 electricity price tariff. The findings could help identify the levels of thermal comfort degradation likely in the occupied spaces for the common building thermal insulation, occupancy and operational scenarios found in the UK housing stock. The results could allow comparison of the impacts and benefits, for example in terms of thermal comfort degradation and energy cost savings, and assist in informed decision making concerning the effectiveness of domestic heat demand management using TES.

Research Task 4: Parametric analysis of the impacts of heat demand shifting using active sensible TES

Aim: achieving research Objective 5

This research task focuses on investigating the thermal condition, heating load and energy demand impact of: 1) changes in the key energy consumption influencing parameters in the buildings and their operational and occupancy conditions, and 2) changes in the TES capacity employed, when heat demand shifting is instigated using active sensible TES. The building operational and occupancy parameters which are investigated include: floor size, built form, thermal insulation, geographical location, heating duration, thermostat set point and occupancy. The TES capacity parameters investigated include physical size and hot water storage temperature. The output observed include the indoor thermal condition, power and energy demands, and how these change when the said parameter are varied. The findings could help identify the levels of thermal comfort degradation likely in the occupied spaces, given the variations in thermal insulation, occupancy, operational scenarios found in the UK homes, and for varying TES capacity. The results could also enable comparison of the potential impacts and benefits, for example in terms of the thermal comfort degradation and energy cost savings, and aid informed decision making concerning the effectiveness of domestic heat demand management using TES.

Understanding their effects of the parameters mentioned could allow thermal and energy performance interventions in buildings to be targeted such that they can be made to provide more effective heat demand shifting. Identifying the building archetypes that allow heat demand shifts with minimal thermal comfort degradation could also enable heat demand shifting interventions to be better targeted.

3.5 Task 1: Model development and validation

3.5.1 Overview

The physical and thermal characteristics of the buildings are some of the main factors within the domestic building energy systems which affect energy consumption. The other main factors include the occupant demographics, location and the weather conditions (Wright, 2008; Yohanis et al., 2010; Hewitt, 2012; Peeters et al., 2009). This section discusses how these parameters are considered and the methodology followed to represent them in the modelling environment. The model validation is also discussed.

Table 3-1. Details of the building archetypes, occupancy scenarios, operational conditions and the TES system options modelled and used in the simulations.

Building archetypes options and simulation parameters developed		
	Number of variants	Description
Building archetypes	12	Covering four built-forms and three occupied floor sizes.
Thermal insulation level	4	Building fabric U-values relating to 1980, 1990, 2002 and 2010 building regulations.
Geographical location	3	Including the north of the UK (Aberdeen), the Midlands (Loughborough) and the South (Gatwick)
Occupancy	2	1 Adult, and 2 adults and 1 child.
Internal gains	1	For people, TV, Cooking and Lighting
HVAC system	1	Wet (water based) central heating system with electrical water heater and convector radiators.
Thermostat settings	3	19°C, 21°C and 23°C
Heating durations	4	6 hours, 9 hours, 12 hours and 16 hours
Active TES system	6	Consisting of 3 sensible TES water tank sizes, 2 water storage temperatures

The modelling activity included creating TRNSYS models of 12 different building archetypes. Representation were generated for 4 thermal insulation levels, 3 geographical locations, 2 occupancy scenarios, 1 internal gain setting, 1 HVAC system, 3 thermostat settings, 4 heating durations and 6 active TES system variations as summarised in Table 3-1, and described in the following sections.

3.5.2 The modelling approach

Domestic buildings in the UK are subjected to numerous variables which are dependent upon and change with time. For example, the external air temperature, number of occupiers, ventilation rate, internal and external gains and space condition requirements. These all vary depending on the time of the day, and also vary on a day to day basis. They have direct relationship with the heat energy consumption and therefore can affect the form of the heating load. This work employed dynamic modelling approach to obtain a better understanding of the potential impact of these variables on the heat energy consumption and thermal comfort in buildings, and the potential heat demand shifting capabilities in buildings using domestic TES. The top level block diagram of the structure of the dynamic model employed during this work is shown in Figure 3-1. It can be seen that the input variables are time dependent.

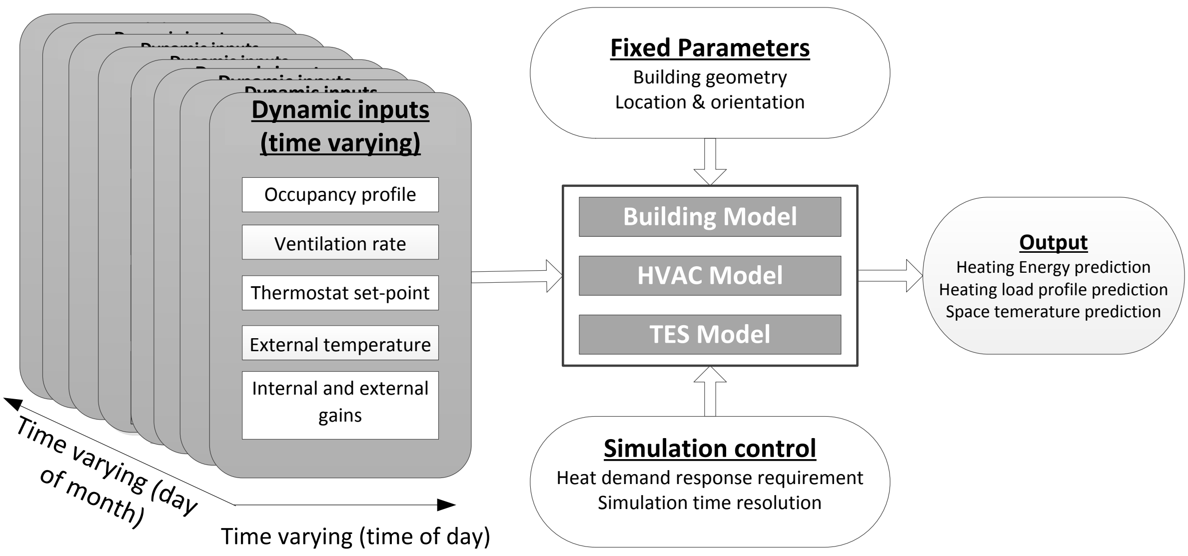


Figure 3-1. Dynamic modelling approach illustrated

A bottom-up modelling approach has been used to create a numerical modelling environment that represented the buildings and the relevant occupancy and operational conditions. Figure 3-2 shows the hierarchical direction followed in developing the housing stock models as different archetypes; and the configuration of the models with the relevant variables, simulation control and output requirement parameters. The modelling process starts at the disaggregated building material level where their thermal and physical properties are defined, for example an external wall component is defined as a structure made of a massive brick face layer, followed by a massless air cavity, followed by a massive concrete block layer and a massive gypsum plaster board layer. The thermal and physical parameters of each of the components in the layers are defined, for example, the massive layer components such as bricks and concrete blocks are assigned values relevant to their thermal conductivity, thermal capacity, physical density and thickness. The massless layers are assigned a thermal resistance value and a thickness. The different building components such as walls, windows, floors and roof are combined to form a building. The orientation of the buildings is defined such that the front walls are north facing. The Heating Ventilation Air Conditioning (HVAC) system for the building is defined for providing the space heating, water heating and ventilation. No air conditioning was present in the buildings. The occupancy and operational conditions such as the profiles of the occupancy, internal gains, space condition requirement and the location of the buildings (through the use of location specific weather data files) are defined. Prior to running the simulation the heat demand management requirements, for example the heat demand shift start and end times, and the demand shift period are defined, and the output parameters to be recorded and their format in terms of units and time resolution are programmed. Simulations are run for the required time period, for example the winter months of January and February when heating dominates the domestic energy consumption, creating scenarios where the supply and demand for heat energy is relatively high.

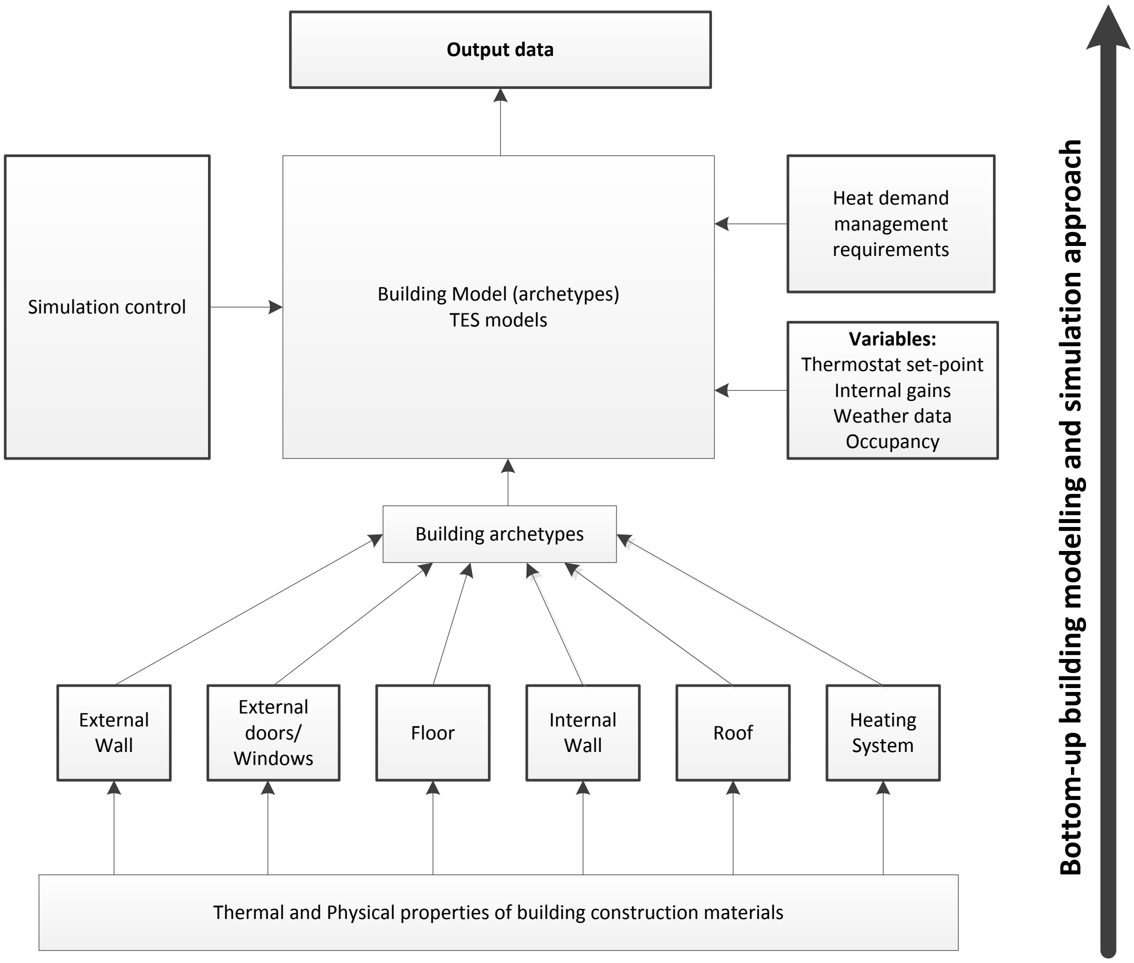


Figure 3-2. Bottom-up building and TES modelling approach

Due to the nature and the inevitable assumptions required to be made during modelling, some features of reality are always lost, which will influence the results. However, efforts have been made to keep this to a minimum, to enable timely completion of the analyses, and still generate scientifically valid and acceptable results that contribute to the discourse of better understanding the subject matter.

3.5.3 Choice of modelling tools

The modelling tool used had to be technically and scientifically proven to be capable and valid for use for achieving the aim of this research. This directed to the use of Transient Systems (TRNSYS) version 17 as the primary tool for conducting the modelling and simulation activities. TRNSYS is a dynamic modular simulation program. Developed by the University of Wisconsin (S.A. Klein et al., 2009), TRNSYS involves interconnecting different modules or TYPES representing different system components or building materials, for example a radiator or TYPE 1231 and a multi-zone building or TYPE 56. TRNSYS was considered appropriate for this research due to its modular nature enabling whole system modelling. Numerous papers demonstrated the capabilities and application of TRNSYS in building energy simulation and modelling (Beckman et al., 1994; Duffy et al., 2009; Kuznik et al., 2010; Crawley et al., 2005).

TRNSYS is made of two parts:

1) A suit of programs, the functions of which include:
    a. **The TRNSYS Simulation Studio**: is the main user interface providing functionality such as creating projects, linking components to build up a system, configuring/editing system components, setting global simulation parameters, and defining the type and form of the output data and creating input files for the simulation engine.
    b. **Simulation Engine** (TRNGLL.DLL and its executable TRNExe): carrying out simulation, and producing graphical outputs.
    c. **Building input data visual interface** (TRNBuild): enables the building component parameters such as the thermal and physical properties, HVAC, orientation and interaction with adjacent buildings to be analysed, configured and edited.
    d. **TRNSED Application** (TRNEdit) used to create stand-alone redistributable programs of the projects
    e. **TRNSYS Add-ons** (Trnsys3d Plugin for Google Sketchup Pro.[15]): this program can be added to Google Sketchup drawing application that can be used to create TRNSYS compatible 3D building models. The building models are linked to Type56 multi-zone building modules in the Simulation Studio. The TRNBuild interface allows the Type56 files to be edited and the thermal and physical building component attributes and the HVAC systems to be defined
2) An extensive library of components (Types) each of which models the performance of a part of the system to be simulated.

[15] Google Sketchup is a commercially available drawing software package which can be used to create 3D drawing of objects such as buildings.

Each component or Type that models the performance of a sub system or a function has a Proforma which describes its function and operational limitations, and a variable control card where the input and output parameters are defined. Each Type is represented by an icon which can be dragged into the simulation studio window from the component library and connected up to other Types according to the input and output data characteristics using the Link Tool.

One of the most critical TRNSYS Types used in this study is Type56, which represented the physical and thermal characteristics of the buildings. As explained in the documentation produced by Solar Energy Laboratory (SEL) of University of Wisconsin, Type56 models the thermal behaviour of a building by dividing it into different thermal zones (SEL, 2012a). For example, different heated zones such as the living room and the bedroom can be separated as different zones and their thermal profiles and the energy balances individually analysed. While it is possible to develop bespoke Types to address specific problems, those used during this work were developed by SEL and their associates. They are supplied with the standard component library.

TRNSYS has a good collection of documentation relating to all aspects of its operation and use in simulating energy and thermal performance of systems. The software and the documentation relating to all the Types used in this work are available from the SEL (SEL, 2014). Technical support from SEL staff is also available concerning all aspects of the use and operation of TRNSYS and the Types.

The procedures involved in creating systems in TRNSYS and simulating their performance is described in a series of documents available from SEL. One example method of creating a system comprising of a multi-zone building connected to a hot water cylinder and a solar thermal collector is illustrated in Figure 3-3. As shown the project is initially created in the Simulation Studio. The building to be simulated is drawn in Google SketchUp (with the Trnsys3d plug-in) and imported into the simulation studio. Using TRNBuild the building orientation, fabric attributes and the heating system parameters and controls are set correctly. Other system components (or Type) which make up the system (for example a hot water storage cylinder and, a solar thermal collector, water mixing and splitting valves, and an on/off controller) are imported into the simulation studio from the component library. Types representing different utilities and measuring programs such as a weather data, calculators, integrators, display scopes, printers and forcing functions as imported into the simulation studio. The input and output variables of all the Types in the system are correctly defined using the component variable descriptor cards. All the system components and utilities are connected up using the link tool depending on the direction of the input and output data flow to and from the components. The global simulation parameters are defined using the control card within the simulation tool, for example the number of days and time resolution of the simulation to be carried out. The required format of the output functions such as the graphical displays, online plotters and printers are set through the variable control cards.

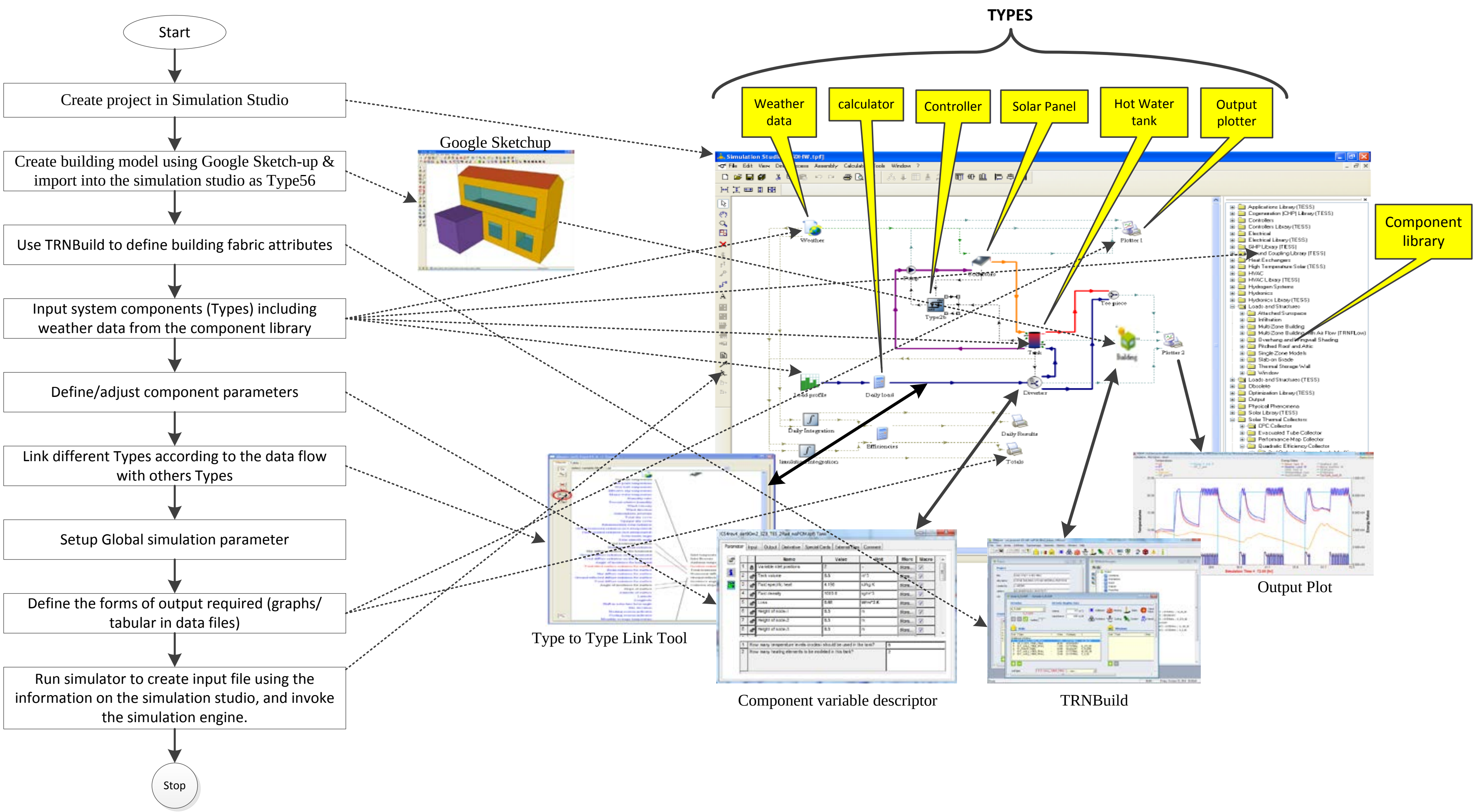


Figure 3-3. Illustration of the processes involved in creating a building system model and simulating it in TRNSYS

3.5.4 Housing stock representation using archetypes

The housing stock is represented in the models through the creation of 12 different archetypes as shown in Table 3-2. The parameters which are used to differentiate between archetypes are: 1) Building construction by built form, and 2) Building size in terms of useable floor area. These two parameters have been chosen as they are considered to be amongst the main heat energy consumption influencing factors associated with the building physical characteristics as discussed in Section 2.5.

The built-form and building geometry parameters considered are consistent with the categorisation used by the EHS and other researchers as previously discussed in Section 2.3., and standard house descriptions by Allen and Pinney (1990) (DCLG, 2013; Yeo et al., 2005; Yohanis, et al., 2010; Firth et al., 2010; Taylor et al., 2013).

Table 3-2. Details of the building archetypes considered.

	Archetype differentiators	
	Built forms	Floor sizes (m^2)
Variables	Detached, Semi-detached, Mid- terrace and purpose built Flat	70, 90 and 150
Total variables	4	3
Total number of archetypes		12

Building typology and the internal living space arrangement

The built forms considered during this research are detached, semi-detached, mid-terrace and purpose built flats. Figure 3-4 shows Google SketchUp screen shots of these dwelling built forms. In this study simplified buildings are considered with straight rectangular or square windows. The models incorporated glazing values ranging from about 16% to 20% of the external wall surface area.

The buildings were arranged to have three thermal zones; Zone 1) Ground Floor (GF), Zone 2) First floor (FF), and Zone 3) Loft, with exception of the flat. The table in Appendix A contains details of the floor area, volume and thermal capacity values used for each of these thermal zones. The GF and the FF zones are living spaces and are connected to the heating system via convector radiators. Zone 3 is not heated, therefore not connected to the heating system. Treating each floor as a single zone is consistent with some of the commonly used steady state models such as BREDEM (Korolija, et al., 2013). There is a 2m^2 air hole between the GF and the FF simulating airflow through the stair case. The flat has only one thermal zone and connected to the heating system by convector radiators. The FF floor and the GF ceiling are identical with a layer of carpet on the FF side and a layer of plasterboard on the GF side. The internal partitions reflect the ground floor and first floor each having 4, 6 or 8 rooms corresponding to the useful floor area of 70m^2, 90m^2 and 150m^2 respectively.

Shading objects were added to represent adjacent properties (see Figure 3-4). The party-walls between the dwellings are defined as boundaries with identical surface temperature as the inside surface temperature of the external walls, to simulate similar heating characteristics.

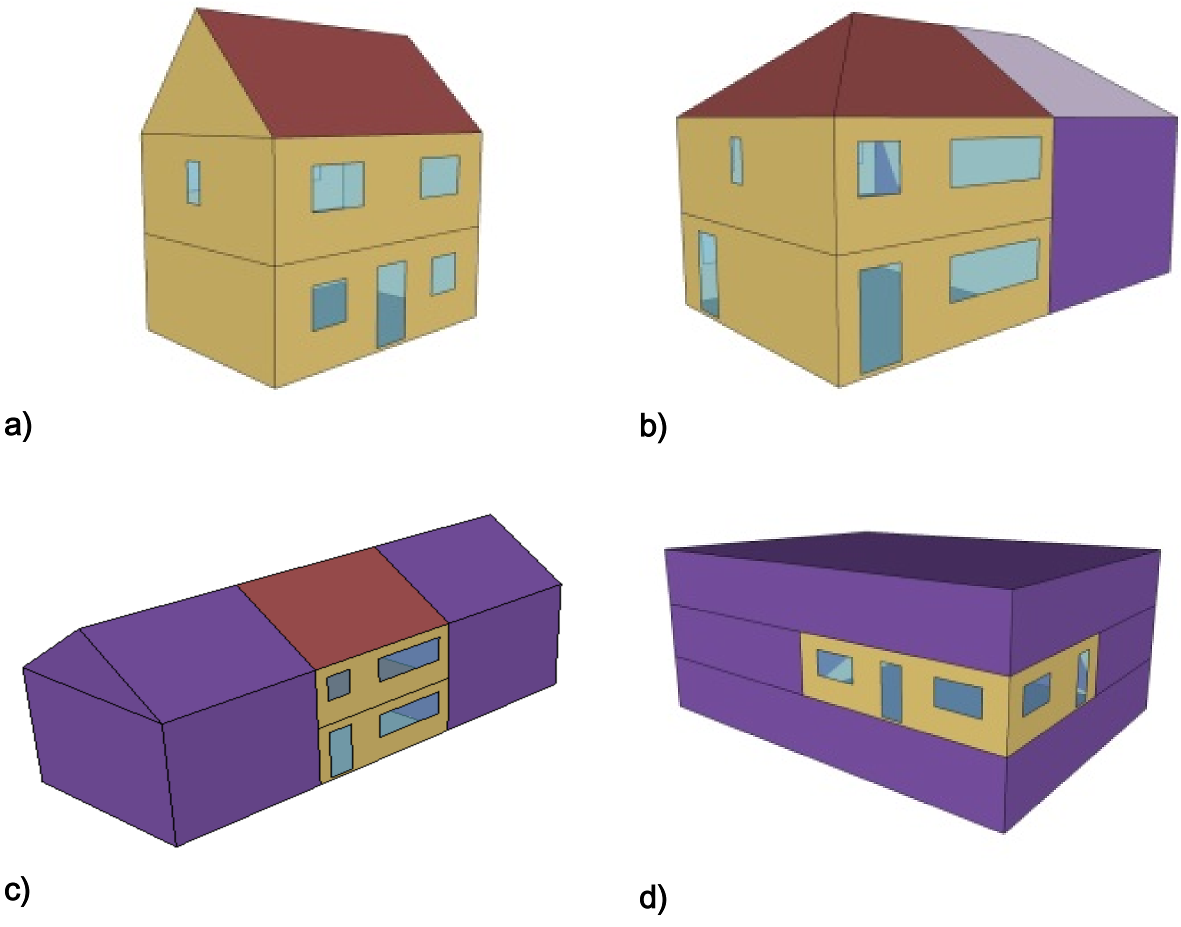


Figure 3-4. Screen shots of Google SketchUp drawings of the buildings illustrating the built forms with adjacent shading blocks: a) Detached – Base Case, b) Semi-detached, c) Mid terrace, and d) Flat.

The sizes of the buildings are identified by the useful occupied floor area that is heated. The size of UK dwellings can vary considerably from around 50m^2 for a flat to over 150m^2 for a detached building, and have an average value of around 90m^2 to be in line with the average floor area of dwellings in the housing stock (DCLG, 2013). In terms of the heating needs, the three sizes of dwellings have been considered in this study represent the majority (approximately 85%) of the existing housing stock in terms of the usable floor area. For example, a floor area of 70m^2 represents dwellings sizes up to and including 70m^2, a floor area of 90m^2 represents floor sizes from 70m^2 to 90m^2, and floor area of 150m^2 represents floor sizes from 90m^2 to 150m^2. The floor area is assumed to be equally split between the Ground Floor (GF) and the First Floor (FF) with the exception of the flat. All building typologies except the flat have loft floor area, though this is not considered as occupied and is not heated.

The thermal characteristics of the housing stock are represented through depicting the thermal insulation levels of the main building fabric components reflecting the recommendations of the 1980, 1990, 2002 and 2010 building regulation standards. This meant that the research focused on investigating the impact of TES in dwellings with thermal insulation levels recommended by these building regulation standards. The reason for this approach is that TES for heat demand management purposes could be more useful in the future where electric heating is wide spread, and when the thermal quality of buildings has improved. It was considered that this approach would provide better insight into how the TES characteristics and its effects could change as lower thermally performing dwellings are brought to the levels required by the later building regulation standards, through retrofits and upgrades of the building components.

Building regulations are used as drivers for improving the thermal performance of the buildings and bringing the dwellings to common levels. This is done by ensuring that the main building fabric components such as the external walls, roof, floor and windows and doors adhere to specific heat transfer rate requirements in terms of the U-value. Research indicated that the U-values of the external walls, external windows & doors, roof, floor and the infiltration level due to air tightness are the main building components which dictate the thermal performance of buildings. The U-values used for these components which correspond to the four building regulation considered are provided in Table 3-3.

The construction of the key building components which are used in the models to make-up the buildings are shown in Table 3-4. The thermal conductivity, specific heat capacity, density and thickness of the key materials used are illustrated. The thickness of the building fabric components and the combined U-values are shown for the four building regulations standards considered. Typical ground floor construction is used with varying material thickness and type. The external walls considered are of cavity wall type, incorporating cavity insulation and internal surface insulation according to the U-value requirements of the building regulation. This is because insulated and uninsulated cavity walls made up a large majority (69% or 15,701,000) of the housing stock in England in 2011 (DCLG, 2013). The window variations included single glazed, double and argon filled triple glazed windows. The roof and the first floor ceiling are separated creating an unheated loft space. The U-value of the first floor ceiling in this study is one that provides the main thermal insulation between the thermal zone and the loft zone, and is comparable to the roof U-values usually referred to in the literature.

The whole building infiltration levels used in the models which correspond with the four building regulation standards considered are shown in Table 3-3. Infiltration results due to inadequate air tightness of the buildings and remains present at all times, and is a source of heat loss from the thermal zones.

Table 3-3. Dominant building fabric U-values and whole building air infiltration and ventilation rates by building regulation standards.

	Floor W/m^2.K	Ext. Wall W/m^2.K	Windows & Doors W/m^2.K	Loft/Roof W/m^2.K	Infiltration ACH
1980 Regulation	0.74	0.60	5.70	0.40	2.00
1990 Regulation	0.45	0.45	3.30	0.25	1.75
2002 Regulation	0.25	0.35	2.00	0.16	0.75
2010 Regulation	0.17	0.22	0.96	0.14	0.40

Table 3-4. Building fabric construction details.

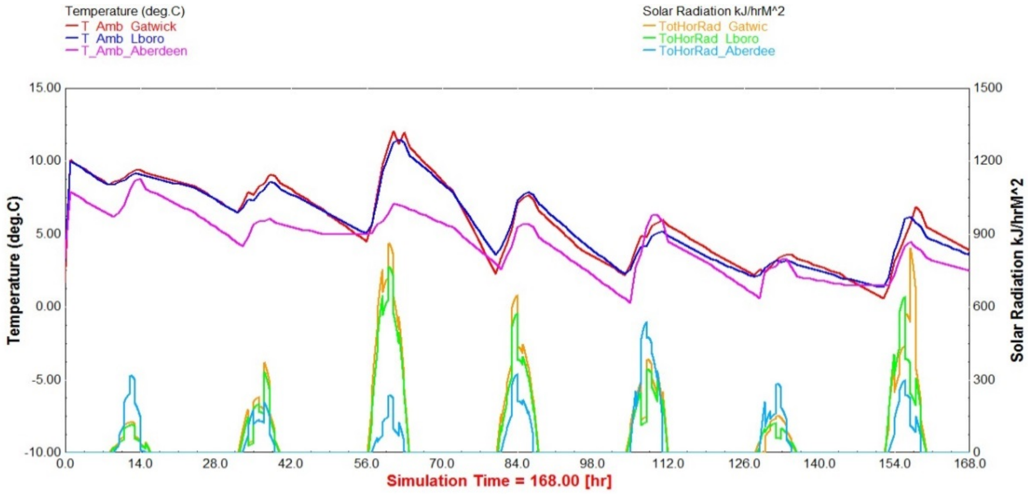
		Conductivity (kJ/hm^2K)				Specific heat capacity (kJ/kgK)				Density (kg/m^3)				Thickness(m)				Overall U-Value (W/m2K)				Internal/external surface resistance	
		Building regulation				Building regulation				Building regulation				Building regulation				Building regulation				R_{si}	R_{se}
	Material	1981	1990	2002	2010	1981	1990	2002	2010	1981	1990	2002	2010	1981	1990	2002	2010	1981	1990	2002	2010	$m^2.K/W$	$m^2.K/W$
Ground Floor	Carpet	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-						
	Timber flooring,	0.504	0.504	0.504	0.504	1.20	1.20	1.20	1.20	650	650	650	650	0.300	0.300	0.300	0.300						
	Air gap,	-	-	-	-	-	-	-	-	-	-	-	-	0.300	0.300	0.300	0.300						
	Insulation	0.090	0.090	-	-	1.25	1.25	-	-	15	15	-	-	0.014	0.030	-	-	0.74	0.45	0.25	0.17	0.13	0.04
	concrete	7.560	7.560	7.560	7.560	1.00	1.00	1.00	1.00	2400	2400	2400	2400	0.400	0.200	0.300	0.350						
	Polystyrene	-	-	0.09	0.09	-	-	1.00	1.00	-	-	15	15	-	-	0.080	0.130						
	Sand gravel	2.52	2.52	-	-	1.00	1.00	-	-	1800	1800	-	-	0.400	0.200	-	-						
External Wall	Plaster board	1.260	1.260	1.260	1.260	1.00	1.00	1.00	1.00	1200	1200	1200	1200	0.015	0.015	0.015	0.030						
	Block inner skin	1.836	1.836	1.836	1.836	1.00	1.00	1.00	1.00	1400	1400	1400	1400	0.100	0.100	0.100	0.100						
	Insulation	0.155	0.144	0.144	0.144	0.84	0.84	0.14	0.14	12	12	10	10	0.060	0.060	0.093	0.150	0.60	0.45	0.35	0.22	0.13	0.04
	Facing brick outer	4.799	4.799	4.799	4.799	0.92	0.92	0.92	0.92	2002	2002	2002	2002	0.100	0.100	0.100	0.100						
Internal Wall	Plaster board	1.260	1.260	1.260	1.260	1.00	1.00	1.00	1.00	1200	1200	1200	1200	0.015	0.015	0.015	0.015						
	Air gap	-	-	-	-	-	-	-	-	-	-	-	-	0.200	0.200	0.200	0.200	1.89	1.89	1.89	1.89	0.13	0.04
	Plaster board	1.260	1.260	1.260	1.260	1.00	1.00	1.00	1.00	1200	1200	1200	1200	0.015	0.015	0.015	0.015						
Roof	Slate tiles,	3.600	3.600	3.600	3.600	1.00	1.00	1.00	1.00	2000	2000	2000	2000	0.025	0.025	0.025	0.025	4.87	4.87	4.87	4.87	0.13	0.04
	Ash-felt	0.610	0.610	0.610	0.610	1.00	1.00	1.00	1.00	1200	1200	1200	1200	0.002	0.002	0.002	0.002						
External Windows & Doors	SG/DG/TG ~15% of floor area																	5.70	3.30	2.00	0.96		
FF floor/GF ceiling	Carpet	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-						
	Timber floor	0.504	0.504	0.504	0.504	1.20	1.20	1.20	1.20	650	650	650	650	0.020	0.020	0.020	0.020	1.33	1.33	1.33	1.33	0.13	0.04
	Air gap,	-	-	-	-	-	-	-	-	-	-	-	-	0.300	0.300	0.300	0.300						
	Plasterboard	1.260	1.260	1.260	1.260	1.00	1.00	1.00	1.00	1200	1200	1200	1200	0.015	0.015	0.015	0.015						
Loft floor/FF ceiling	Insulation	0.144	0.144	0.144	0.144	0.84	0.84	0.84	0.84	12	12	12	12	0.090	0.145	0.240	0.275	0.40	0.25	0.16	0.14	0.13	0.04
	Plasterboard	1.260	1.260	1.260	1.260	1.00	1.00	1.00	1.00	1200	1200	1200	1200	0.015	0.015	0.015	0.015						

3.5.5 Building location and weather data

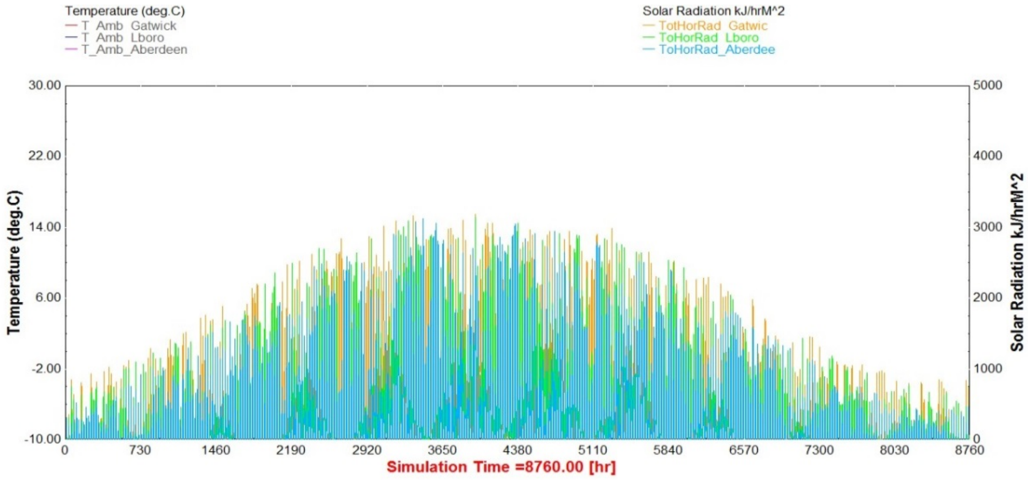
The external ambient temperature in the UK can vary significantly depending on the location. Energy consumption is a function of the external temperature, internal temperature and the heat loss and gain coefficient of the buildings. Therefore, location is an important factor and needs to be taken into account. For time constraint reasons, three main locations have been considered in this research: 1) Gatwick - south of the city of London, 2) Loughborough - in the East Midlands, and 3) Aberdeen in Scotland, as illustrated in Figure 3-5. These enabled the two extremes of the weather impacts in the UK to be analysed, as well as the middle of the country with moderate weather conditions.

Figure 3-5. Geographical location of the buildings used in the simulation.

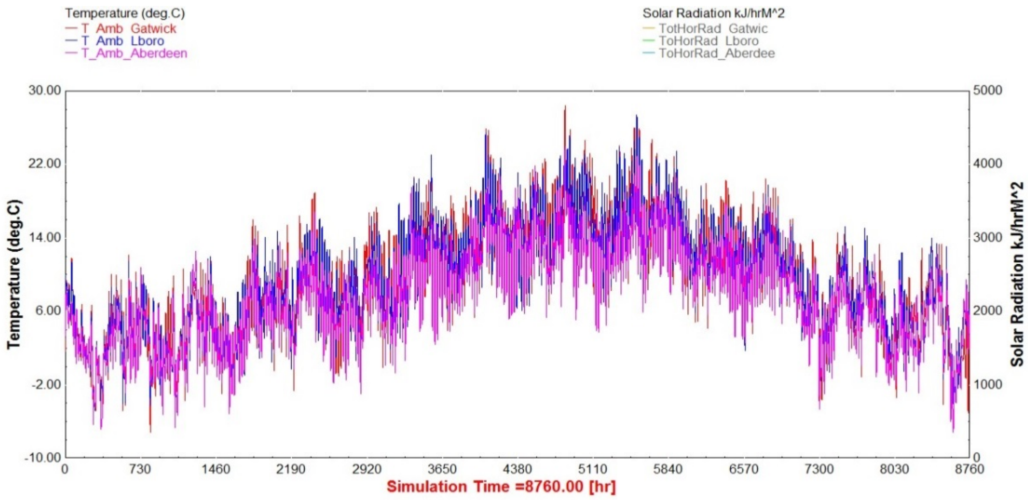
The weather data used for the locations were supplied by TRNSYS and produced using Meteornorm meteorological software application. Meteonorm is a meteorological reference tool and provides access to a catalogue of meteorological data for applications such as solar energy, building design, heating and cooling systems, renewable energy system design and environmental research (Meteonorm, 2014). It contains worldwide weather data which can be arranged into various weather data formats such as Typical Meterological Year (TMY) and EnergyPlus weather (EPW). The weather and radiation data is based on long term monthly mean values including: global radiation; ambient air temperature; cold water supply temperature; humidity; precipitation; wind speed; wind direction and sunshine duration. Stochastically generated hourly values are extrapolated from monthly data which are imported into photovoltaic, solar thermal or building simulation software such as TRNSYS (Meteonorm, 2014; SEL, 2011; Meteonorm, 2007). The weather data used in TRNSYS, and utilised in this work, was in the TMY2 format which comprises of a set of hourly values of solar radiation and meteorological elements for a period of 1 year. Figure 3-6(a-c) illustrate the ambient external temperature and the total solar radiation from the three weather data files corresponding to the three locations considered. It can be seen that the solar radiation and the external ambient temperature during the winter months are lower compared to the summer months. During the first week in January the average hourly solar radiation in Gatwick is slightly higher compared to both Loughborough and Aberdeen, the latter location having the lowest values. The external temperature for the locations follow the same pattern as one would expect. To further investigate and validate the format of the weather data, the daily average solar insolation was analysed for the three locations, see Figure 3-7(a), and compared with those of similar locations produced using data from the National Aeronautics and Space Administration (NASA), see Figure 3-7(b). As can be seen there is similarity between the two sets of graphs indicating that the weather data files used in this work are reasonable, and as one would expect for the locations considered.



a) 7 day: 1st January to 7th January



b) Solar radiation over one year: 1st January to 31st December



c) External ambient temperature over one year: 1st January to 31st December

Figure 3-6. Illustration of: a) the external temperature (T_Amb_'location') and the total solar radiation (TotHorRad 'location') for the three locations for 7 days in January, b) total solar radiation (TotHorRad 'location') over a year, and c) external temperature (T_Amb_'location') over a year.

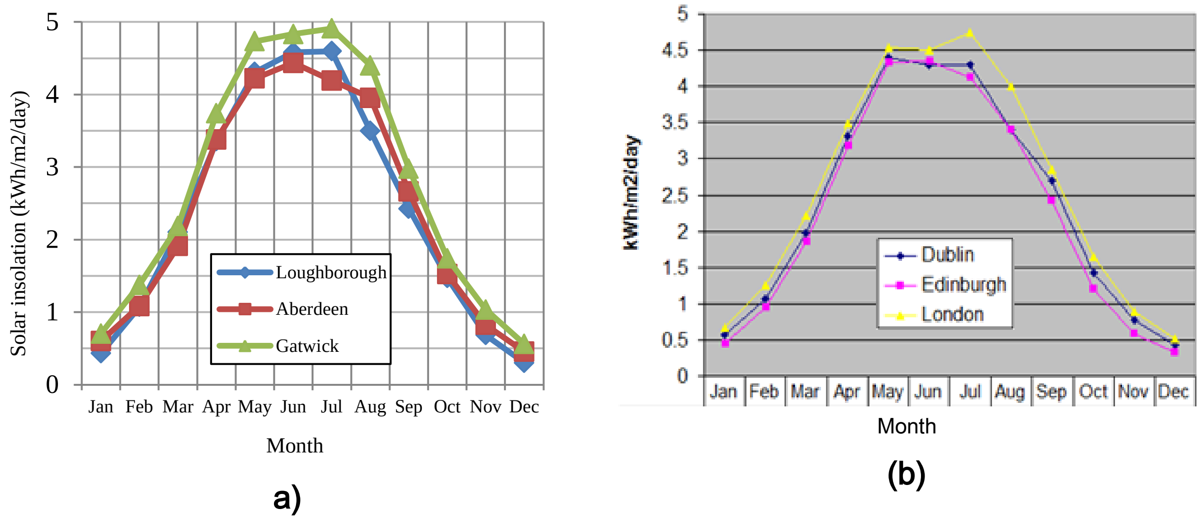
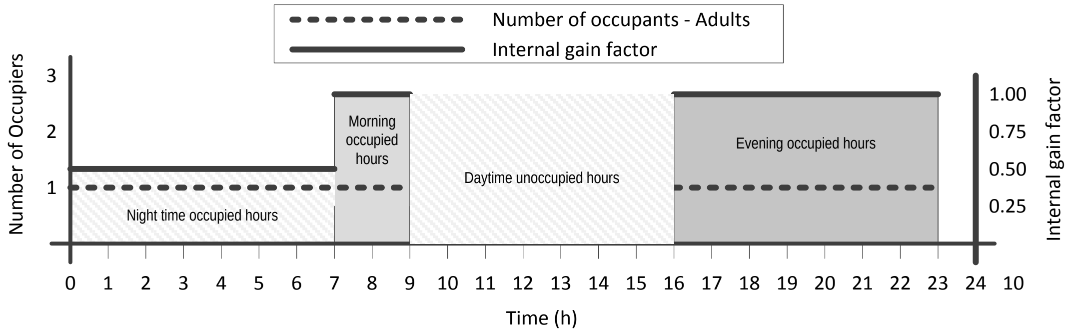


Figure 3-7. Comparison of: a) daily average solar isolation for the Gatwick, Loughborough and Aberdeen over twelve months based on Meteonorm weather data used in this work and, b) the daily average solar insolation data, averaged over 10 years, produced using metrological data from NASA for some similar locations (Contemporary Energy, 2014)

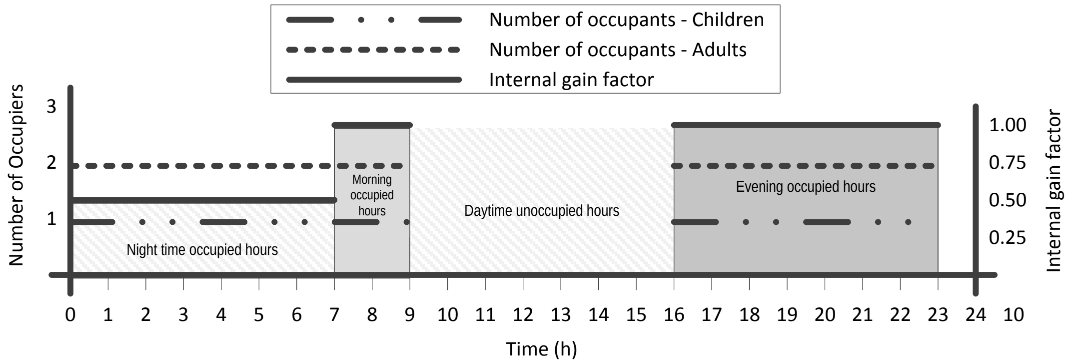
3.5.6 Occupancy, Heating duration, DHW demand and internal gains

The internal gain in the model comprise of gains from occupants (during all occupied hours), lighting and TV (during the daytime occupied hours between 07:00 to 24:00), and cooking (during the hours of 07:30-08:30 and 18:00-19:00). The occupant numbers considered covers 81.1% of the English household occupancy. The two occupancy schedules used are illustrated in Figure 3-8, for occupancy Type A and Type B. Internal gains from the occupants are provided in Table 3-5. Night time (24:00 to 07:00) internal gain from the occupants is 50% of the day time gain, achieved by multiplying the people gain by an internal gain factor as shown in Figure 3-8. The internal gains only apply to the relevant occupied thermal zones, for example the cooking and TV gains only apply to the ground floor zone and the night time people gain only apply to the first floor zone.

Four heating durations and three thermostat setting levels have been considered as detailed in Table 3-5. These represent the heating durations and thermostat settings found in domestic buildings during the winter days based on monitoring studies of Kane (2013) as described in Section 2.5.3. For simplicity the heating duration is kept identical for both weekdays and weekends. The thermostat is located in the ground floor. This study assumes that portable heating devices in addition to the main heating systems are not used in the buildings. Forced or active cooling, for example through the use of air-conditioning system, is not considered in this study.



Type A



Type B

Figure 3-8. Details of the two occupancy options considered and the corresponding internal gain factor: a) Type A: one adult, and b) Type B: two adults and one child.

Table 3-5. Occupancy scenarios and operational conditions considered in the simulation.

Occupancy and operational scenarios		
	Variant	Description
Internal gain	1	People – adult standard gain: Sensible 90W, Latent 60W Link to Adult occupancy schedule at gain factors as in Figure 3-8 . People child: sensible 70W, Latent 40W Link to Adult occupancy schedule at gain factors as in Figure 3-8 . Cooking: Sensible 1kW, Latent 50W 20% between 07:30 – 08:30, and 100% 18:00 – 19:00 TV: Sensible 200W, Latent 50W Link to Adult occupancy schedule Lighting gain:=5W/m^2 Link to Adult occupancy schedule
Heating duration	1 2 3 4	16 Hours, 07.00-23.00 12 Hours, 07.00-11.00 & 15.00-23.00 9 Hours, 07.00-90.00 & 16.00-23.00 6 Hours, 07.00-09.00 & 17.00-21.00
Thermostat setting	1 2 3	19°C 21°C 23°C

3.5.7 HVAC System

This section describes the heating system model used during this research. A summary of the key components of the heating system and their values is provided at the end of this section (see Table 3-6).

The top level block diagram of the heating system (without any thermal storage) and its connection to the building models is shown in Figure 3-9. The model represents a standard wet central heating system which provides the space heating with the exception that an electrical resistance element water heater is used as opposed to the conventional gas boiler. DHW services are met through the use of the same water heater. As mentioned before, air conditioning (or space cooling) is not included in the model. No ventilation of the occupied space is used for example via opening of windows. This is because the thesis focuses on research questions relating to heating and heat demand shift impacts during the winter period when ventilation via opening of windows is less likely.

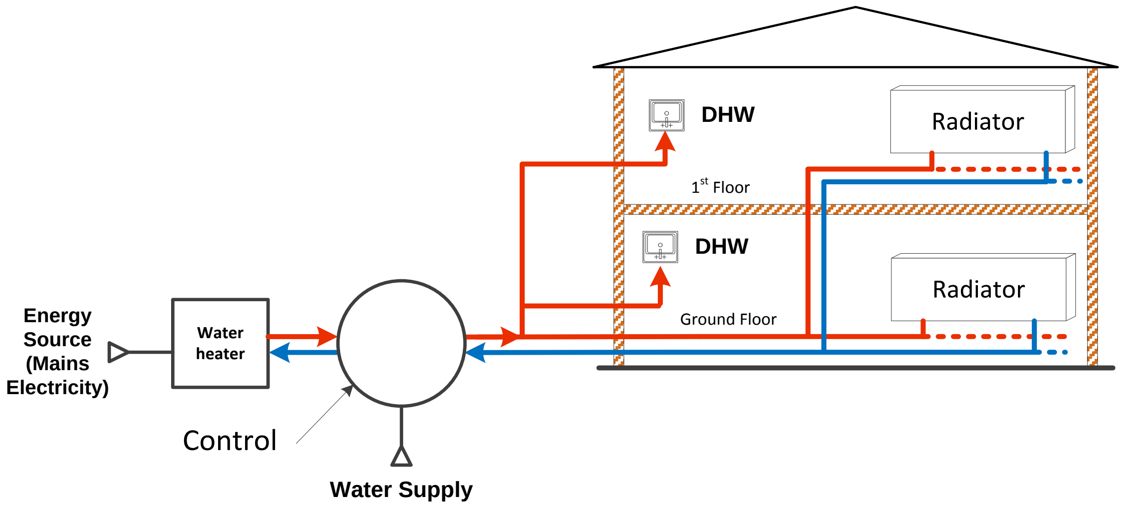


Figure 3-9. HVAC system and domestic building arrangement block diagram.

The standard heating system modelled in TRNSYS and its configuration is shown in Figure 3-10. The mathematical description of the components (Types) used are well documented and can be found in the TRNSYS17 HVAC Mathematical Reference manual (TESS, 2014). The system comprised of three loops:

1. Primary loop: isolating the water heater from both the DHW and heating loops
2. Intermediate loop: is where the DHW is drawn from and is isolated from both the water heater and the space heating loop
3. Space heating loop: circulating water around the heating system and is isolated from the intermediate loop.

The three isolated water loops were used to enable different water temperatures typically found in domestic heating and DHW systems, for example space heating water flow temperature, DHW draw-off temperature and DHW storage temperature. This configuration also allowed the DHW stage to be isolated which is important for health and safety purposes. Also, this configuration allowed a higher temperature TES system to be integrated into the system as discussed later in 3.5.8.

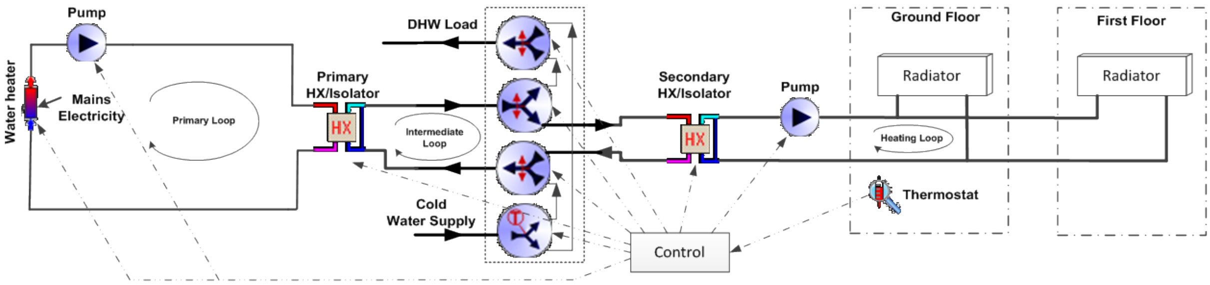


Figure 3-10. The standard DHW and the space heating system configuration.

The main heating system component variables and their values are shown in Table 3-6. The primary loop consists of an electrical resistance element water heater (Type-6), a constant flow water pump (Type-114) and a primary heat exchanger (Type-650) set at a 95% heat transfer rate. Heat from the primary loop is transferred to the intermediate loop via the primary loop heat exchanger, and is maintained at a temperature of 80°C. DHW is drawn off from the intermediate loop. Heat from the intermediate loop is transferred to the space heating loop via a secondary heat exchanger (Type-699) set at a 95% heat transfer rate. The heat exchangers circulated water through itself and a bypass in appropriate proportion ensuring a heating loop water temperature of 75°C.

As discussed earlier, an aim of this work was to understand the heat energy use characteristics of the **existing** UK housing stock given the large diversity which includes varying thermal insulation, size and built form. Therefore the buildings considered include both poorly and well insulated ones (1980s to 2010s building regulation); occupied floor area from 70m^2 to 150m^2 (compared to a housing stock mean of 90m^2) and four built forms. The energy consumption and heat transfer rate required in these buildings can be expected to vary significantly. The power rating of the water heater therefore had to be chosen such that the heat transfer rate from the heating element to the water, and into the space via the radiators, can adequately compensate for the heat loss and ensuring thermal comfort in all building archetypes and for all operational conditions. For this reason, the power rating of the water heater was set to 20kW, 25kW and 30kW depending on the dwelling floor size as shown in Table 3-6. This eliminated the potential uncertainty factor that could be introduced in the performance predictions in cases where large quantity of heat and a high heat transfer rate is needed to ensure adequate thermal comfort. A demonstration of this is provided by the graphs in Appendix B. They compare the daily space temperature and the power demand profiles, averaged over 60 winter days from 2nd of January, for a detached 150m^2 building with a 1980s thermal insulation level, and with a 30kW and a 15kW water heater. It can be seen that the space temperature was unable to reach the thermostat set-point with the 15kW water heater, indicating lower than required heat transfer, whereas it behaved as one would expect with a 30kW water heater. It must be noted that resistance element heaters with such high power rating are unlikely to be used widely in reality by design. For example a 5% penetration of this in the housing stock (assuming 27million homes) and an average peak power demand of 20kW, could add a peak load of 27GW to the grid which is unlikely to be acceptable. Instead, more efficient systems such as heat pumps would most probably be used which could reduce the peak load by a factor in between 2 and 3 depending on the COP of the heat pumps (Wilson et al., 2013). However, as discussed by Wilson et al. (2013), the eventual solution is likely to include a combination of resistance element heating and heat pumps. For this reason, to cover the worst case scenarios, resistance element heaters have been considered in this work.

Water is heated to 85℃ and circulated through the heat exchanger which transfers heat to the intermediate loop ensuring a constant water temperature of 80℃. This is done by the heat exchanger circulating water through itself and a bypass in appropriate proportions. Type-31 fluid flow pipes of 22mm diameter were used to represent the plumbing pipe work carrying water around the heating system. The loss coefficient and the length of the pipework were set at 0.83W/m^2.K and 70m respectively. The heat loss from the pipework was fed back into the building as internal gain.

As mentioned earlier, the DHW draw off point is the intermediate loop and is set at a constant temperature of 52℃. This is consistent with the average draw temperature published by the EST based on a study of 119 dwellings as previously discussed in Section 2.3 (EST, 2008). The DHW draw temperature is achieved through a combination of tampering valve (Type-11h,) mixing valve (Type-11d) and diverter valve (Type-647) which mix hot water (at 80℃) from the intermediate loop with cold water from the mains water supply in appropriate proportions. The cold water supply temperature is around 9℃, and is based on and provided by the Meteornorm weather data as discussed in Section 3.5.5. The DHW delivery rate is set to 53lt/day/person, which is consistent with the average DHW demand observed by the EST in the monitoring study mentioned above (EST, 2008). To simplify the modelling process, the delivery of the DHW is assumed to take place only during the morning and the evening occupied hours, from 07:00 to 09:00 and 16:00 to 23:00 respectively, and at constant rate of 5.9lt/person/hour. This assumption means that the hourly DHW draw rate is 5.9lt/h and 17.7lt/h for the Type A and Type B occupancy schedules respectively. This implies that during the critical occupied hours (16:00 to 23:00) and for the Type B occupancy, the DHW draw rate would be relatively high compared to the mean peak demand of about 9lt/h found in the EST study (See Section 2.3.7). However, as also illustrated in the EST study, in some dwellings the peak DHW demand during the critical period can reach up to around 30lt/h, for example when baths or showers are in use. In scenarios where DHW and space heating services are met from a common heat store, the DHW draw rate will influence the space heating provision. As extreme utilisation of DHW during the critical hours is not modelled in this study, the assumed higher draw rate used is considered reasonable which takes into account the potential impact on space heating provisions of a higher rate of DHW use during the critical period.

The space heating loop consists of two Type-1231 radiators serving the two thermal zones (one for the flat), a constant flow rate pump (Type-114) in addition to a shared heat exchanger (Type-650) with the intermediate loop. The radiators supplied heat into the thermal zones by radiation (20%) and convection (80%). As discussed earlier the radiator sizes were selected to reflect the diversity of the buildings in the existing housing stock. The radiators for the three building sizes considered were as shown in Table 3-6. These sizes are based on the heat loss of the buildings calculated using the CIBSE guidelines, provided in the Environmental Design: CIBSE Guide A, for existing buildings (CIBSE, 2006). The worst case thermal insulation (1980s building regulation), a 20% glazing to floor area, a -3℃ outside design temperature and a 21℃ inside design temperature was used. The values selected also compare well with those that can be determined by using freely available online radiator sizing calculators (Plumbnation, 2014).

The water pump circulates hot water through the radiators at flow rates varying from of 0.3kg/s to 0.5kg/s depending on the size of the building and the radiator size. The water flow and return temperatures were set to 75℃ and 65℃ respectively ensuring an average surface temperature of 70℃ and a ∆T (difference between the average surface temperature and the ambient space temperature) of 50℃ as per BS EN 244 recommendations (BSI, 1996). The space heating system was controlled using an on/off control algorithm connected to a thermostat (Type-1502) located in the ground floor thermal zone. This study assumes that the radiators in the different thermal zones are not individually controlled, for example through the use of thermostatic radiator valves.

Table 3-6. Summary of the key HVAC system variable settings.

Key variables	Values used			
Radiator power rating Fluid mass flow rate	Total of 5kW (per thermal zone) 0.3kg/s	Total of 6kW (per thermal zone) 0.35kg/s	Total of 8kW (per thermal zone) 0.4kg/s	Total of 12kw (per thermal zone) 0.5kg/s
Corresponding floor area	$63m^2$	$70m^2$,	$90m^2$,	$150m^2$
Water heater power rating (electrical resistance element type)	20kW		25kW	30kW
Central heating water Flow/Return temperature	75°C/65°C			
Thermostat setting	19°C, 21°C, 23°C			
DHW temperature	52°C			
DHW draw off rate	53lt/person/day (5.9lt/person/hour, for 9hr occupied hours)			
Heat exchanger conversion efficiency	95%			

3.5.8 TES system model

The main focus of this work was to investigate the impacts and benefits of TES in domestic buildings in terms of DHW and space heating energy demand management by demand shifting. It was more important to accurately model the quantity of energy stored and used as opposed to how it is stored (or the technology used). As discussed previously in the Literature Review, Section 2.4, sensible heat storage is the method of choice for reasons of relatively low complexity and cost, and has been used in domestic environments for many decades. Therefore active sensible heat storage method of TES was used in this research. The storage device used was thermally insulated cylindrical water tanks. The maximum water storage temperature was 95℃, and the maximum size was $0.75m^3$. It was assumed existing hot water tanks in dwellings can be relatively easily replaced with new TES tanks with heat storage capability for heat demand shifting applications, and integrated into the existing heating systems for meeting both the DHW and space heating needs.

The water storage temperature and the tank volume were changed to vary the thermal storage capacity, to allow its impact on the heat demand shifting abilities and the thermal condition of the heated spaces to be investigated.

Table 3-7 shows the combination of TES sizes and storage temperatures considered. Figure 3-11 illustrates how the TES system is configured with the heating system and the building structure. It was assumed that the heating system and the TES system will be housed inside the building. This meant that the ambient temperature around the TES tank was same as the space temperature. The heat loss from the TES tank was also fed into the ground floor as internal gain.

Table 3-7. Combination of TES sizes and water storage temperatures modelled in TRNSYS.

TES size and storage temperature utilised		
	Active Sensible TES options	
TES type options	TES size (m^3)	TES storage temperature (°C)
Active	0.25, 0.5, 0.75	75, 95
Total number of TES capacity combinations		6

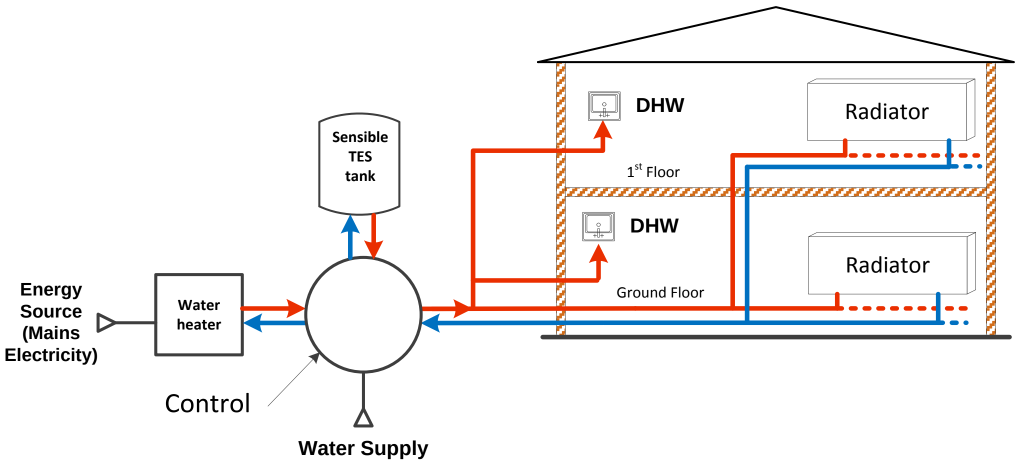


Figure 3-11. Configuration of the sensible TES with the heating system and the building structure.

Sensible TES system for space heating and DHW

A thermally stratifying cylindrical hot water tank (hereafter referred to as the TES tank), is used to represent a rechargeable active sensible TES. The configuration of the TES tank with other related system components is shown in Figure 3-12. The TRNSYS Type4c is used to represent the TES tank which models a fluid-filled sensible energy storage tank that is subject to thermal stratification. The configuration was such that six vertically stratified zones of equal height as shown in

Figure 3-12 were created. The height of each stratified zone was approximately 0.3m and depended on the overall height of the TES tank as detailed below. For all analyses, an external resistance element electric water heater (Type-6) was used to heat the water to the required temperature and circulated through the TES tank. A water temperature heating dead-band of 2℃ was applied. The tank sizes considered were 0.25m^3 (250litre), 0.5m^3 (500litres) and 0.75m^3 (750litre). The tank diameter (D) and the height (H) were 0.42m and 1.8m; 0.6m and 1.8m; and 0.73m and 1.8m respectively, which correspond to the three tank sizes. During charging, the cold water from the bottom zone of the TES tank is pumped through the electric water heater and back into the top zone as hot water. During discharging, the hot water is delivered from the top zone of the TES tank to a heat exchanger and cold water from the heat exchanger is returned back to the TES tank at the bottom zone. The temperature sensor in the TES tank is located at the bottom zone. The tank heat loss coefficient was set to 0.68W/m^{2}K. The sizes and heat loss parameters are such that real and commercially available hot water storage tanks are represented (Evinox, 2014).

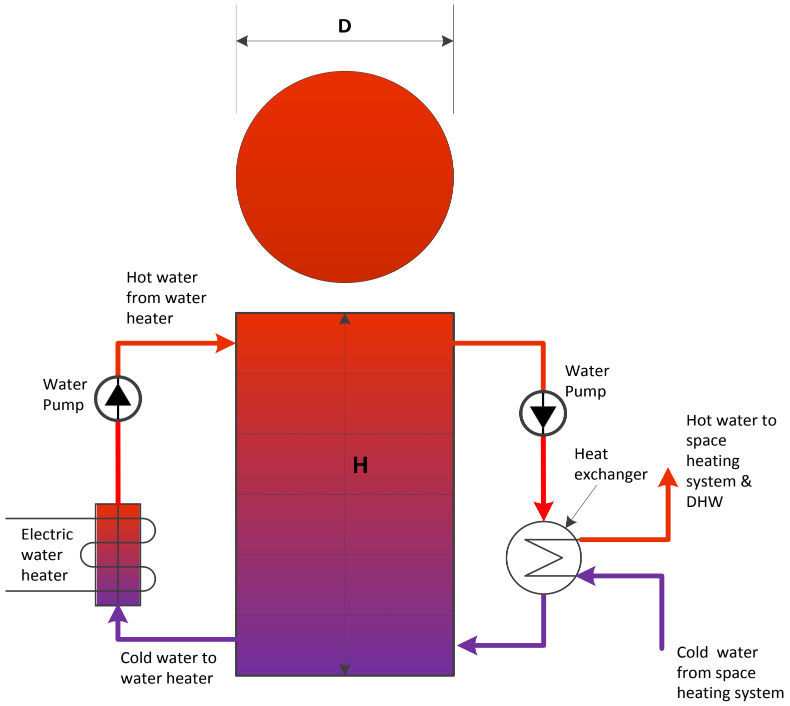


Figure 3-12. Illustration of the cylindrical hot water storage tank used as active sensible TES system.

The TES tank sizes selected provided options for simulating HDS in buildings of different physical sizes with tank sizes that can be physically housed in them. For example, it may be more realistic to use 0.25m^3 tanks in smaller buildings such as those with 70m2 floor area. Therefore exploring the impacts this tank size could have on the temperature, power and energy demands of such buildings could be useful. The TES tank is configured to the heating system as shown in Figure 3-13. The heat input side of the TES tank is connected to the water heater via a mixing valve (Type-649) and a diverter (Type-647) valves. The heat output side of the TES is connected to the primary loop heat exchanger via a further mixing valve (Type-649) and a diverter (Type-647) valve. During charging the controller diverts hot water from the water heater into the top of the TES, and cold water from the bottom of the tank to the water heat. During discharging the controller diverts hot water from the top of the TES tank into hot side of the primary loop heat exchanger and returns cold water from the heat exchanger to the bottom of the TES. When the TES is not in use the controller bypasses the TES tank completely, by appropriately setting the mixing and diverter valves in the primary loop. The function of the intermediate loop and the heating loop remain unchanged and as described in Section 3.5.7.

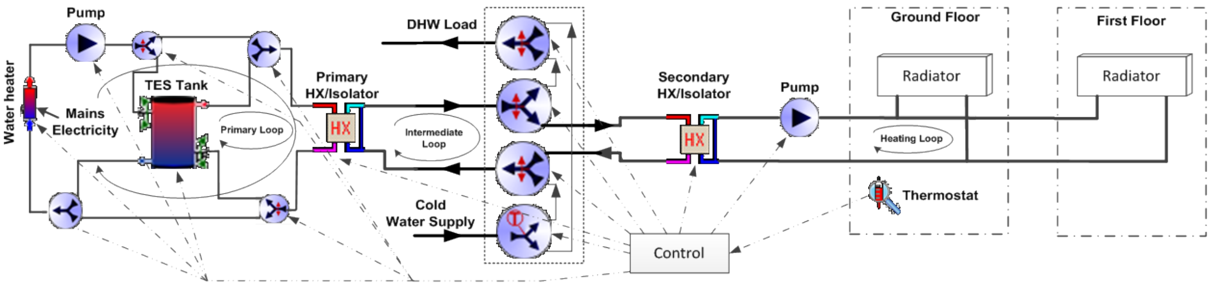


Figure 3-13. The DHW and the space heating system configuration, incorporating an active sensible TES tank arranged for storing water at temperatures from 75°C to 95°C.

3.5.9 The model output parameters and performance analysis metrics

The models were arranged to generate output data to reflect three areas of model performance: 1) Thermal condition, 2) Power demand, and 3) Heat energy demand and cost. The variables within these three performance areas for which data is recorded are as described below:

Thermal condition analysis: containing:

1. Air temperature of the ground floor zone (*GF_T*)
2. Air temperature of the first floor zone (*FF_T*)
3. Air temperature of the external environment (*Amb_T*)

Power demand analysis: consisting of:

4. Instantaneous mains supply electrical load for the whole building *(Mains_supply_load_kW)*

5. space heating only power demand which is based on the heat transfer from the radiators into the occupied spaces ***(Heating_load_kW)***
6. DHW only power demand which is based on the heat transfer to the cold water supply to raise the temperature to the DHW draw off temperature ***(DHW_load_kW)***

Heat energy demand and cost analysis: the energy demand (in KWh) is calculated over a 24 hour period from 00:00 to 24:00, by integrating the load profile over the 24 hour period. The energy demand and the cost predictions derived are:

7. whole building energy demand ***(Whole_building_kWh)***: based on energy transfer to the water from the mains electricity supply
8. Space heating only energy demand ***(Heating_only_kWh)***: derived from load profile resulting from the heat transfer from the radiators to the occupied spaces.
9. DHW only energy demand ***(DHW_only_kWh)***: derived from the load profile resulting from the heat transfer to the DHW consumed.

The output data is analysed and processed to extract information corresponding to ten key performance metrics which are:

Metric 1: Daily 60 day mean ground floor air temperature ***(Daily_mean_GF_T)***

Metric 2: Ground floor 60 day mean ground floor air temperature during the occupied hours of 17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00) ***(DSP_hours_mean_GF_T)***

Metric 3: Whole building daily 60 day mean mains supply power demand ***(Daily_mean_MS_power_kW)***

Metric 4: Space heating only power demand during the occupied hours from 17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00 ***(DSP_space_ heating_MS_kW)***

Metric 5: Whole building 60 day mean energy demand ***(Daily_mean_MS_energy_kWh)***

Metric 6: Daily 60 day mean energy cost for the building ***(Daily_mean_energy_cost_£/day):*** The daily cost of the heat energy is calculated by multiplying the energy demand predictions in kWh by the cost of electricity based on the Tariff Comparison Rate (TCR) from British Gas Ltd. of 16.09p/kWh, as in September 2015, which represents the typical cost per kWh for the standard electricity tariff, taking into account surcharges and discounts such as standing charge and dual fuel discounts. The TCR figure used in this work only includes the standing charge.

Metric 7: 60 day minimum ground floor air temperature during the DSP ***(DSP_minimum_GF_T)***

Metric 8: 60 day mean percentage DSP time air temperature remaining above 18°C ***(%DSP_T>18°C),*** also referred to as the 'thermal comfort' value in this thesis.

Metric 9: 60 day mean heat energy supplied by the TES tank during the DSP ***(TES_tank_energy_kWh)***

Metric 10: represents the potential energy bill saving due to buying the shifted energy at a discounted price equivalent to the currently available Economy7 electricity price tariff ***(Energy_cost_saving/day)***

These metrics enabled simple comparison of the main performance parameters for the different simulation options, and investigate how they change with variables such as thermal insulation, occupancy and operational conditions. The performance metrics are described in more details in the results chapters.

3.5.10 Model validation

Overview

This section describes the processes employed to validate the models used in this work. Two methods have been used to verify that the model development activities and the results generated are plausible and represent reality: 1) inter model performance comparison, which involved simulating and comparing the thermal and energy performance of a 1990s dwelling in IES Virtual Environment (IES-VE) and TRNSYS, and 2) comparing the simulated thermal and energy performances of the dwellings considered in this work with published results of thermal and energy performance measurement of similar dwelling with similar occupancy and operational conditions.

The purposes of these exercises were to ascertain whether the models, when reproduced in a different dynamic energy and building modelling software and simulated with similar sets of input data, produces the same results. A further purpose was to ensure that the output generated by the models are realistic and plausible given the various assumptions which are necessary in this type of work, and the estimated nature of certain simulation parameters such as the weather data.

Ultimately the cross checking of the results generated in two different modelling software and the comparison of the predicted energy consumption data with published monitored data (for buildings of similar sizes and operational conditions) showing similar results provided confidence in the modelling and the simulation processes followed during the research, and the results obtained as described in the results chapters.

Inter model comparison

Inter model comparison was carried out by means of creating and simulating models in TRNSYS and IES-VE of a building with identical construction, occupancy and operational conditions. The assumptions and methods used in creating the building models and the heating system components are identical to those described in sections 3.3.4 to 3.3.7. The thermal and energy performance were simulated in both modelling tools and the results compared (see Figure 3-14).

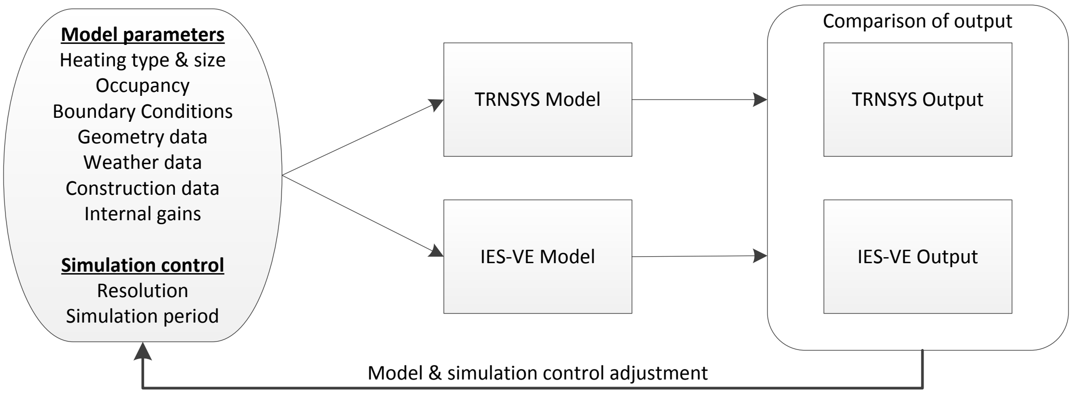


Figure 3-14. Inter model validation block diagram comparing the simulated energy and thermal performance of a dwelling with identical construction, occupancy and operational conditions in TRNSYS and IES-VE

The physical properties of the building modelled here was different to the building models described in Section 3.5.4, and is based on a real detached test house building located on the Loughborough University campus. The building is of standard brick construction and built to the 1990's building regulation standards. The construction parameters of the main building components are as described in Table 3-8. One occupancy schedule (occupancy Type B as previously described in Figure 3-8) and heating system operational schedule corresponding to a 9 hour heating duration (7:00 to 09:00 and 16:00 to 23:00) with a thermostat setting of 21℃ was used. The internal gain parameters utilised was as described in Table 3-5. The air infiltration level was set to 1 ACH and only applied during the daytime occupied hours.

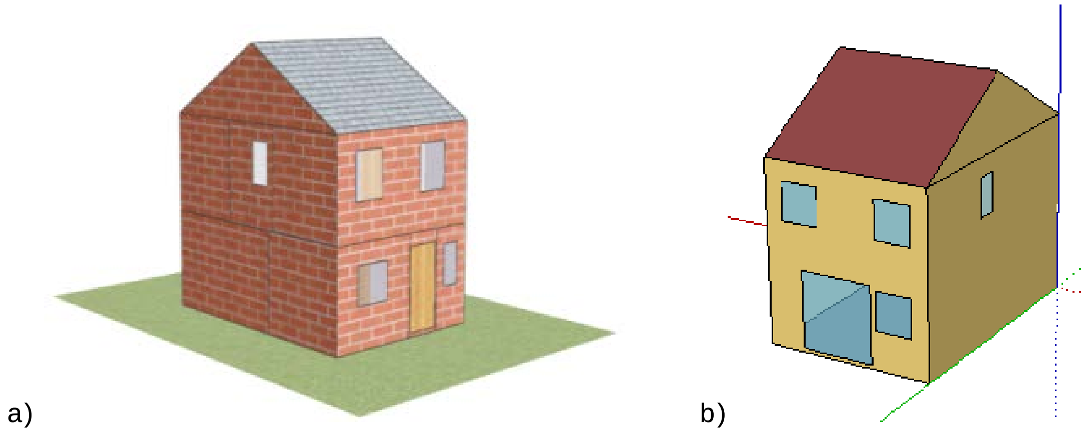


Figure 3-15. Screen shots of building model created in: a) IES-VE front view, and b) TRNSYS rear view.

The building model was initially created in IES-VE (see Figure 3-15a) with the build and construction details extracted from the original drawings. Parameters, which were not present on the drawings, were based on the standard specifications of the 1990's building regulation requirements. A TRNSYS model of the same building was created using a Type-56 multi-zone building model (see Figure 3-15b), and was adapted to include construction materials with identical or closely matching thermal and physical properties to those used in IES-VE, thus possessing similar overall thermal characteristics. For example, the external wall representation in IES-VE and TRNSYS had overall U-values of 0.715 W/m²K and 0.702 W/m²K respectively.

Table 3-8. Building fabric construction details used in the IES-VE and TRNSYS models.

	U-value (W/m²K)	Building material & thickness (m)
Ground Floor	1.39	0.01 Synthetic carpet 0.05 Rubber underlay 0.02 Timber flooring 0.30 Air gap 0.15 Cast concrete 0.15 Stone chipping 0.75 London clay
External Wall	0.72	0.100 Facing brick outer 0.058 Cavity insulation 0.150 Block inner skin 0.015 Plaster finish
Internal Partition Walls	1.59	0.150 Gypsum plasterboard 0.100 Cavity 0.150 Gypsum plasterboard
Roof	4.87	0.025 Slate tiles 0.01 Ashfelt
External Windows PVC	1.98	Double glazed 0.006 Pilkington glass 0.012 Cavity 0.006 Pilkington glass
Internal Doors	2.29	0.04 plywood
External Doors	2.55	0.047 Oak door
FF floor/GF ceiling	1.28	0.01 Synthetic carpet 0.05 Rubber underlay 0.02 Timber flooring 0.300 Cavity 0.150 Gypsum plasterboard
Loft floor/FF ceiling	0.22	0.170 Insulation 0.150 Gypsum plasterboard

Model configuration and simulation control

The heating system in IES-VE was modelled within the ApacheHVAC modeller, as water based central heating system with convector radiators adding up to 10kW, connected to a 20kW generic electrical heat source. On/Off controllers were used to control the heating. The heating system also provided the domestic hot water. The TRNSYS heating system configuration was as described in Section 3.5.7.

The weather data used in TRNSYS and IES-VE are based on two locations; 1) approximately 5 miles north, and 2) approximately 15 miles north of the building location respectively. Simulations were performed for 60 days from 1st of January.

It can be appreciated that the use of two separate weather data files, although they are based on virtually the same geographical location, have some inherent differences, and therefore the two simulations cannot be considered identical. In any case, it would be wrong to suggest that the IES-VE model, even with identical parameter values but without it being validated first with some scientifically acceptable means, could be used to validate the TRNSYS model. However, as stated earlier, IES-VE is a commercial package with tightly controlled modelling environment, that has been tested using ASHRAE Standard 140 and qualifies as a Dynamic Model in the CIBSE system of model classification (Crawley et al. 2005), and widely used both in industry and academia. With the due care and attention, it can be used to generate acceptable thermal and energy performance results of simple buildings, such as the one used in this exercise, relatively easily and with minimal uncertainty. With this in mind, this exercise was carried out with the aim to: a) see whether there is a trend wise agreement between the results produced by the two models in the short time scale, and b) see whether there is agreement between the results over the long term, where the short term differences, for example the day to day differences in the external ambient temperature, average out to a certain degree.

Comparison of the simulation results

Figure 3-16 and Figure 3-17 illustrate the occupied space temperature, the external ambient temperature and the heating load curves for an example day of 7th January for both the TRNSYS and IES-VE simulations. The main parameters simulated by the two applications are summarised in Table 3-9 for the example day and for the 60 day simulation period from the 1st of January. It can be seen that there is considerable trend wise agreement between the responses generated by the two applications. The space temperature transient response are similar, both having a rise time to the thermostat setting of around 35 to 40 minutes from the start of the heating system. The space temperature fluctuates around 21℃ as the heating system cycles on and off with the space temperature rising and falling outside a 2℃ dead-band, centred at the thermostat setting of 21℃. The heating system energy demands during the example day were 67.1kWh and 65.7kWh for TRNSYS and IES-VE respectively. The difference between these values could be due to the slightly lower external ambient temperature in the TRNSYS weather data (see Figure 3-17) requiring more heat to maintain the space temperature.

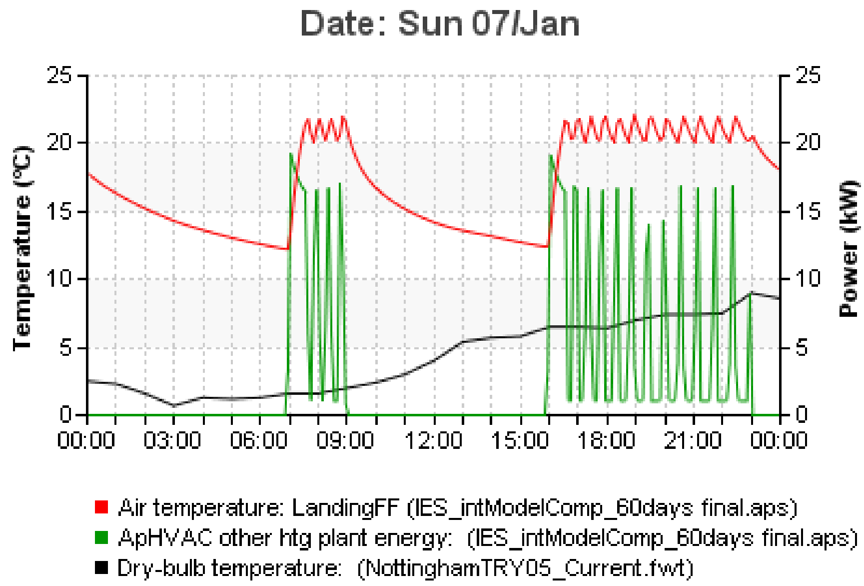


Figure 3-16. Example of the thermal response on 7th January from the IES-VE.

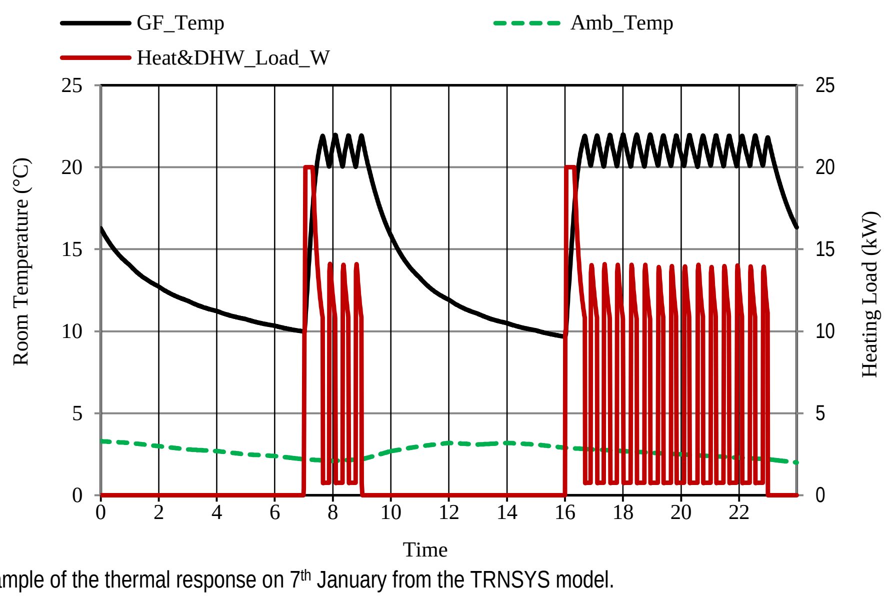


Figure 3-17. Example of the thermal response on 7th January from the TRNSYS model.

The 60 day average space temperature and the heat energy demand predictions (for space heating only, DHW only and combined total) are similar for both IES-VE and TRNSYS. The noteworthy differences are that the TRNSYS predictions for the space heating energy demand is marginally higher; the difference between the maximum and the minimum daily space heating energy demand prediction over 60 days is slightly bigger, and the mean and the minimum occupied space temperatures are marginally lower (see Table 3-9). However these could be explained by the slightly poorer external ambient conditions inherent in the TRNSYS weather data, for example over the 60 day simulation period the maximum, minimum and the mean external ambient temperature in the TRNSYS weather data being 12.2℃, -5.0℃ and 3.4℃ respectively. The same figures in the IES-VE weather data are 12.4℃, -2.9℃ and 4.29℃ respectively. Therefore it is reasonable to expect a marginally higher average heating energy demand and a marginally lower space temperature predictions (outside of the heating periods) in TRNSYS compared to those of IES-VE. Some differences were also expected due to the minor variations in the building fabric models used in the two simulation packages as previously explained, for example the external wall U-value in the in IES-VE and TRNSYS models being 0.715 W/m^2K and 0.702 W/m^2K respectively.

In summary, the differences in the predictions generated by the two simulation tools mentioned are relatively small, for example the difference between the space heating energy demand prediction by TRNSYS and IES-VE over the 60 day simulation period is 2.6%. Further analysis of the results indicated good correlation between the weather data parameters, such as solar radiation and external ambient air temperature, and the space temperature responses and the heat energy demands predictions generated by the two applications. For example the heat demand and the minimum room temperatures varied correspondingly with the external ambient temperature and the solar radiation levels.

Table 3-9. Comparison of the key heat consumption and space condition predictions by IES-VE and TRNSYS for a sample day of 7th January and for a 60 day simulation period from 1st January.

	TRNSYS		IES-VE	
	7th January	60 days from 1st January	7th January	60 days from 1st January
Mean space temperature (°C)	15.6	15.7	17.1	17.5
Minimum space temperature (°C)	9.7	9.7	12.4	10.79
Maximum space temperature (°C)	22.0	22.0	22.1	22.3
Space heating energy (kWh)	57.8	55.3	56.2	54.3
DHW energy (kWh)	9.2	9.2	9.4	9.4
Total energy (kWh)	67.1	65.4	65.7	63.7
Maximum total heat energy (kWh)	-	81.5	-	76.5
Minimum total heat energy (kWh)	-	48.0	-	49.4

Validation through comparison of published measured data

Further validation of the model performance and the results generated was carried out by comparing the simulated heating energy consumption prediction with published measured thermal and energy performance data of similar buildings with similar occupancy and operational conditions. For example, the MKEP energy consumption study analysed by Summerfield et al. (2010) presented a measured average gas based heating energy consumption, for 36 dwellings of an average size of 98m^2 floor area and of various built forms 67kWh/day as discussed earlier in Section 2.5.4. The dwellings had energy efficiency measures that corresponded with something close to the 2002 Building Regulations. This published average energy consumption was compared with the average energy demand prediction of around 68.6kWh/day generated by the TRNSYS models with 2002s thermal properties in this research, as detailed in Results Chapter 4, Section 4.5.3. The difference between these figures is approximately 2.4%. The buildings monitored by Summerfield et al. (2010) when compared with those with similar physical, thermal and occupancy conditions as used in this research, indicated that the models represent the real world reasonably well, and that the results generated are realistic.

As discussed previously in Section 2.5.4, Buswell et al. (2013) reported some results from a whole house monitoring trial in the East Midlands, England, where the heat use is disaggregated from high resolution measurements of gas, hot water and the power consumption. The heat and DHW energy consumption measured for a semi-detached and a detached dwelling monitored during the month of January are stated as 73.3kWh/day (58.6kWh/day for space heating and 14.7kWh/day for DHW) and 69.5kWh/day (56.5kWh/day for space heating and 13.0kWh/day for DHW) respectively. Both dwellings had approximately 100m^2 floor areas and a thermal insulation roughly corresponding to the 2002 building regulation. They were occupied by 4 adults and 2 children, and 1 adult and 1 child respectively. There is good agreement between the energy consumption they measured for the semi-detached dwelling and the value extrapolated from the simulated mean of 60 day results (approximately 70kWh) of similar dwelling as described in Results Chapter 4 - Section 4.5.3. The difference between the two values is about 3.3kWh (4.5%). Comparing the energy consumption values for space heating only shows a difference of about 3%.

Conversely, there is a relatively large difference, around 9%, between the measured (69.5kWh measured by Buswell et al. (2013)) and the simulated energy consumption (76kWh simulated as described in Results Chapter 4 - Section 4.5.3) for the detached dwelling. The difference is greater when the space heating only figures are compared and is about 15%. One possible explanation for this is that the measurements were taken on a relatively warm day when less heat was needed. The fact that a higher energy consumption was measured for the semi-detached in comparison to that of the detached building, contrary to the generally accepted view that detached dwellings are less energy efficient, can be said to support this assumption. Despite the large difference, it is still well within the minimum and maximum energy consumption variation usually seen, and also simulated in during this work, due to the ambient temperature variation expected over a winter period, which is 60 days from 2nd January in this work.

In summary, the heat demand prediction generated by the models used in this work and the measured data published by Buswell et al. (2013) and Summerfield et al. (2010) as discussed above are in relatively good agreement. Considering the similar size and thermal property parameters used in the models compared to those of the buildings from which the measured data was collected provide confidence in the validity of the results.

3.6 Task 2: Understanding the thermal performance characteristics of domestic buildings.

The results relating to this research task is presented in Chapter 4

3.6.1 Overview

This research task, carried out without the use of TES systems, has two parts;

1. **Base Case - Heat demand and thermal performance characteristics of domestic buildings**: comprised of simulating twelve building archetype models with key energy consumption and thermal condition influencing factors such as thermal insulation level, size, occupancy and operational condition scenarios. Characteristic predictions were generated relating to the DHW and space heating power demand, energy consumption, thermal condition of the occupied space and the heating energy cost predictions.

2. **Impacts of varying thermal insulation, heating habits, location and occupancy:** involved generating characteristic predictions with the main energy consumption influencing parameters used in the Base Case models changed to those commonly found in the UK. The changes include the use of 4 building thermal insulation levels, 4 heating durations, 4 thermostat settings, 2 locations and 2 occupancy scenarios.

3.6.2 Base Case: Model and simulation configuration

It is essential to gain an appreciation of the thermal and energy performance characteristics of the most typical domestic buildings in the UK with commonly accepted occupancy and operational conditions. The findings could be used as the Base Case performance characteristics. The impacts of changing building thermal performance and energy consumption driving variables could then be investigated by comparing the results with the Base Case characteristics. It was considered appropriate to produce the Base Case performance characteristics based on twelve dwelling archetypes comprising of four built forms and three sizes. These were simulated with commonly accepted occupancy and operational conditions, and performance predictions generated. The performance impacts due to changes in variables such as insulation, location and thermostat set-points are then generated and compared as described later in Section 3.6.3. This approach required twelve dwelling archetype models (Building Archetype IDs) to be simulated with a set of commonly accepted occupancy and operational condition variables, forming twelve Base Case scenarios (Base Case 1 to Base Case 12) as shown in Table 3-10.

Table 3-10. Attributes used in generating predictions of thermal conditions, DHW and space heating power and energy demands, and heating energy costs for a Base Case scenarios comprising of a detached building archetype and common occupancy and operational conditions.

Heat demand and space condition analysis of UK domestic buildings												
Base Case Name	Base case 1	Base case 2	Base case 3	Base case 4	Base case 5	Base case 6	Base case 7	Base case 8	Base case 9	Base case 10	Base case 11	Base case 12
Building Archetype ID	Det70	Det90	Det150	SDet70	SDet90	SDet150	MTer70	MTer90	MTer150	Flat70	Flat90	Flat150
Building Built form & Size Variables	Detached 70m^2	Detached 90m^2	Detached 150m^2	Semi-detached 70m^2	Semi-detached 90m^2	Semi-detached 150m^2	Mid-terrace 70m^2	Mid-terrace 90m^2	Mid-terrace 150m^2	Flat 70m^2	Flat 90m^2	Flat 150m^2
1. Building regulation	1990											
2. Thermostat setting	21°C											
3. Heating duration	9 hours											
4. Location	Gatwick											
5. Occupancy	Type B (2 adults & 1 child)											
6. DHW consumption	53lt/person/day Spread equally during daytime occupied hours											
7. Internal gain	TV, Cooker, Lighting, Occupant											
8. HVAC System	As per Figure 3-10											
9. Simulation period	60 days from 2nd January											
10. TES Intervention	None											
11. TES water temperature	n/a											
12. Demand Shift Period (DSP)	n/a											

Note: The Base Case ID correspond to the respective dwelling built form type and floor area size, for example Det70 refers to a model comprising of a detached building with a floor area value of 70m^2.

The block diagram in Figure 3-18 illustrates the model configuration. Nine variables have been considered for the Base Case simulations and their values are as defined in Table 3-10, and were chosen to reflect:

1) The average state of the current BER rating which largely conforms to the 1990 (Variable 1) building regulation (see Section 3.5.4)
2) Dwelling built forms which are often used by researchers due to their higher heat energy consumption (see Section 3.5.4).
3) The average floor area of the UK housing stock which is approximately 90m^2 (see Figure 3-4(a) in Section 3.5.4).
4) The location of Gatwick (Variable 4) near the city of London where a large concentration of dwellings exist (see Section 3.5.5)
5) Commonly accepted heating duration (Variable 3) of 9 hours (07:00 – 09:00 and 16:00 – 23:00) per day.
6) A thermostat setting (Variable 2) of 21℃ as per the BREDEM assumptions (see a Section 3.5.6)
7) A household size (Variable 5) which is in line with the average household size of 2.3persons/household (See Section 2.3.3)
8) A DHW consumption (Variable 6) of 53lt/person/day which correspond with the average DHW consumption in the UK (See Section 3.5.6)
9) The internal gains (Variable 7) that are most energy and thermal comfort influencing (See Section 3.5.6)
10) The heating system configuration (Variable 8) that reflect a standard wet central heating system comprising of radiator/convector heat emitters but with mains electricity powered water heater (see Section 3.5.7)
11) A simulation period (Variable 9) that represent 60 winter days when the demand for DHW and space heating energy is at its highest (See Section 2.2.3)

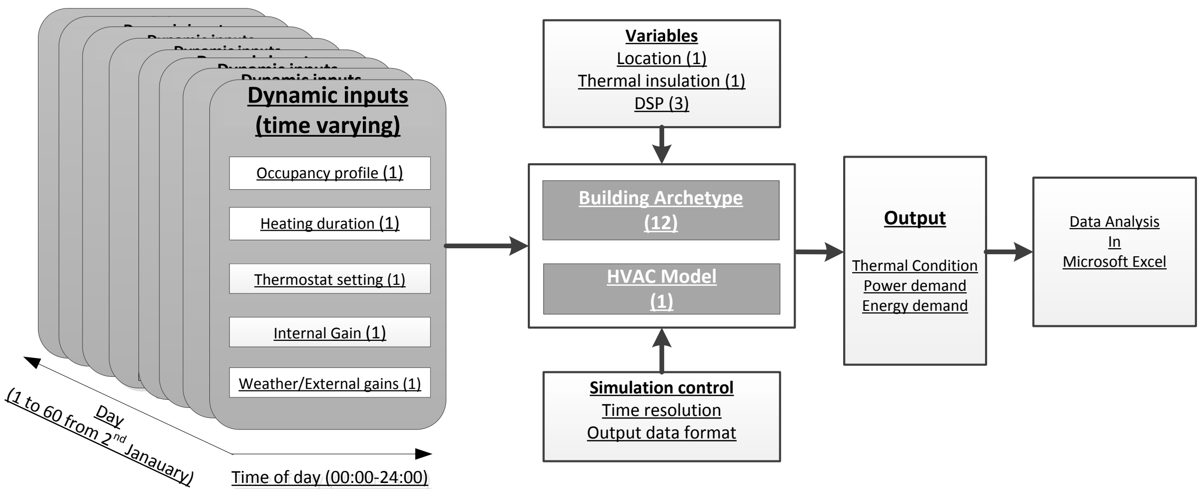


Figure 3-18. Model configuration used for generating heat energy demand predictions for the Base Case scenarios comprising of 12 building archetypes and common occupancy and operational conditions.

Simulation output

Predictions are generated for three output types: 1) thermal condition of the occupied spaces; 2) the heating load power, and 3) energy demand, as previously described in Section 3.5.9, and is further described in more details in Section 4.2.

The heat energy consumed per hour during the evening occupied periods from 17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00 is extracted from the output data. These could provide a basis from which the functional characteristic requirement of TES systems could be determined, taking into account the effects of the differences in dwelling type, occupancy and operational conditions.

The daily heating energy consumption predictions are multiplied by the current electricity price charged by British Gas Plc. to generate heating cost prediction for the respective Base Case scenario.

Simulation is carried out for 60 winter days from the 2nd of January, when heat demand is usually at its highest. The output data was recorded in text and graphical formats. Microsoft Excel was used to analyse the data to extract information relating to the three areas of model performance and the seven performance metrics as described in Section 3.5.9, which are relevant to answering the research questions.

3.6.3 Impacts of varying thermal insulation, occupancy and operational conditions

The UK housing stock is diverse with varying thermal performance determining factors, and can be occupied at different times by varying number of people with different social and behavioural backgrounds. The result often can be fluctuating levels of energy demand and demand profiles for dwellings with similar or identical physical character. The overall energy demand and the demand response in domestic buildings result from the combined interaction of these determinants. Better understanding of the impact of these determinants is necessary to enable easier pursuance of the wider energy demand reduction in dwellings, and the future ability to manage the heat demand response in buildings through the use of thermal energy storage. This work attempted to achieve this by exploring, through dynamic simulation, the impact on the heat energy demand and the thermal performance characteristics of the most common dwelling in the housing stock (represented by the twelve Base Case building models), and changes in five key energy consumption influencing factors which include: 4 building thermal insulation levels, 4 heating durations, 4 thermostat settings, 2 locations and 2 occupancy scenarios.

As in the Base Case scenarios, nine simulation variables have been considered during this analysis, and their arrangements are detailed in Table 3-11. The differences in the values used for variables 1 to 5 are illustrated by the underlined bold text. To ensure that the impacts of these changes can be compared with the Base Case, only one variable was changed during each simulation whilst the rest remained as per the Base Case settings. For example, to explore the impact on the detached dwelling by a thermal insulation variable change from the 1990 building regulation level to 2002 building regulation level (variable 2), only this variable in the detached dwelling building model was changed accordingly and all others (3 to 11) kept as per the Base Case values, and a new simulation performed. Therefore, the differences in the output performance predictions of the Base Case simulation and the new simulation could be unambiguously taken as the result of the change made to the thermal insulation level, and appropriate conclusions made on its impact.

Table 3-11. Attributes used in generating predictions of thermal conditions, DHW and space heating power and energy demands, and heating energy costs for common UK buildings with varying thermal insulation, size, location, occupancy and operational conditions.

Heat demand and space condition analysis of UK domestic buildings												
Base Case name	Base case 1	Base case 2	Base case 3	Base case 4	Base case 5	Base case 6	Base case 7	Base case 8	Base case 9	Base case 10	Base case 11	Base case 12
Building Archetype ID	Det70	Det90	Det150	SDet70	SDet90	SDet150	MTer70	MTer90	MTer150	Flat70	Flat90	Flat150
Building Built form & Size Variables	Detached 70m²	Detached 90m²	Detached 150m²	Semi-detached 70m²	Semi-detached 90m²	Semi-detached 150m²	Mid-terrace 70m²	Mid-terrace 90m²	Mid-terrace 150m²	Flat 70m²	Flat 90m²	Flat 150m²
1. Building regulation	**<u>1980,</u>** 1990**<u>, 2002, 2010</u>**											
2. Thermostat setting	Gatwick**<u>, Aberdeen</u>**											
3. Heating duration	**<u>16 hours, 12 hours</u>** ,9 hours**<u>, 6 hours</u>**											
4. Location	**<u>19°C</u>**, 21°C**<u>, 23°C</u>**											
5. Occupancy	2 adults & 1 child (Type B)**<u> ,1 adult, (Type A)</u>**											
6. DHW consumption	53lt/person/day Spread equally during daytime occupied hours											
7. Internal gain	TV, Cooker, Lighting, Occupant											
8. HVAC System	As per Figure 3-10											
9. Simulation period	60 days from 2nd January											
10. TES Intervention	None											
11. TES water temperature	n/a											
12. Demand Shift Period (DSP)	n/a											

Note: The Building Archetype ID correspond to the respective dwelling built form type and floor area size, for example Det70 refers to a model comprising of a detached building with a floor area value of 70m².

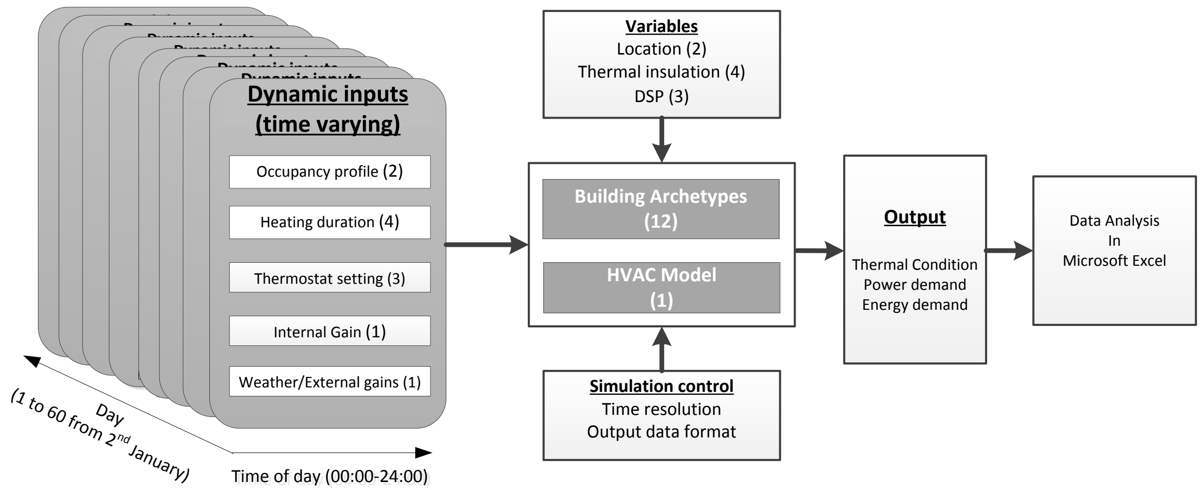


Figure 3-19. Illustration of model configuration used for generating heat energy demand predictions of common UK domestic buildings with varying physical, thermal, occupancy and operational conditions, brackets showing the number of variables within the respective parameter.

The block diagram in Figure 3-19 illustrates the model configuration and the variables within the main simulation parameters. As shown in Table 3-11, the thermal insulation changes related to the levels recommended by the 1980, 2002 and 2010 Building regulations. The physical sizes or useful floor area considered are 70m^2 and 150m^2. Aberdeen in Scotland was used as the second location. Two heating system thermostat settings (19℃, 23℃) and three heating durations (16 hours, 12 hours, 6 hours) were used. The occupancy was changed to just one adult (Type A) as previously described in Section 3.5.6.

Simulation output

The model output predictions generated were as per the Base Case simulations as previously described Section 3.5.9 and Section 3.6.2. The output variables are also described in the results chapter (Chapter 4).

3.7 Task 3: Impacts and benefits of domestic HDS using sensible TES

The results relating to this research task is presented in Chapter 5

3.7.1 Overview

This research task involved carrying out two actions: 1) Zero TES Case simulations performed on the 12 Base Case archetypes with the heating system switched off during three fixed DSPs and no TES applied, and 2) TES Reference Case simulations performed on the 12 Base Case archetypes to simulate HDS for three fixed DSPs, from the grid peak time between 17:00 – 21:00 to an off peak time of 00:00 to 07:00, with a TES Reference Case level of thermal storage applied.

The DSPs were 2 hours, 3 hours and 4 hours each starting from the time of 17:00. The HDS was realised by integrating an active sensible TES system model options into the standard heating system model and supplying heat into the buildings from the TES during the DSPs. The temperature of the **occupied space was allowed to deteriorate during the shift periods** as the stored heat was used up.

Predictions of the effects of the HDS on the overall energy consumption, heating power demand and the temperature of the occupied space were generated. The heating cost predictions were calculated based on the currently available Time-of-Use electricity price tariffs.

3.7.2 Model configuration and simulation arrangement

This analysis explores the impact of: firstly, avoiding heating the building during the DSPs without applying any TES and, secondly, shifting the heat energy demand in time from the mains grid peak period to an off-peak period through the use of rechargeable active sensible TES. Table 3-12 illustrate the variables utilised during this analysis and how these compare with the Base Case simulation as described previously in Section 3.6.2. The variables changed are highlighted by the bold underlined text.

Figure 3-20 illustrate the configuration and arrangement of the various parts of model including buildings archetypes, heating system and the operational parameters. The buildings, occupancy and operational conditions used are described in Section 3.6 and also summarised in Table 3-12. The heating system incorporating the TES tank (see Figure 3-13) as previously discussed in Section 3.5.8 is configured to heat the water to 75℃. Tank size was setup to have 0.25m^3 (250litre) of water storage capacity. During charging, the water is heated to the required temperature during 00.00 to 07.00 each day, and no further heating of the water outside this period is allowed. During discharging, the hot water in the TES system circulates through the intermediate loop and the heating loop for servicing the DHW and space heating needs, as described in Sections 3.5.7 and Section 3.5.8.

Table 3-12. Variable settings used in generating predictions of the impacts of heat demand shifting using active sensible TES, and how the impacts change with varying parameters including built form, thermal insulation, occupancy, operational conditions and TES capacity.

Heat demand shift analysis of UK domestic buildings – Simulations scenario options			
	Base Case	Zero TES Case	TES Reference Case
Archetypes used	12	12	12
1. Building regulation	1990	1990	1990
2. Thermostat setting	21°C	Gatwick	Gatwick
3. Heating duration	9 hours	9 hours	9 hours
4. Location	Gatwick	21°C	21°C
5. Occupancy	2 adults & 1 child	2 adults & 1 child (Type B)	2 adults & 1 child (Type B)
6. DHW consumption	53lt/person/day Spread equally during daytime occupied hours	53lt/person/day Spread equally during daytime occupied hours	53lt/person/day Spread equally during daytime occupied hours
7. Internal gain	TV, Cooker, Lighting, Occupant	TV, Cooker, Lighting, Occupant	TV, Cooker, Lighting, Occupant
8. HVAC System	As per Figure 3-10	As per Figure 3-13	As per Figure 3-13
9. Simulation period	60 days from 2nd January	60 days from 2nd January	60 days from 2nd January
10. TES Intervention	None	None	0.25m³
11. TES water temperature	n/a	n/a	75°C
12. Demand Shift Period (DSP)	n/a	2 hours: 17:00-19:00 3-hours: 17:00-20:00 4-hours: 17:00-21:00	2 hours: 17:00-19:00 3-hours: 17:00-20:00 4-hours: 17:00-21:00
13. TES Top-up Period (TTP)		n/a	00:00 – 07:00

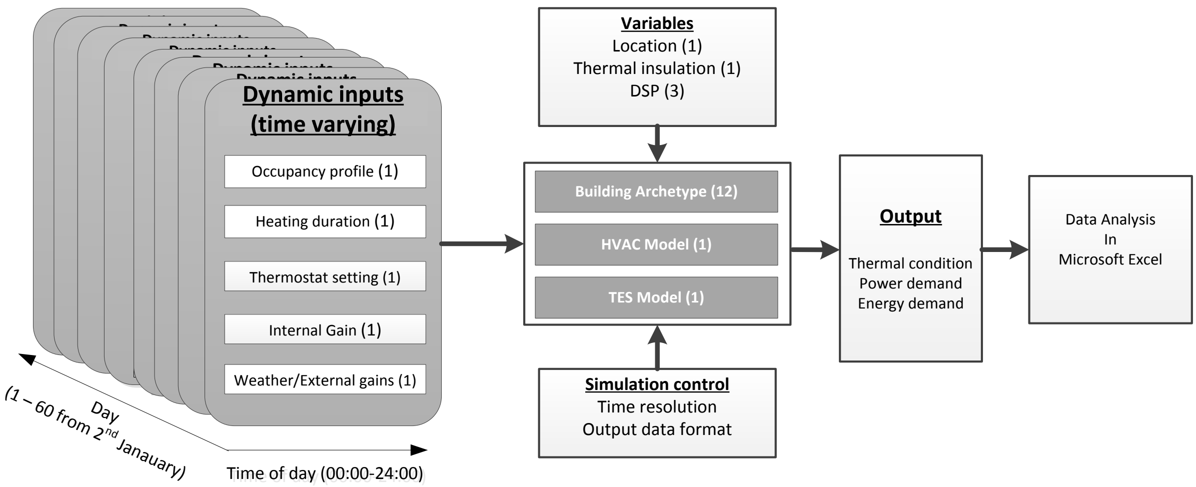


Figure 3-20. Illustration of model configuration used for simulating the heat energy demand generating heat energy demand predictions of common UK domestic building with varying physical, thermal occupancy and operational conditions, brackets showing the number of variables within the respective parameter.

Two groups of simulations were performed which are:

1. **Zero TES Case:** Simulations are performed on the Base Case scenarios with a 9 hour heating duration and a 21°C thermostat setting, and with the heating system switched off during the three DSPs (17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00) and without activating the TES system. The aim of this was to gain an insight into how and to what extent the occupied space thermal conditions in the most common housing scenarios in the UK would deteriorate if HDS was applied without TES. The results would enable comparisons to be made of the impacts of HDS with and without TES, and how these impacts change with factors such as built form and building size.

2. <u>**TES Reference Case:**</u> The TES Reference Case predictions are generated by simulating the Base Case scenarios with typical occupancy and operational conditions, and with three DSPs (17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00), a 0.25m^2 TES store and a water storage temperature of 75℃. (See Table 3-12). The aim of this was to generate a set of reference predictions of the thermal condition, energy and power demands based on a TES intervention which can be relatively easily implemented in most homes. The results would enable comparisons to be made of the impacts of HDS with and without TES of different heat storage capacity and varying DSP durations, and how these impacts could change with critical factors such as thermal insulation and thermostat set-point.

During the Zero TES simulations, the TES was not charged up at all, and no heat was supplied to the radiator during the DSP. The only heat delivered into the space during the DSP was the heat stored in the radiators due to their thermal mass.

The HDS is achieved by serving both the DHW and the space heating needs during the DSPs using heat stored in the TES. During the DSPs the occupied space receives heat only from the TES store, even when it has been depleted and not able to sufficiently maintain the temperature at the thermostat set point. This results in the occupied space temperature to drop below the thermostat set-point and degrade thermal comfort. The duration and the magnitude of the degradation are dependent on the TES capacity and the rate at which heat is lost from the building through the building fabric, and the amount of DHW used during the DSP. The heating system is only allowed to use energy from the mains grid to restore the occupied space and the DHW temperature to the required level at the end of the DSP.

The rationale for selecting the DSP periods as mentioned in Table 3-12 was to centre the DSPs about the middle of the national grid peak load time which is approximately 18:00 hours as previously illustrated in Figure 1-2. Demand shifting from around this time is most likely to help reduce the overall grid peak demand, peak electricity generation capacity needs and therefore benefit the daily grid load balancing efforts. Conversely, the national grid load level is lowest during the period 00:00 to 07:00 (see Figure 1-2) and therefore this is the TES Top-up Period (TTP) or recharge time, which is the preferred time to where the peak heat demand can be moved as discussed previously in Section 2.2.3.

Predictions were generated for the output variables previously described in Sections 3.5.9, and as also discussed later in Chapter 5.2. The daily heating energy consumption predictions are multiplied by the current electricity price charged by

British Gas Plc. to generate heating cost prediction. Simulations are performed for 60 winter days from the 2nd of January when heat demand is usually at its peak. A simulation time resolution of 1 minute is used. The output data was recorded in text and graphical formats. Microsoft Excel was used to analyse the data to extract information relating to the three areas of model performance and the seven performance metrics as described in Section 3.5.9, which are relevant to answering the research questions.

3.8 Task 4: Parametric analysis of the impacts of heat demand shifting using TES

The results relating to this research task is presented in Chapter 6

3.8.1 Overview

This research task involved simulating the impacts of the TES capacity, building insulation, occupancy and the operation conditions changing from the TES Reference Case. Four building archetype models are used which correspond to the mean floor area of the UK housing stock, of approximately 90m^2, and the four most common built forms which are detached, semi-detached, mid terrace and purpose built flats. The TES capacity variation included changing the physical size and the water storage temperature. The values selected are: 1) Three TES tank sizes (0.25m^3, 0.5m^3 and 0.75m^3) and 2) Two hot water storage temperatures (75℃, 95℃). Five parameters are varied in this exercise to account for building insulation, occupancy and operational condition differences commonly found in the UK. These are: 1) Thermal insulation (1980, 1990, 2002s and 2010 levels); 2) Location (London Gatwick and Aberdeen); 3) Heating duration (6 hours, 9 hours, 12 hours and 16 hours); 4) Thermostat set point (19℃, 21℃ and 23℃), and 5) Number of occupiers (one person and three persons).

As in tasks 2 and 3, predictions were generated indicating the effects of these parameter changes on the overall energy consumption, heating power demand and the thermal condition of the occupied space.

3.8.2 Model configuration and simulation arrangement

The heat demand shift achievable in buildings and its impact on thermal comfort would depend on the heat energy storage capacity of the TES and the heat loss or gain resulting from the operational conditions and the building fabric. The parameters changed to account for these are: TES capacity, building insulation, size, location, heating duration, thermostat set point and number of occupants as discussed below. Two groups of simulations are performed which are:

1. **TES capacity impacts** – The objective here was to explore and predict the effects of varying TES physical size and hot water storage temperatures on the HDS achievable, and its impacts on the thermal comfort of the occupied space, power and energy demand in comparison with the TES reference case simulations. Simulations were performed with three physical TES sizes and two water storage temperatures. The building thermal insulation, occupancy and operational parameters as per the Base Case were used. The differences in the parameters are illustrated by the underlined bold text in Table 3-13.

2. **Impacts of thermal insulation, thermostat setting, location, heating duration and occupancy** - The objective here was to explore the effects of varying building archetypes, occupancy and operational options on the thermal conditions in the occupied space and the energy consumption of the dwellings in comparison with the Base Case HDS effects. Predictions are generated with varying building thermal insulation, size, location, heating duration, thermostat settings, and occupancy in comparison with the TES Reference Case values as shown in Table 3-13.

Table 3-13. Summary of the model variable configuration used to simulate the impact of TES capacity and building thermal performance and operational conditions on heating energy demand shifting capabilities and the thermal comfort impacts in common UK buildings.

Parametric analysis - Simulations scenario options			
	TES Reference Case	TES capacity impacts	Impacts of thermal insulation, thermostat setting, location, heating duration and occupancy
Building Archetype Used	12	4 (Det90, SDet90, MTer90, Flat90)	4 (Det90, SDet90, MTer90, Flat90)
1. Building regulation	1990	1990	1980, 1990, 2002, 2010
2. Thermostat setting	Gatwick	Gatwick	Gatwick, Aberdeen
3. Heating duration	9 hours	9 hours	6, 9, 12, 16 hours
4. Location	21°C	21°C	**19°C, 21°C, 23°C**
5. Occupancy	2 adults & 1 child (Type B)	2 adults & 1 child (Type B)	2 adults & 1 child (Type B) , 1 adult (Type A),
6. DHW consumption	53lt/person/day Spread equally during daytime occupied hours	53lt/person/day Spread equally during daytime occupied hours	53lt/person/day Spread equally during daytime occupied hours
7. Internal gain	TV, Cooker, Lighting, Occupant	TV, Cooker, Lighting, Occupant	TV, Cooker, Lighting, Occupant
8. HVAC System	As per Figure 3-13	As per Figure 3-13	As per Figure 3-13
9. Simulation period	60 days from 2nd January	60 days from 2nd January	60 days from 2nd January
10. TES Intervention	0.25m^3	0.25m^3, 0.5m^3, 0.75m^3	0.25m^3
11. TES water temperature	75°C	75°C, **95°C**	**75°C**
12. Demand Shift Period (DSP)	2 hours: 17:00-19:00 3-hours: 17:00-20:00 4-hours: 17:00-21:00	2 hours: 17:00-19:00 3-hours: 17:00-20:00 4-hours: 17:00-21:00	4-hours: 17:00 - 21:00
13. TES Top-up Period (TTP)	00:00 – 07:00	00:00 – 07:00	00:00 – 07:00

Figure 3-21 illustrate the configuration and arrangement of the various parts of the model including buildings archetypes, heating system and the operational parameters. The buildings, occupancy and operational conditions used are summarised in Table 3-13. The HVAC and the TES systems are configured as described previously in Section 3.5.7 and Section 3.7.2. During the TES charging, the water is heated to the required temperature during 00.00 and 07.00 hours each day, and no further heating of the water outside this period is allowed. The discharging of the TES occurs during the DSP when the hot water in the TES system circulates through the heating system servicing the DHW and space heating needs. The heating system switches to the mains grid at the end of the DSP, and restore the space temperature to the desired set point.

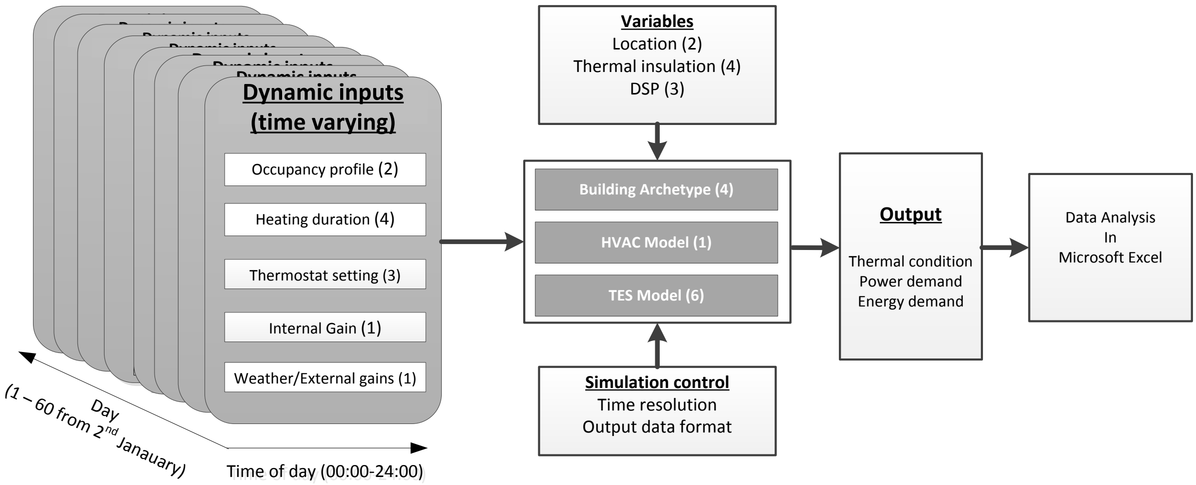


Figure 3-21. Illustration of model configuration used for carrying out parametric analysis of the impacts of varying TES storage capacity and the building thermal insulation, location, heating duration, thermostat set point and occupancy.

As described in Section 3.7, the HDS is achieved by serving both the DHW and the space heating needs during the DSP using heat energy stored in the TES. The real-time occupied space heating period does not change from the original setting. The rational for selecting 17:00 as the start of the DSP is that the national grid load starts to rise at around this time and peaks shortly after, at around 18:00.

To ensure that the impacts of these changes can be compared, only one variable was changed during each simulation whilst the rest remained as per the TES Reference Case setting as explained previously in Section 3.7.2. Predictions were generated for the output variables previously described in Sections 3.5.9, and as also discussed later in Chapter 6.2. As before, simulations are performed for 60 winter days from the 2nd of January and with a time resolution of 1 minute. Also as before, the output data was recorded in text and graphical formats and Microsoft Excel was used to extract information relating to the three areas of model performance and the seven performance metrics as described in Section 3.5.9.

3.9 Summary

This research work is based on three research questions: **1)** What are the dynamics of heat demand in buildings and how do they vary with building typologies, fabric thermal insulation, occupancy and operational conditions?; **2)** What is the scope of heat demand shifting in time by using residential building scale TES, and what are the key parameters which impact on their effectiveness?, and **3)** What are the potential benefits and impacts of using residential building scale TES?

This chapter outlined the methodology used in carrying out four research activities to explore the answers to these questions, as summarised below:

1) Task 1: model development and validation – consisting of producing twelve Base Case building archetype models incorporating wet central heating systems powered by resistance element heating and sensible TES systems in TRNSYS. To ensure validity of the models and plausibility of the results, validation exercises were carried out through inter model comparison, and by comparing the results generated in this work with published measured data for similar buildings and operational conditions;
2) Task 2: simulations performed to analyse the energy consumption, heating energy cost and the thermal performance characteristic of most common building, occupancy and operational options found in the UK housing sector, without Thermal Energy Storage (TES) and heat demand shifting.
3) Task 3: simulations performed to generate predictions of heat energy demand shift using active sensible TES, from the grid peak times to the grid off-peak times by three fixed durations (2 hours, 3 hours and 4 hours), and the related impacts and benefits.
4) Task 4: simulations performed to simulate how the effectiveness of TES and its impacts changes with varying parameters such as TES capacity, building thermal insulation, physical, occupancy and operational conditions.

4 CHAPTER FOUR RESULTS – THERMAL PERFORMANCE CHARACTERISTICS OF DOMESTIC BUILDINGS

4.1 Introduction

This chapter presents the results of the simulations carried out to gain an understanding of the thermal and energy performance of domestic buildings, and how these are affected by changes in the building thermal insulation, physical, occupancy and operational conditions. No TES was applied during this activity.

This chapter is arranged as described below:

Section 4.2: Output variables and the performance analysis metrics: Provides an overview of the simulation output variables for which results are generated, and the metrics used to compare the energy and thermal performance of the different building, occupancy and operational scenarios.

Section 4.3: Demonstration of the simulated input and output variables: Provides an overview of the model performance, demonstrating and discussing: the input variables, function of the heating system, indoor temperature profiles, heating load profiles and the energy demand predictions for several sample days.

Section 4.4: Performance analysis of the Base Case buildings: Contains the results of the occupied space thermal condition, heating power and energy demand characteristic predictions for the 12 Base Case scenarios. The heating energy cost predictions based on currently available standard electricity price tariff is presented.

Section 4.5: Performance impacts of thermal insulation, thermostat setting, location, heating duration and occupancy: Contains the results of the impacts on the thermal condition, heating power and energy demand characteristic predictions due to changes in the thermal insulation level, thermostat set point, heating duration, location and occupancy variables.

Section 4.6: Provides a summary of this chapter.

4.2 Output variables and performance analysis metrics

Nine performance predictions were generated as shown in Table 4-1, relating to the areas of space temperature, power demand and energy demand. The performance predictions generated were with: a) the simulation input variables set according to the Base Case scenarios (see Table 3.11 of Section 3.6.), and b) the main energy and thermal performance influencing variables changed from the Base Case settings to represent differences in building thermal insulation, and occupancy & operational conditions found in the UK (see Table 3.12 of Section 3.6).

Simulations were performed for 60 winter days from the 2nd of January, and outputs were generated at a time resolution of one minute. For the output variables named

GF_T, FF_T and Amb_T, the model generated air temperature predictions. For the output variables Main_supply_load_kW, Heating_load_kW and DHW_load_kW, the models generated the power demand predictions. For the output variables Mains_supply_kWh, Heating_only_kWh and the DHW_only_kWh, the models generated the heat energy demand predictions. The data was analysed in Microsoft Excel to produce the daily maximum, minimum and the 60 day average daily mean temperature and heating power demand predictions. Daily average heat energy draw profiles were generated to determine and compare the energy use times.

To enable performance comparison of the simulation scenarios, six metrics were used (see Table 4-1). These were derived by averaging over the 60 day simulation period. Metrics 1 (*Daily_mean_GF_T)* and Metric 2 (*DSP_hours_mean_GF_T)* represent the mean ground floor air temperature over 24 hours and the mean air temperature of three future heat demand shift period in the evening occupied hours from 17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00. Metrics 3 and 4 (*Daily_mean_MS_power_kW* and *DSP_space_heating_power_kW)* represent the whole building daily mean mains supply power demand, and the space heating only power demand during the occupied hours from 17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00. Metrics 5 (*Daily_mean_MS_energy_kWh*) represents the whole building daily mean mains supply energy demand. Metric 6 (Daily_mean_energy_cost_£/day) represents the daily average cost of providing DHW and space heating based on the currently available (August 2015) electricity price tariff offered by one of the six major electricity suppliers in the UK, namely British Gas Plc (See Section 3.5.9). By comparing the differences between these metrics it was possible to identify the differences in performance and the effects of the changes in the input variables.

Table 4-1. Performance analysis variables used and the corresponding data generated, recorded and analysed for extracting the relevant heat demand and thermal comfort information.

Performance analysis	Output variable Name	Variable description	Performance analysis metrics
Space temperature	1. GF_T	Ground floor air temperature	1. Daily_mean_GF_T 2. DSP_hours_mean_GF_T
	2. FF_T	First floor air temperature	
	3. Amb_T	External air temperature	
Power demand	4. Mains_supply_load_kW	Whole building power demand	3. Daily_mean_MS_power_kW
	5. Heating_load_kW	Space heating only power demand	4. DSP_hours_MS_power_kW
	6. DHW_load_kW	DHW only power demand	
Energy demand	7. Mains_supply_kWh	Mains supply daily energy demand	5. Daily_mean_MS_energy_kWh 6. Daily_mean_energy_cost_£/day
	8. Space_heating_only_kWh	Heating only daily energy demand	
	9. DHW_only_kWh	DHW only daily energy demand	

Note: See section 3.5.9 for description of the output variables and the performance analysis metrics

4.3 Demonstration of the simulated input and output variables

This section demonstrates the correct functioning of the model through illustrating the forms of the key input variables applied, internal calculations performed and the output predictions generated for a Base Case simulation scenario (see Section 3.4). The function of the heating system is illustrated showing water temperature profiles at different stages. The indoor space temperature, power demand and the energy demand profile predictions are demonstrated for a number of sample days and for the overall simulation period of 60 days from the 2nd of January.

Inputs

The graphs in Figure 4-1 illustrate the main variables applied to the model which are used to generate the thermal conditions of the occupied spaces, power and the energy demand predictions. They illustrate the external ambient temperature, DHW demand, occupancy profile and the thermostat setting for a sample day in January for the Base Case archetype Det90. The ground floor temperature prediction is also included showing the morning and the evening heating periods. The 'occupancy' trace is a multiplier based on the number of occupants present in the building (occupancy Type B), and is used to calculate their internal gains and DHW consumption. During the daytime occupied hours the thermostat is set to 21℃. The DHW draw off rate applied is 5.9lt/hour/person equating to 17.7lt/hour, and only active during the daytime occupied hours, for reasons previously discussed in Section 3.5.6. The external ambient temperature, which is derived from the weather data file, is relatively low during this sample day and remains between 2℃ and 4℃. This is consistent with the low solar radiation for this day as shown in Figure 4-2.

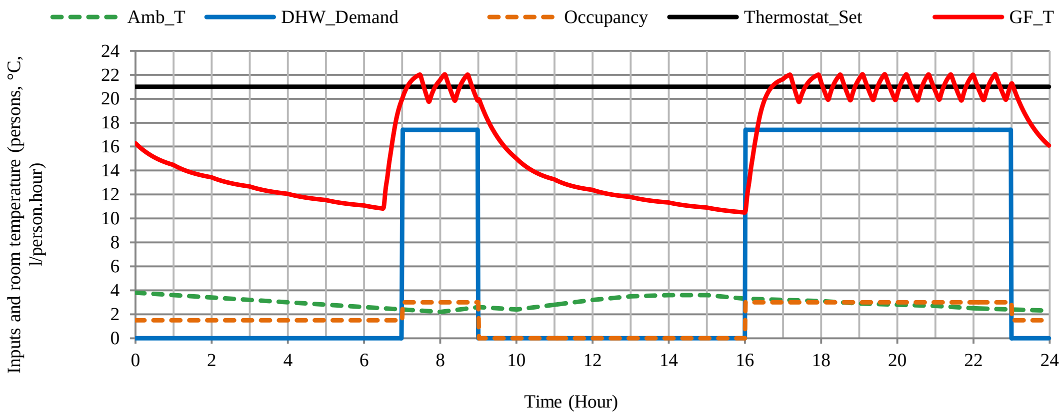


Figure 4-1. Illustration of the applied patterns of the thermostat setting, DHW demand, occupancy, ground floor room temperature and the external ambient temperature for a sample day of 6th January.

The profiles of the internal gains resulting from factors such as the heat gain from the occupiers, cooking and lighting are shown in Figure 4-2. It can be seen that the 'Internal_gain' occurs predominantly during the daytime occupied hours whilst it is minimal during the night-time. DHW (DHW_Temp) draw off also occurs during the occupied hours and at a temperature of about 52℃. These input variables in conjuntion with other Base Case scenario configurations (See Section 3.6) define the occupied space thermal condition and the heating load profile characteristics.

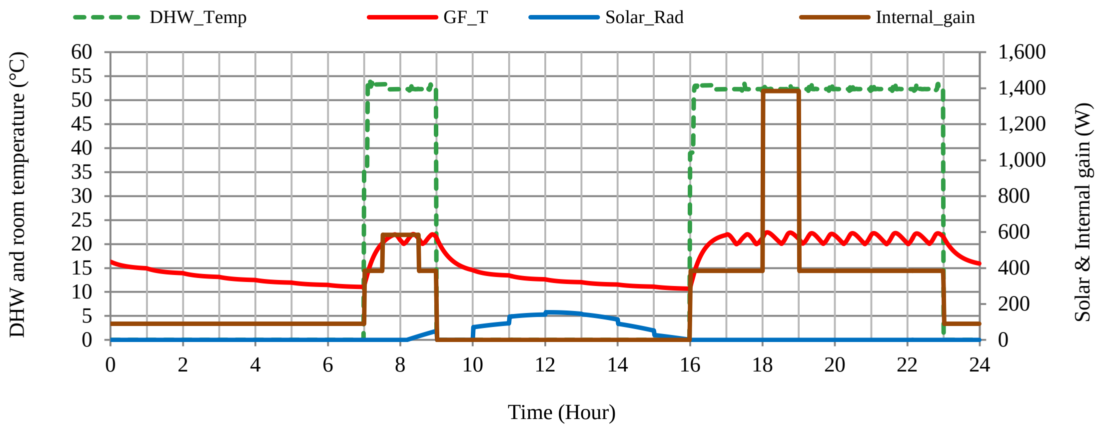


Figure 4-2. Illustration of the profiles of the internal gain (combined gains from occupants, cooking, lighting and TV), solar radiation and DHW supply temperature shown for January 6th.

Heating system operation

The water temperature output at the primary and the intermediate loops were set to 85℃ and 80℃ respectively, as per the HVAC system setting described in Section 3.5.7. The resulting water temperature at the radiator input (Flow_T) and the output (Return_T) are around 75℃ and 65℃, and the radiator surface temperature is about 70℃ respectively, as illustrated in Figure 4-3.

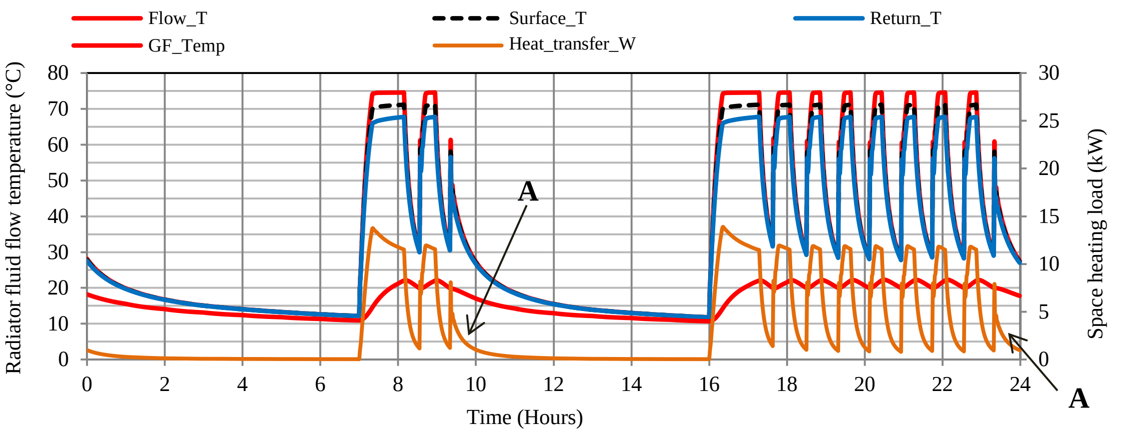


Figure 4-3. Graphs illustrating the water temperatures at: Radiator flow (Flow_T); Radiator surface (Surface_T) and Radiator return (Return_T), and the space heating load (SpaceHeatload_W) for 6th January.

The heat supplied to the occupied space through the radiators is illustrated by 'Heat_Transfer_W'. The thermal mass effect of the radiators during the heating system off periods is taken into account. The effect of this is illustrated by the gradual drop of the heat transfer even after the heating system switches off at the end of the heating period (9 am and 11 pm) as can be seen in the trace 'Heat_transfer_W' in Figure 4-3, indicated by A. It can also be seen that the surface temperature of the radiator drops as the heat is transferred into the space, and over time approaches the ambient room temperature value.

Space condition, heating power and energy demand

The daily mean, maximum and the minimum values of the space temperature, power demand and energy demand were extracted from the respective performance prediction data for all the Base Case models. Figure 4-4 shows the indoor Ground Floor (GF_T), First Floor (FF_T) and the external ambient (Amb_T) temperature

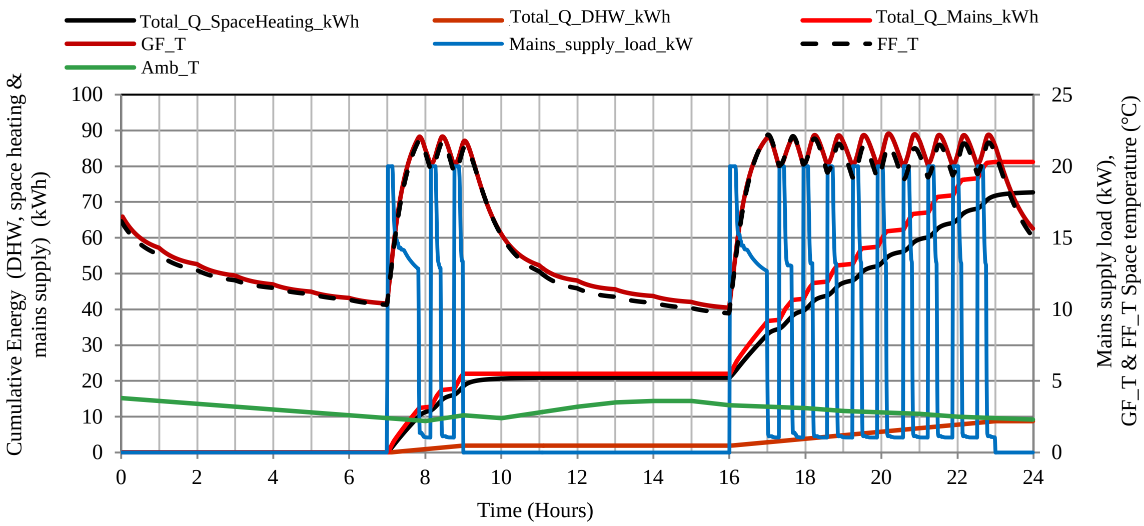


Figure 4-4. Space temperature and heating load profiles for the detached dwelling in London with a 21°C thermostat setting and a 9 hour heating duration for a sample day of 6th January.

profile predictions for a sample day in January for the Det90 Base Case archetype.

The heating of the occupied spaces can be clearly seen during the morning and evening occupied hours from 07:00 to 09:00 and 16:00 to 23:00. The temperature cycles 1℃ above and below 21℃ due to the 2℃ thermostat dead band. The mains grid power demand (Mains_supply_load_kW) for ensuring the required indoor temperature profile is shown. It cycles on and off correspondingly as the heating system cycles on and off. The mains supply load never reduces to zero even when the space heating system turns off during the heating periods, and this is due to the continuous draw off of DHW throughout these periods. As the heating system switches on at 07:00 and 16:00 the heating load peaks to the maximum value of 20kW (as shown in Figure 4-4) and the indoor space temperature begins to rise. The difference between the space and the radiator temperature becomes smaller as the space temperature gets closer to the thermostat setting, and therefore less heat transfer occurs from the radiators to the space. This results in a gradual drop in the heating load and a slow temperature rise towards the thermostat setting. Conversely, when the heating system switches off at the end of the heating periods the space temperature drops rapidly and slows down as the space temperature approaches the external ambient temperature. The mean time it takes for the ground floor space temperature to reach 18℃ (normally accepted minimum temperature for thermal comfort) is approximately 30 minutes after the heating system turns on, and 20 minutes for it to drop below 18℃ after the heating system turns off during both the morning and the afternoon heating periods (see Figure 4-4). The delayed rise and fall of the space temperatures indicates the effect of the thermal mass, resulting from the heat capacitance effect of the building components.

The cumulative mains energy consumption predictions (Total_Q_Mains_kWh), the DHW energy use (Total_Q_DHW_kWh) and the space heating energy use (Total_Q_SpaceHeating_kWh) profiles are illustrated in Figure 4-4. These are generated by integrating the corresponding power demand profile over the same time period. The flat parts with zero gradient in the Total_Q_Mains_kWh profile represents periods when no load was applied to the grid, whilst the parts with non-zero positive gradients represents periods when load was applied to the grid. The Total_Q_SpaceHeating_kWh and the Total_Q_DHW_kWh profiles in combination with the energy loss from the pipes make up the Total_Q_Mains_kWh profile.

It can be seen that the mains energy used begins to accumulate from the morning heating period start time of 07:00, and stops at 23:00 when the heating system switches off at the end of the evening heating period. The space heating energy continues to rise marginally even after the heating system has turned off due to the radiator thermal mass effect.

The final energy use for the sample day is the value reached at 24:00, and this is when the monitoring sub-routine resets for the following day.

The external ambient temperature is one key factor that dictates the nature of the temperature profile in the occupied space, and therefore the nature of the heating load profile. Figure 4-5 and Figure 4-6 show the space temperature profiles and the corresponding heating load responses for two further sample days in January when the external ambient temperature is relatively high (between 5℃ and 10℃) and relatively low (between -5℃ and 0℃). It can be seen that when the external temperature is high, the space temperature reaches the thermostat setting relatively quickly, taking about 30 minutes (Figure 4-5). The heating system, thereafter, cycles on and off during the two hour morning heating period, as the space temperature fluctuates above and below the 2℃ dead-band. As the external ambient temperature falls, the heat loss through the building fabric rises. Therefore the space temperature increases at a slower rate taking around 90 minutes, as shown in Figure 4-6, to reach the thermostat set-point. During the occupied hours the heating system cycles on and off more frequently due to the higher rate of heat loss causing the room temperature to fall quickly triggering the thermostat.

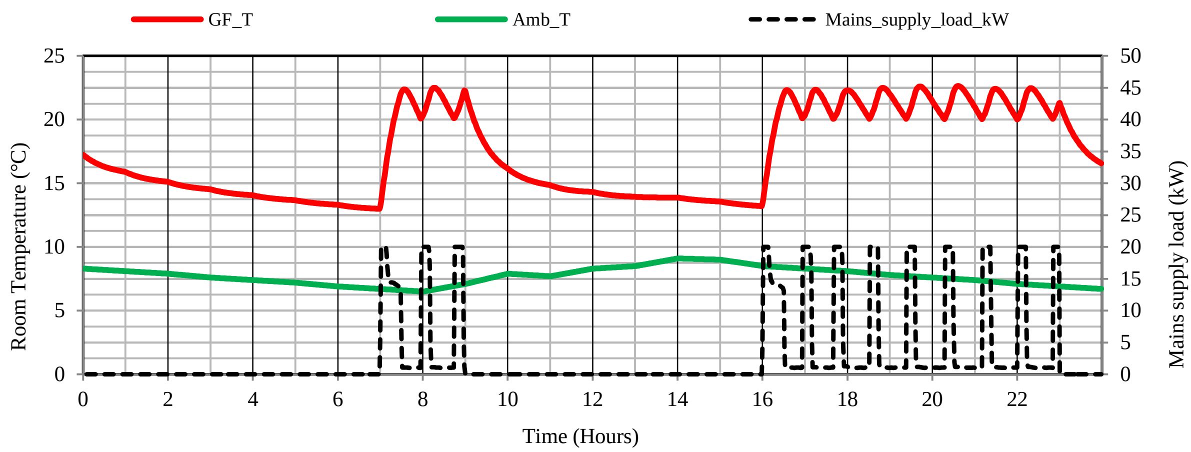


Figure 4-5. Occupied space temperature profile and the heating load profile for an example day with relatively high (between 6°C to 9°C) external ambient temperature.

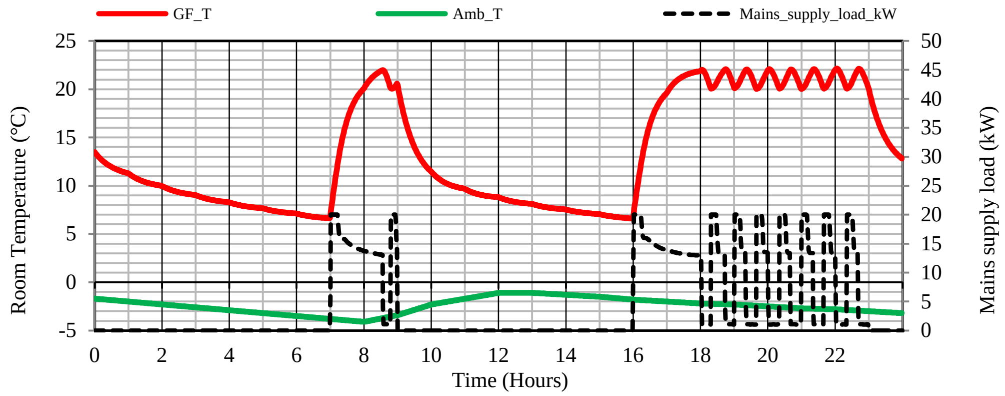


Figure 4-6. Occupied space temperature profile and the heating load profile for an example day with relatively low (between -5°C to -1°C) external ambient temperature.

Averaging over 60 days

The time series data for the 60 day simulation is split into 60 individual daily profiles and averaged to create the mean air temperature (GF_T), the mains supply power demand (Mains_supply_load_kW), DHW power demand (DHW_load_kW) and the space heating only power demand (Heating_load_kW). A sample of the average profiles generated for the Det70 Base Case is shown in Figure 4-7. The mains supply and the heating only power demand profiles average out towards the end as shown although a significant 'on/off' cycling remain. The power demand for DHW remains flat at approximately 1kW. This becomes zero outside the occupied hours as no DHW demand occurs during these periods as discussed previously in Section 3.5.7.

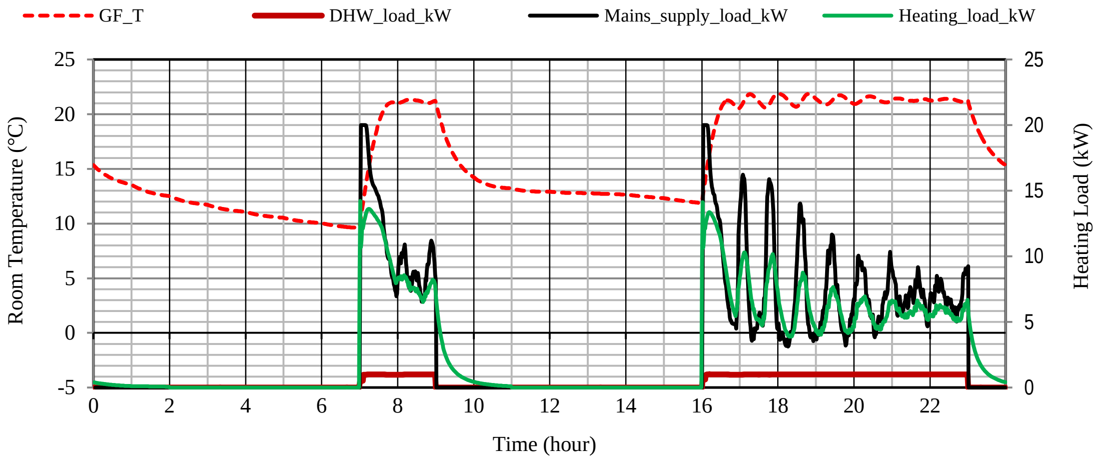


Figure 4-7. Illustration of the daily average DHW load (DHW_Load_W), Space heating load (Heating_Load_W) and Mains Supply load (Mains_Supply_Load_W) profiles for the 60 day simulation period.

Figure 4-8 shows the energy draw profile over a 24 hour period averaged over the 60 day simulation period for the Det70 Base Case archetype. The average indoor space temperature and the mains supply power demand are shown to indicate reference points. It can be seen that the whole building (or Mains Supply Energy) heating energy consumption accumulates at the end of the 24 hour period to a figure of about 77kWh. The space heating only energy demand values reaches a value of about 66kWh. The DHW energy demand was 8.82kWh. These energy consumption figures are realistic and compare well with published data as discussed in Sections 2.5.4 and 3.5.1.

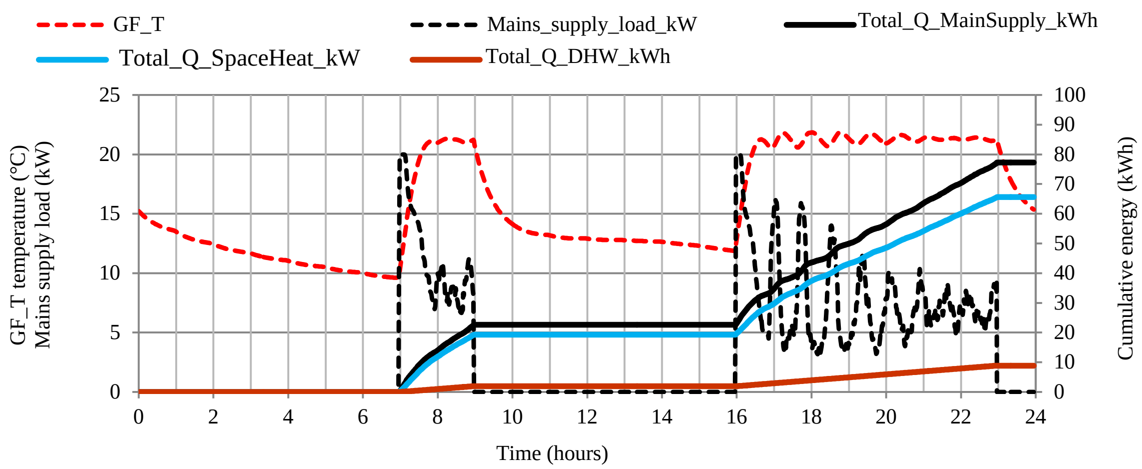


Figure 4-8. Cumulative energy consumption profile averaged over the 60 day simulation period.

Figure 4-9 illustrates the daily mean mains supply (Whole Building), space heating only and the DHW only for the 60 day simulation period from the 2nd of January for Base Case scenario Det90. It can be seen that the 'Whole building' energy consumption varies from a minimum value of 56kWh to a maximum value of about 102kWh. The lowest and the highest values of space heating only energy demands are 49.04kWh and 94.55kW. The DHW energy demand remains relatively similar for the 60 days at approximately 9.5kWh for the reason that the DHW consumption is assumed to remain constant throughout the occupied hours and over the 60 day simulation period.

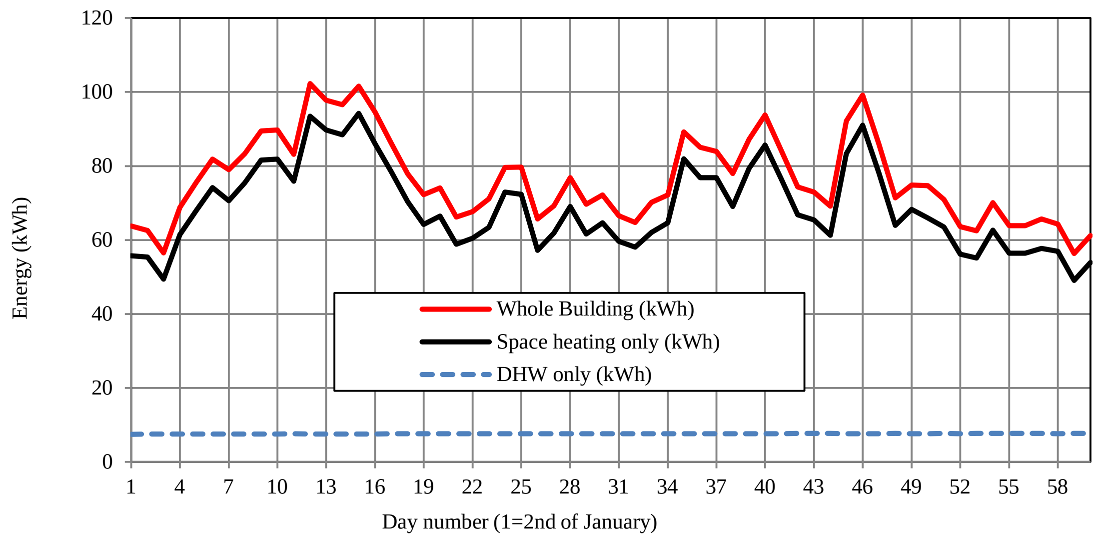


Figure 4-9. Daily average energy consumption over the 60 days relating to the whole building, space heating only and DHW only use categories, for the Base Case simulation scenario for the Det90 building archetype.

4.4 Performance analysis of the Base Case buildings

This section presents the thermal, power and energy demand characteristic predictions of the Base Case scenarios, and how the characteristic predictions change when five of the key performance influencing parameters (thermal insulation, location, heating duration, thermostat setting and occupancy) are varied. The heating energy cost predictions are also presented. The model configuration, variables and the methodology utilised is described in Section 3.6.

4.4.1 Space temperature

Table 4-2 provides the mean of the means, mean of the maximums and the mean of the minimums daily occupied space temperatures, for the twelve Base Case scenarios considered. The results are arranged by dwelling size and further categorised by built form to enable easier comparison. Temperatures are shown for all hours (00:00 to 24:00), and the three heated period (17:00-19:00, 17:00-20:00 and 17:00-21:00). Also, a summary of the temperatures are provided in Table 4-3, showing the mean of the 60 days categorised by floor sizes and the built forms considered. An overall mean of all 12 Base Case scenarios is also provided.

The room temperatures during the heated hours (Metric 2) remains within 1℃ of the thermostat set point of 21℃ (see Table 4-2 and Figure 4-10). This indicates that the heating system performed as expected, maintaining the space temperature within the required limits during the heated period. The lowest, highest and the mean temperatures averaged for all twelve of the Base Cases (see Figure 4-10) are 11.13℃, 22.53℃ and 16.65℃ respectively.

The thermal performance of the buildings, in terms of retaining heat, can be determined from the 24 hourly temperature predictions (Metric 1) as illustrated in Figure 4-11 and Table 4-3. As shown, the mean of the daily average temperatures are higher for the flats, followed by the mid terrace, then the semi-detached, and then the detached dwellings with the lowest values. The lowest temperature is 16.11℃ for the detached buildings whilst the highest is 17.16℃ for the flats. This indicates that the detached dwellings are worst for retaining heat whilst the flats are the best out of the four built forms investigated. As shown further in Figure 4-11, the average daily temperature of the 150m^2 size dwellings is about half a degree lower at 16.34℃ compared with the 90m^2 and the 70m^2 dwellings. Although the larger (150m^2)

dwellings appear to cool down more compared to the other two sizes, it is not the case when the 90m² and the 70m² dwellings are compared. The 90m² dwellings have a temperature of 16.85℃ which is marginally higher than the 70m² dwellings' value of 16.76℃. This is marginally against the trend and is most probably due to the 70m² dwellings' glazing to heated volume ratio being higher than the 90m² dwellings. For example, for Det70 it is about 9.0% compared to about 8.5% for the Det90. The space temperature is likely to be more sensitive in the smaller dwellings due to their lower thermal mass.

Table 4-2. Mean, maximum and minimum space temperature predictions for all hours and for three heated hours, averaged over 60 days from 2nd January for the 12 Base Case scenarios.

Indoor space temperature predictions for the 12 Base Case scenarios													
		All hours 00:00-24:00			Heated hours 17:00-19:00			Heated hours 17:00-20:00			Heated hours 17:00-21:00		
Size	Base Case ID	Mean (Metric 1) (°C)	Max. (°C)	Min. (°C)	Mean (Metric 2a) (°C)	Max. (°C)	Min (°C)	Mean (Metric 2b) (°C)	Max. (°C)	Min (°C)	Mean (Metric 2c) (°C)	Max. (°C)	Min (°C)
70m²	Det70	16.25	22.45	10.44	21.10	22.35	19.97	21.30	22.40	19.96	21.30	22.45	19.96
	SDet70	16.55	22.59	10.79	21.20	22.48	20.01	21.38	22.54	20.00	21.38	22.58	20.00
	MTer70	17.06	22.69	11.86	21.23	22.55	20.01	21.40	22.63	20.01	21.41	22.68	20.00
	Flat70	17.19	22.73	12.25	21.34	22.65	20.02	21.47	22.68	20.01	21.48	22.71	20.01
90m²	Det90	16.32	22.45	10.47	21.14	22.34	20.00	21.29	22.39	19.99	21.31	22.43	19.99
	SDet90	16.77	22.51	11.48	21.17	22.40	20.02	21.32	22.46	20.01	21.34	22.50	20.01
	MTer90	17.03	22.64	11.61	21.22	22.52	20.02	21.38	22.59	20.01	21.41	22.63	20.01
	Flat90	17.28	22.71	12.67	21.33	22.64	20.02	21.47	22.67	20.02	21.48	22.70	20.01
150m²	Det150	15.76	22.34	8.96	21.05	22.24	19.98	21.21	22.29	19.97	21.24	22.33	19.97
	SDet150	16.15	22.36	10.03	21.06	22.27	20.01	21.23	22.31	20.00	21.25	22.34	20.00
	MTer150	16.43	22.40	10.69	21.11	22.31	20.02	21.24	22.35	20.01	21.26	22.38	20.01
	Flat150	17.02	22.43	12.34	21.17	22.38	20.02	21.31	22.41	20.02	21.31	22.42	20.01

Note
Metric 1: Daily_mean_GF_T (daily mean ground floor space temperature averaged over 60 days)
Metric 2(a,b,c): DSP_hours_mean_GF_T (DSP mean temperature averaged over 60 days where: a=17:00-19:00, b=17:00-20:00, c=17:00-19:00)

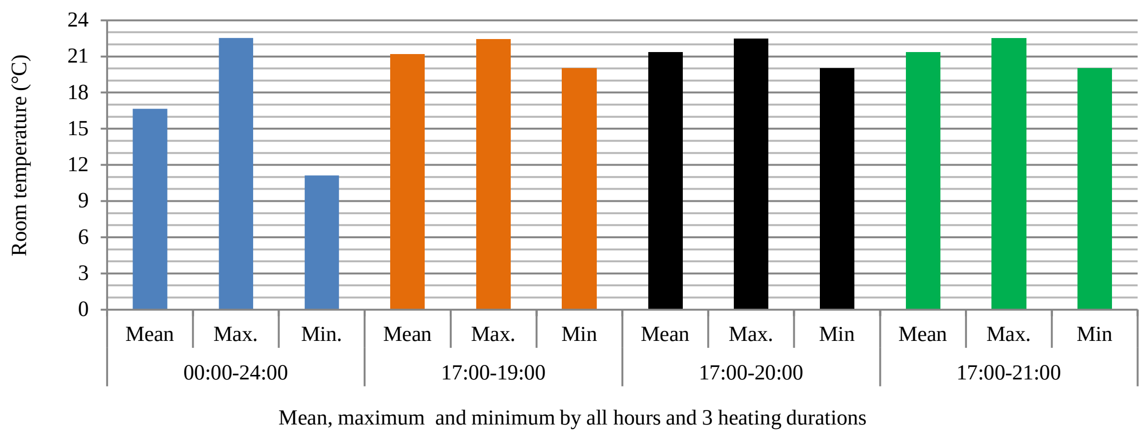


Figure 4-10. Overall average of the mean, maximum and minimum indoor temperature predictions for all 12 Base Cases by all hours (00:00 to 24:00) and for the three heated periods (17:00-19:00, 17:00-20:00 and 17:00-21:00).

Table 4-3. Mean, maximum and minimum space temperature predictions for all hours and for three heated hours categorised by dwelling size, built form and the overall average of all the scenarios.

		All hours 00:00-24:00			Heated hours 17:00-19:00			Heated hours 17:00-20:00			Heated hours 17:00-21:00		
Arche-type variable	Value	Mean (Metric 1) (°C)	Max. (°C)	Min. (°C)	Mean (Metric 2a) (°C)	Max. (°C)	Min (°C)	Mean (Metric 2b) (°C)	Max. (°C)	Min (°C)	Mean (Metric 2c) (°C)	Max. (°C)	Min (°C)
Size	$70m^2$	16.76	22.62	11.34	21.22	22.51	20.00	21.39	22.56	20.00	21.40	22.60	19.99
	$90m^2$	16.85	22.58	11.56	21.22	22.47	20.02	21.37	22.53	20.01	21.38	22.57	20.00
	$150m^2$	16.34	22.38	10.50	21.10	22.30	20.01	21.25	22.34	20.00	21.26	22.37	20.00
Built form	Detached	16.11	22.41	9.96	21.09	22.31	19.98	21.27	22.36	19.98	21.28	22.40	19.97
	Semi detached	16.49	22.49	10.76	21.15	22.39	20.01	21.31	22.44	20.01	21.32	22.47	20.00
	Mid terrace	16.84	22.58	11.39	21.19	22.46	20.02	21.34	22.52	20.01	21.36	22.56	20.01
	Flat	17.16	22.63	12.42	21.28	22.56	20.02	21.42	22.58	20.02	21.42	22.61	20.01
Overall average of all 12 Base Cases		16.65	22.53	11.13	21.18	22.43	20.01	21.33	22.48	20.00	21.35	22.51	20.00

Note

Metric 1: Daily_mean_GF_T (daily mean ground floor space temperature averaged over 60 days)

Metric 2(a,b,c): DSP_hours_mean_GF_T (DSP mean temperature averaged over 60 days where: a=17:00-19:00, b=17:00-20:00, c=17:00-19:00)

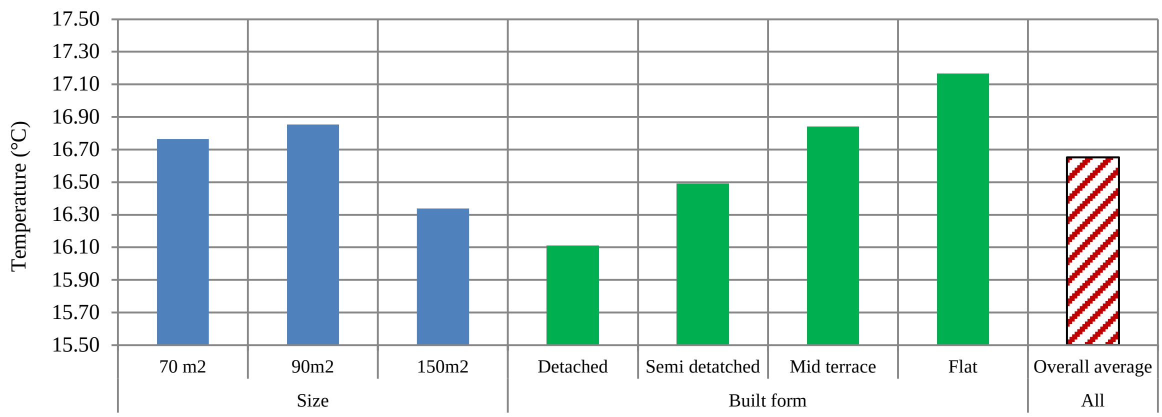


Figure 4-11. Mean of the daily average space temperature predictions for all hours (00:00 to 24:00) indicating how changes due to variations in dwelling size and built form. Overall average of all the Base Case scenarios is provided for comparison..

4.4.2 Power demand

The mean of the means, mean of the maximums and the mean of the minimum power demand predictions for the mains supply for all hours (00:00 to 24:00) and the space heating only power demand during the three heated hours (17:00-19:00, 17:00-20:00 and 17:00-21:00) are provided in Table 4-4. The results are organised by floor area to enable easier comparison. Average power demand predictions of all the Base Case scenarios are also presented in Table 4-5.

The maximum power demand over all hours varies from 20kW to 30kW, and is due to the maximum power rating of the water heater. The minimum power is zero when the heating system is not in use. The mean power demand values in the tables are averages of the relevant time periods, and are not the instantaneous power demand, which can be as high as the power rating of the water heater. Therefore, it may be more appropriate to use the average power demand data to appreciate the general direction the power demand takes as a result of the differences in the building archetypes. Obviously, the archetypes which have higher average power demand are likely to have higher overall heating energy consumption as well.

Table 4-4. Mean, maximum and minimum power demand for the whole building over all hours, and for space heating power demand for the three heated hours, averaged over 60 days from 2nd January for the 12 Base Case scenarios

		Mains Supply			Space heating only								
		All hours 00:00-24:00			Heated hours 17:00-19:00			Heated hours 17:00-20:00			Heated hours 17:00-21:00		
Size	Base Case ID	Mean (Metric 3) (kW)	Max. (kW)	Min. (kW)	Mean (Metric 4a) (kW)	Max. (kW)	Min (kW)	Mean (Metric 4b) (kW)	Max. (kW)	Min (kW)	Mean (Metric 4c) (kW)	Max. (kW)	Min (kW)
70m²	Det70	2.79	20.00	0.00	5.82	9.15	3.70	5.38	9.15	2.91	5.16	9.15	2.91
	SDet70	2.57	20.00	0.00	5.09	8.73	3.22	4.74	8.73	2.79	4.55	8.73	2.79
	MTer70	2.33	20.00	0.00	4.49	8.34	2.33	4.21	8.34	2.33	4.05	8.34	2.33
	Flat70	2.19	20.00	0.00	4.07	7.56	1.59	3.85	7.56	1.59	3.79	7.56	1.59
90m²	Det90	3.44	25.00	0.00	7.33	12.36	3.98	6.83	12.36	3.98	6.57	12.36	3.98
	SDet90	3.16	25.00	0.00	6.52	10.85	3.68	6.10	10.85	3.68	5.91	10.85	3.68
	MTer90	2.89	25.00	0.00	5.76	10.95	2.82	5.44	10.95	2.82	5.24	10.95	2.69
	Flat90	2.64	25.00	0.00	5.00	10.17	1.84	4.85	10.17	1.84	4.76	10.17	1.84
150m²	Det150	4.92	30.00	0.00	10.77	18.06	5.48	10.00	18.06	5.48	9.62	18.06	5.48
	SDet150	4.71	30.00	0.00	9.96	16.92	4.88	9.55	16.92	4.88	9.18	16.92	4.88
	MTer150	4.50	30.00	0.00	9.52	16.06	4.79	9.04	16.06	4.75	8.67	16.06	4.75
	Flat150	4.92	30.00	0.00	10.77	18.06	5.48	10.00	18.06	5.48	9.62	18.06	5.48

[a] Metric 3: Daily_mean_MS_power_kW (Whole building daily mean mains supply power demand)
[b] Metric 4(a,b,c): Space heating only mean power demand during the occupied hours from 17:00 to 19:00, 17:00 to 20:00 and 17:00 and 21:00.

It can be seen that the power demand is highest for the detached built form and lowest for the flats in all size categories. The power demand is concentrated towards the front end of the heated period, for example the mean demand for the average sized (90m²) detached dwelling is 7.33kW during 17:00 to 19:00 whereas it is 6.57kW during 17:00 to 21:00. For the larger (150m²) dwelling types the mean of the maximum power demand values vary from 16.06kW to 18.06kW indicating that the peak demand at the beginning of the heating period is more critical and could be considerably larger than the average over the whole heating period. This is expected due to the initial need for more heat to bring the occupied space to the thermostat set point from a low pre-heating period ambient. This could be problematic for the grid in future scenarios where electric space heating is dominant and starts to operate at similar times, resulting in high grid loads around these times.

Table 4-5. The average of the Mean, maximum and minimum power demand predictions for the whole building over all hours, and for space heating power demand for three heated hours, organised by size and built form for the 60 day period from 2nd January for the 12 Base Case scenarios

		Mains Supply			Space heating only								
		All hours 00:00-24:00			Heated hours 17:00-19:00			Heated hours 17:00-20:00			Heated hours 17:00-21:00		
Arche-type variable	Value/ Type	Mean (Metric 3) (kW)	Max. (kW)	Min. (kW)	Mean (Metric 4a) (kW)	Max. (kW)	Min (kW)	Mean (Metric 4b) (kW)	Max. (kW)	Min (kW)	Mean (Metric 4c) (kW)	Max. (kW)	Min (kW)
Size	70m²	2.47	20.00	0.00	4.87	8.45	2.71	4.55	8.45	2.40	4.39	8.45	2.40
	90m²	3.03	25.00	0.00	6.15	11.08	3.08	5.81	11.08	3.08	5.62	11.08	3.05
	150m²	4.76	30.00	0.00	10.25	17.27	5.16	9.65	17.27	5.15	9.27	17.27	5.15
Built form	Detached	3.72	25.00	0.00	7.97	13.19	4.38	7.40	13.19	4.12	7.12	13.19	4.12
	Semi detached	3.48	25.00	0.00	7.19	12.17	3.92	6.80	12.17	3.78	6.55	12.17	3.78
	Mid terrace	3.24	25.00	0.00	6.59	11.78	3.31	6.23	11.78	3.30	5.99	11.78	3.25
	Flat	3.25	25.00	0.00	6.61	11.93	2.97	6.23	11.93	2.97	6.06	11.93	2.97
Overall average of all 12 Bases Cases		3.42	25.00	0.00	7.09	12.27	3.65	6.67	12.27	3.54	6.43	12.27	3.53

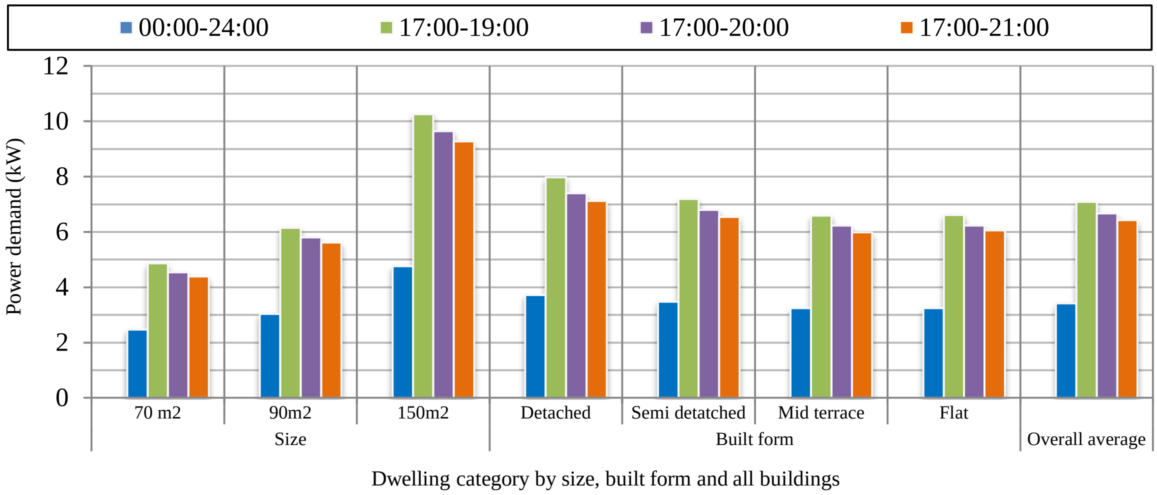


Figure 4-12. Mean of the daily average power demand predictions for all hours (00:00-24:00) and for three heated hours categorised by dwelling size and built form. The mean of daily averages for all the Base Case scenarios is also provided.

The average power demand predictions by floor area, built form and the overall average power demand for all twelve of the Base Case scenarios are presented in Table 4-5. The effects of the varying floor size and built form on the average power demand is illustrated in Figure 4-12. As expected, floor size clearly has a relatively large impact on the power demand prediction. The average power demand over the more critical (17:00 to 19:00) heated period for the 70m² dwellings is 4.87kW, and increases to 10.25kW for the 150m² dwellings. Built form has a moderate impact on power demand, the detached dwelling being the worst, and the flat and the mid terrace having similar but smaller demand compared to the detached built form. In the same heated period, the detached dwellings have an average power demand of 7.97kW whilst the flats have an average demand of 6.61kW.

The overall average power demand predictions of all dwellings during the critical (17:00 to 19:00) heating period is 7.093kW whilst the mean of all maximum demand predictions for the same period is 12.27kW. For the other two heating periods the overall average power demand reduced to 6.67kW and 6.43kW as shown in Table 4-5.

4.4.3 Energy consumption

The energy consumption predictions for the 12 Base Case scenarios are presented in Table 4-6. For each of the Base Case scenarios the daily mean, the worst case daily maximum and the worst case daily minimum energy demand predictions are shown, and are organised by the size of the dwellings to enable easier comparison. Based on these energy consumption predictions and the currently available electricity price tariff as previously discussed in Section 3.5.9, daily mean energy cost predictions are calculated, and are shown in Table 4-6.

The daily 60 day mean energy consumption for the whole building including DHW, varies from a minimum of 52.60kWh for the 70m^2 flat (Flat70) to 117.82kWh for the 150m^2 detached dwelling (Det150). The corresponding energy cost prediction varies from £7.94/day *(£2.47/day)* to £17.78/day *(£5.54/day)*. The values in brackets show the equivalent cost based on the currently available standard gas price[16] tariff from British Gas Ltd. The 60 day minimum and the maximum energy consumption for the same archetypes are 36.80kWh and 159.65kWh, and the corresponding cost predictions are £5.55/day *(£1.73/day)* and £24.09/day *(£7.50/day)* respectively. These values are based on the assumption that resistance element heating, with a COP of 1, is used as the worst form of heating electrification. Assuming that the energy is supplied by heat pumps, which is more likely to be the case in the future as discussed in Sections 2.2.3 and 3.5.7, and a COP of 3 is used, then the cost figures mentioned above would reduce by a factor of 3. This would bring it down to within around 7% of the gas equivalent. For example, the cost prediction for the Det150 dwelling of £17.78/day when reduced by a factor of 3 becomes £5.93/day. This is 6.9% higher than the gas equivalent of £5.54/day.

The impact of external weather variation (over the 60 day simulation period) on the energy consumption is represented by the worst case minimum and worst case

[16] Cost of gas (4.70p/kWh) is based on the Tariff Comparison Rate from British Gas Ltd. as available in December 2016.

maximum values. For example for the Det70 dwelling, the 60 day lowest mains supply energy consumption figure is 48.02kWh, and the 60 day highest mains supply energy consumption figure is 89.24kWh, which is an 86% increase. This increases to over 92% for the larger and more energy consuming buildings.

Table 4-6. Presents the mean of the daily average, the worst case daily maximum and the worst case daily minimum space heating only and mains supply energy demand predictions for all hours (00:00 to 24:00) and for three heated hours; for the 12 Base Case scenarios; and the corresponding daily average heat energy cost predictions for 60 winter days from 2nd January.

			Space Heating				Mains Supply	
		Building Archetype	All hour 00:00-24:00 (kWh)	Heated hours 17:00-19:00 (kWh)	Heated hours 17:00-20:00 (kWh)	Heated hours 17:00-21:00 (kWh)	Energy Metric 5 (kWh)	Cost @ 15.08p/kWh.[17] Metric 6 (£)
Mean	70m^2	Det70	55.81	11.71	16.25	20.71	66.93	10.10
		SDet70	50.79	10.24	14.30	18.28	61.57	9.29
		MTer70	45.69	9.03	12.68	16.26	55.92	8.44
		Flat70	42.72	8.21	11.61	15.23	52.60	7.94
	90m^2	Det90	71.89	14.77	20.57	26.40	82.53	12.45
		SDet90	65.38	13.12	18.36	23.71	75.67	11.42
		MTer90	59.53	11.56	16.40	21.05	69.32	10.46
		Flat90	53.24	10.07	14.62	19.11	63.25	9.54
	150m^2	Det150	107.07	21.72	30.11	38.65	117.81	17.78
		SDet150	102.19	20.08	28.75	36.86	112.95	17.04
		MTer150	97.06	19.20	27.19	34.79	107.79	16.27
		Flat150	85.14	16.29	23.67	30.76	94.78	14.30
Maximum	70m^2	Det70	77.44	18.25	25.63	31.93	89.24	13.47
		SDet70	72.14	16.57	22.64	28.73	83.91	12.66
		MTer70	64.10	14.35	20.02	24.99	76.01	11.47
		Flat70	59.26	12.55	17.21	22.99	69.55	10.50
	90m^2	Det90	99.40	23.20	31.86	40.43	111.11	16.77
		SDet90	90.92	20.45	28.39	36.11	104.03	15.70
		MTer90	83.19	17.64	25.27	32.58	94.86	14.31
		Flat90	72.84	15.29	22.39	29.17	84.50	12.75
	150m^2	Det150	147.93	33.40	46.02	58.72	159.66	24.09
		SDet150	141.97	31.78	44.53	56.63	155.13	23.41
		MTer150	132.19	30.20	41.99	52.87	143.72	21.69
		Flat150	116.41	24.78	35.51	45.77	126.58	19.10
Minimum	70m^2	Det70	38.22	6.77	9.50	12.19	48.02	7.25
		SDet70	32.54	5.19	7.86	10.48	41.97	6.33
		MTer70	29.99	4.77	7.16	9.29	39.69	5.99
		Flat70	27.54	4.19	5.39	7.81	36.80	5.55
	90m^2	Det90	49.72	8.14	11.61	15.18	60.08	9.07
		SDet90	43.94	7.45	10.50	13.64	53.74	8.11
		MTer90	40.18	6.46	9.15	12.49	49.72	7.50
		Flat90	36.61	6.07	9.06	12.02	45.28	6.83
	150m^2	Det150	74.40	11.19	16.95	23.88	83.14	12.55
		SDet150	70.33	10.93	15.62	21.59	78.66	11.87
		MTer150	68.53	10.51	14.86	21.76	76.84	11.60
		Flat150	59.67	10.66	16.58	21.14	67.36	10.16

[a] Metric 5 representing Daily_mean_MS_energy_kWh
[b] Metric 6 representing Daily_mean_energy_cost_£/day

[17] Cost of electricity is based on the Tariff Comparison Rate from British Gas Ltd., which represents the typical cost per kWh for the standard electricity tariff, taking into account surcharges and discounts such as standing charge and dual fuel discounts depending on the supply. In this work only the standing charge is included.

The change in energy consumed during the DSPs due to the varying weather condition over the 60 days gets even worse. For example for the Det70 dwelling, the minimum energy used during 17:00 to 19:00 is 6.77kWh, whilst the maximum energy used is 18.25kWh, which is a 170% increase. These indicate that the difference in energy consumption varies significantly for different built forms, sizes of dwellings and external weather conditions. Therefore, the energy storage capacity that would be needed to shift heat demand for different dwelling types, sizes and weather conditions would vary accordingly too as discussed later in this section.

The space heating only energy demand predictions are around 11kWh lower (~9Wh for DHW and ~2kWh for pipe losses) compared to the mains supply demand. As previously discussed, the DHW demands are relatively small and less varying. Heat loss through the pipes is also relatively small. Thus space heating energy demand is the factor that could significantly affect the mains grid power demand and therefore is analysed in detail in the subsequent sections of this thesis.

The graphs in Figure 4-13 illustrate the 60 day mean relationship between the floor size and space heating energy consumption. These graphs show a virtually linear relationship between the floor size and energy consumption, and can be used to determine the space heating energy requirement of dwellings of the built forms and sizes considered in this research. Likewise, the bar chart in Figure 4-14 illustrates how built form relates to energy consumption for the three sizes of dwellings considered. As can be seen, the energy consumption impact resulting due to floor size variation is much greater compared to that caused by the variation in built form.

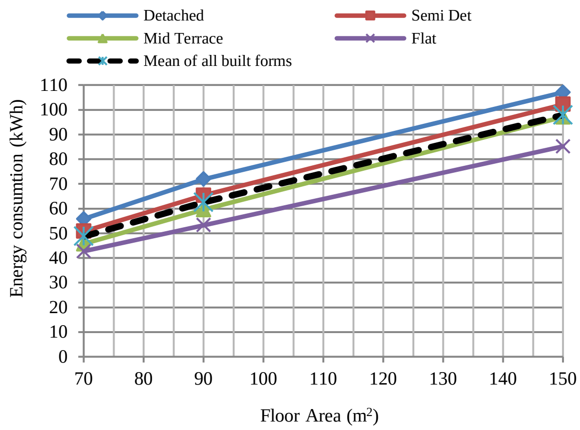


Figure 4-13. Daily mean space heating energy demand prediction by floor area size, for the four building archetypes considered, and the mean energy consumption of all built forms by floor size.

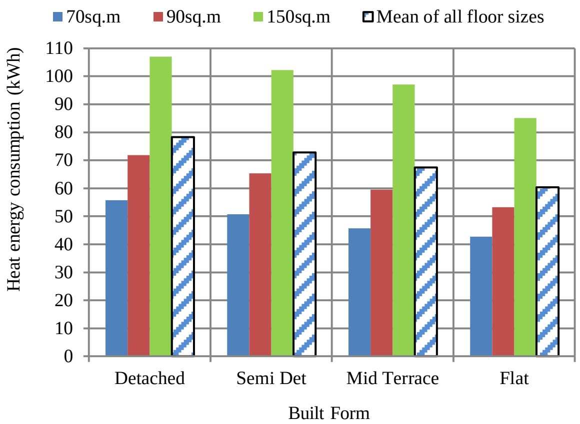


Figure 4-14. Daily mean space heating energy consumption prediction by built form, for the three floor sizes considered, and the mean energy consumption of all floor sizes by built form.

The energy consumption prediction averaged and organised by floor size and built form are summarised in Table 4-7. The mean of all building archetypes is also shown. The mean of the daily mean, mean of the maximum and the mean of the minimum space heating only and mains supply (Metric 5) energy consumption predictions are presented. The energy cost per day (Metric 6) is also provided. This table shows the effect of dwelling size on energy consumption, where the mean values vary considerably from 48.75kWh to 97.86kWh for the 70m^2 and 150m^2 dwellings, which is a 105% increase. Even more significant is the impact of external weather variation (over the 60 day simulation period) on the daily energy consumption as discussed above. This is represented by the mean of the maximum and the mean of the minimum consumption predictions, for example the space heating energy varying from 32.02kWh to 68.24kWh for the 70m^2 floor size dwellings, which is a 113% increase. The weather condition impact on the daily average (of all dwellings) energy consumption is illustrated in Figure 4-15, showing the 60 day mean, minimum and maximum values by floor area. The shaded region represents the potential space heating energy demand variation due to changes in external weather condition for different building floor sizes, when the built form effect is averaged out. The energy consumed during the DSP hours vary accordingly as well, as shown in Table 4-7 and discussed in detail later in this section, which has to be taken into account in determining the thermal storage capacity of any TES systems to be used for heat demand shifting.

The energy consumption impact of built form differences can be difficult to perceive, and this work shows that it is relatively significant. The bar chart in Figure 4-16 illustrates the daily space heating energy demand variation due to built-form, which is based on the mean of all building floor sizes and 60 days simulation period. The average of all built forms, floor sizes and 60 days is also shown, and is 69.71kWh. On average, the semi-detached, mid terrace and the flats consumed 7.0%, 13.8% and 22.7% less energy per day for space heating compared to the detached built form respectively. Likewise, the energy consumption during the DSPs varies significantly with built form as discussed later in this section.

Table 4-7. Space heating only mean heat energy consumption prediction for all hours and for three heated hours, and the mains supply (whole building) heat energy demand and cost predictions, averaged over 60 day from 2nd January.

			Space Heating				Mains Supply	
			All hour	Heated hours	Heated hours	Heated hours	Energy	Cost @ 15.08p/kWh[1]
			00:00-24:00	17:00-19:00	17:00-20:00	17:00-21:00	Metric 5a	Metric 6b
	Archetype category	Options	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(£)
Mean	Size	70m²	48.75	9.80	13.71	17.62	59.25	8.94
		90m²	62.51	12.38	17.49	22.57	72.69	10.97
		150m²	97.86	19.32	27.43	35.27	108.33	16.35
	Built form	Detached	78.26	16.06	22.31	28.59	89.09	13.44
		Semi detached	72.79	14.48	20.47	26.29	83.39	12.58
		Mid terrace	67.42	13.26	18.76	24.03	77.68	11.72
		Flat	60.37	11.52	16.63	21.70	70.21	10.59
	Overall average of all Base Cases		69.71	13.83	19.54	25.15	80.09	12.09
Maximum	Size	70m²	68.24	15.43	21.37	27.16	79.68	12.02
		90m²	86.59	19.15	26.98	34.57	98.63	14.88
		150m²	134.62	30.04	42.01	53.49	146.27	22.07
	Built form	Detached	108.26	24.95	34.50	43.69	120.00	18.11
		Semi detached	101.68	22.93	31.85	40.49	114.36	17.26
		Mid terrace	93.16	20.73	29.09	36.81	104.86	15.82
		Flat	82.84	17.54	25.04	32.64	93.55	14.12
	Overall average of all Base Cases		96.48	21.54	30.12	38.41	108.19	16.33
Minimum	Size	70m²	32.07	5.23	7.48	9.94	41.62	6.28
		90m²	42.61	7.03	10.08	13.33	52.21	7.88
		150m²	68.23	10.82	16.00	22.09	76.50	11.54
	Built form	Detached	54.11	8.70	12.69	17.08	63.75	9.62
		Semi detached	48.94	7.86	11.33	15.24	58.13	8.77
		Mid terrace	46.23	7.25	10.39	14.51	55.42	8.36
		Flat	41.28	6.97	10.35	13.66	49.81	7.52
	Overall average of all Base Cases		47.64	7.69	11.19	15.12	56.78	8.57

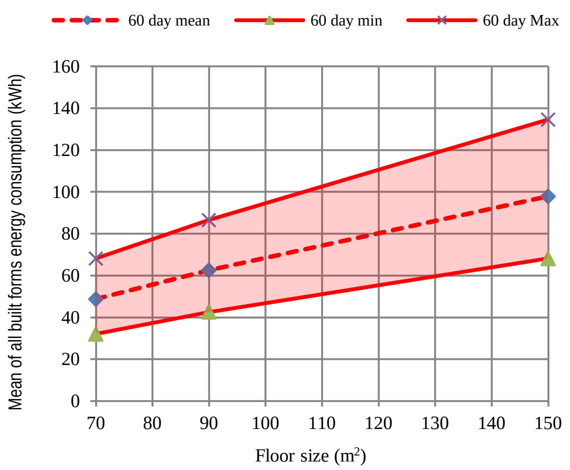


Figure 4-15. Illustration of the daily space heating energy demand prediction variation over the 60 days by floor size, averaged over all built forms.

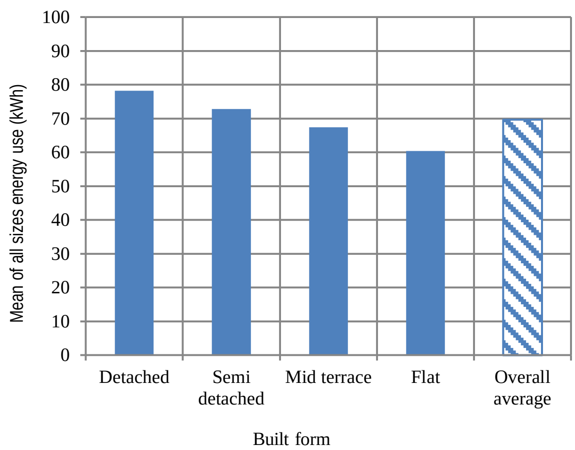


Figure 4-16. Daily mean space heating energy demand prediction by built form, averaged over floor size, and the mean energy consumption of all built forms and floor sizes.

Heat requirement during the future demand shift periods

Predictions of the mean energy consumption during the three evening occupied heated hours of 17:00-19:00, 17:00-20:00 and 17:00-21:00 (DSP periods) are included in Table 4-6 and Table 4-7. These periods are considered as the heating periods from which the demand for energy could be shifted to off peak times in the future. The related heat demand values indicate the amount of energy the TES system will be required to store and deliver into the space in order to maintain the space temperature at the thermostat set point. A good understanding of the energy demand dynamics during these periods are paramount for enabling an informed investigation of the heat demand shifting potential in the buildings, and the TES capacity and functionality needs.

The energy demand values during the DSP vary considerably, from a lowest value of 4.19kWh to 58.72kWh (See Table 4-6) for the smallest flat dwellings to the largest detached dwellings, and indicate the range of TES storage capacities necessary to enable energy demand shifting in the buildings, operational scenarios and weather conditions considered.

The bar chart in Figure 4-17 illustrate the 60 day mean space heating energy demand predictions during the three DSPs, for the twelve Base Case scenarios. As can be seen, the larger dwellings require more heat during the DSPs compared to the smaller dwellings, and vary from 8.21kWh to 38.65kWh. Likewise, the energy demand during the DSPs varied with built form, for example, compared to the detached buildings the energy consumed during a 2 hour DSP reduced by 10%, 17% and 28% for the semi-detached, mid terrace and the flats respectively.

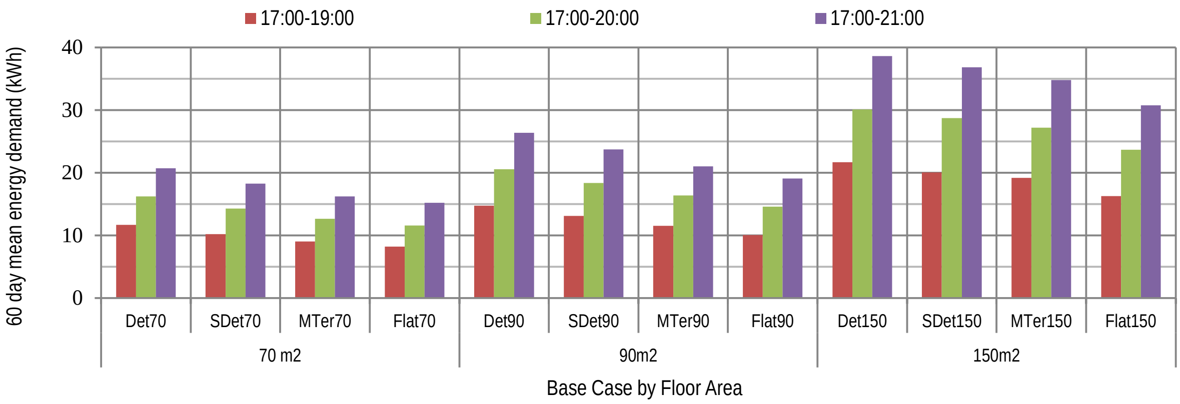


Figure 4-17. 60 day mean space heating energy consumption for the periods 17:00-19:00, 17:00-20:00 and 17:00-21:00 for the 12 Base Case scenarios considered organised by floor area.

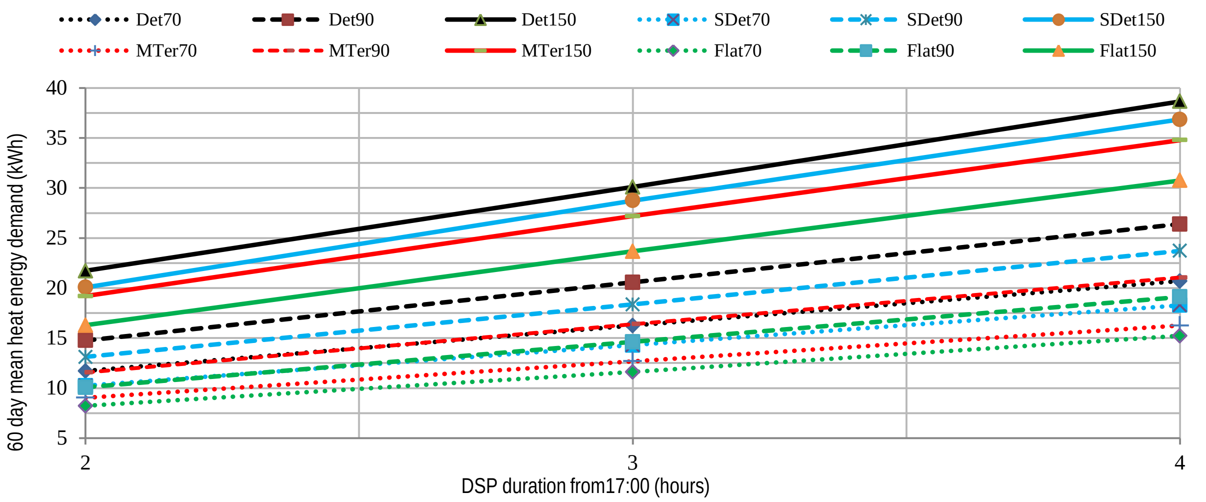
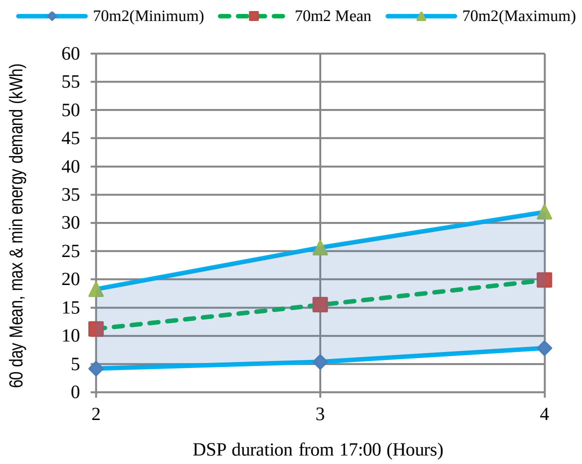


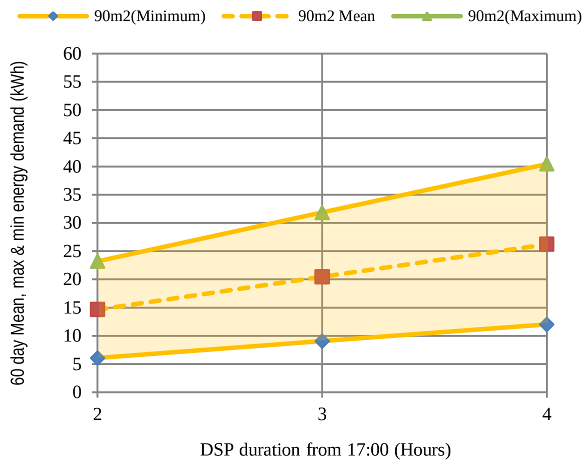
Figure 4-18. Relationship between the heat demand and DSP duration, for the 12 building archetypes considered, based on the mean of the 60 day results.

Both the impact of building floor size and built form ultimately is dependent on the duration of the DSP. The effects of DSP duration can be seen in Figure 4-17. For the three DSP durations considered, the energy demand varies from 8.21kWh to 20.71kWh, 10.07kWh to 26.40kWh and 16.29kWh to 38.65kWh for the three sizes of dwellings respectively. A useful relationship between the DSP duration and the space heating energy demand is demonstrated by the graphs in Figure 4-18. The graphs illustrate how the 60 day mean heat demand varies with the DSP duration (in hours from 17:00), for the twelve Base case scenarios. These can be used to determine the average TES capacity requirements for heat demand shifting periods from 2 to 4 hours, for the 12 building archetypes considered. For example, to achieve a 2.5 hour heat demand shift in a 90m^2 mid terrace property, the TES must be able to store and deliver around 14kWh of energy.

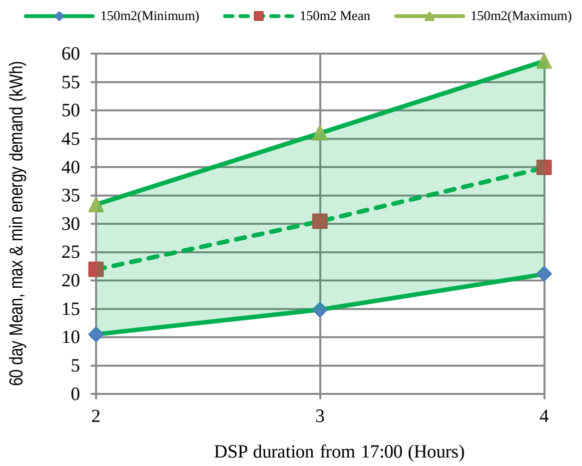
As discussed earlier, the energy consumed during the DSP due to the varying weather condition over the 60 days can change significantly. For the Det70 dwelling, the minimum energy used during 17:00 to 19:00 is 6.77kWh, whilst the maximum energy use is 18.25kWh, which is a 170% increase. The mean energy use for this dwelling was 11.71kWh. It can be concluded from this that a 2 hour heat demand shifted without degrading thermal comfort, during the worst of winter days, would require a TES that can store and supply over 18.25kWh heat, which is almost double the mean value. This could be problematic, for example in terms of installation cost and indoor space use, and could be inefficient when the mean energy shifted is compared with the storage capacity, and therefore discourage uptake.



(a)



(b)

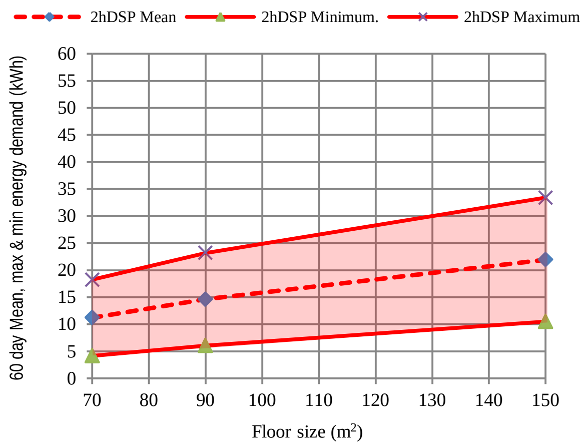


(c)

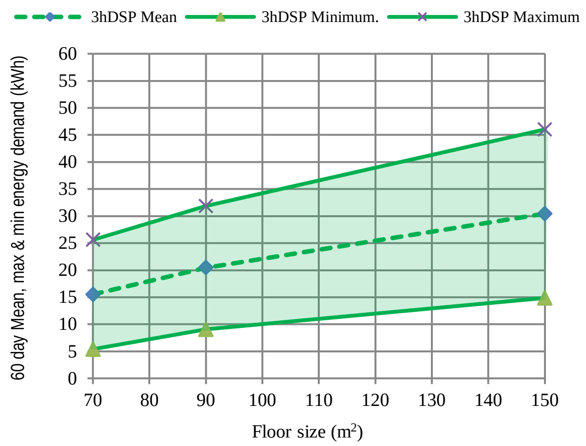
Figure 4-19 (a,b,c). Relationship between the heat demand variations over 60 days (due to changes in weather conditions) and DSP duration for: a) floor size of 70m^2; b) floor size of 90m^2 and; c) floor size of 150m^2.

The graphs in Figure 4-19 (a, b & c) illustrate the heat demand that ensures 21°C room temperature by DSP duration (in hours from 17:00) for the three building floor sizes, showing the mean and the absolute minimum and absolute maximum variation over the 60 day simulation period. The broken traces show the average of 60 day heat demand as DSP duration varies from 2 hours to 4 hours. The 'Maximum' traces show the maximum (of all built forms) energy demand over the coldest of the 60 winter days, whilst the 'Minimum' traces show the minimum (of all built forms) energy demand over the warmest of the 60 winter days used in the simulations. These graphs can be used as guidelines in determining the TES capacity for certain heat demand shift requirements, such that the effects of weather conditions are taken into account. For example, to shift the heat demand by 2.5 hours in a 90m^2 building, a

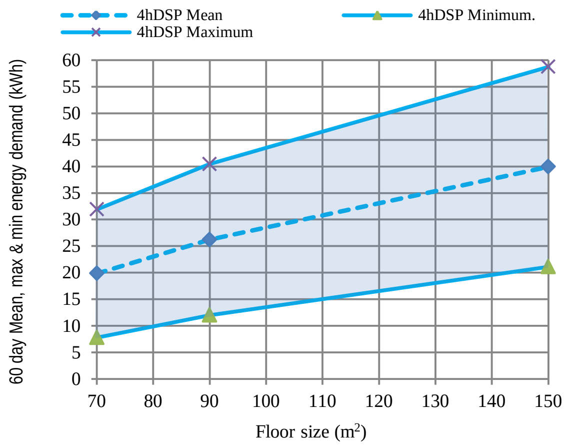
TES storage capacity between 27.5kWh and 7.5kWh could be chosen, where choosing the larger value means the TES could provide heat to ensure thermal comfort for the DSP duration in the worst of the winter days.



(a)



(b)



(c)

Figure 4-20. Relationship between the heat demand variation over 60 days (due changes in weather conditions) and floor size for: a) a 2 hour DSP duration, b) a 3 hour DSP duration, and c) a 4 hour DSP duration.

As mentioned earlier, the occupied floor size is one of the major contributors of space heating energy demand. Therefore, understanding the dynamics of energy use during the DSPs for different floor sizes can be beneficial in determining TES sizes. The graphs in Figure 4-20 (a, b & c) illustrate the energy consumption that ensures a 21°C room temperature by floor size for the three DSPs considered, showing the 60 day mean, maximum and the minimum levels. These graphs can also be used as guidelines in determining the TES capacity based on building sizes ranging from 70m^2 to 150m^2. For example, to shift the heat demand by 3 hours in a 120m^2 building, a TES storage capacity between 38kWh and 12kWh could be chosen, where choosing the larger value means the TES would be able to provide heat to ensure thermal comfort in the building for the worst of the winter days.

4.5 Performance impacts of thermal insulation, thermostat setting, location, heating duration and occupancy

The performance predictions presented here have been generated with five of the main building performance influencing variables changed as previously described in Section 3.6.3. The five variables changed are thermal insulation level, location, heating duration, thermostat set point and the occupancy. The impacts of these variables in terms of thermal comfort, power and energy demand, and their potential impact in heat demand shifting using TES are discussed.

4.5.1 Space temperature

The graphs in Figure 4-21 to Figure 4-22 show the mean ground floor occupied space temperature averaged over the 60 day simulation period, each corresponding to one of the five variables changed. These figures illustrate how the daily temperature profile varies as the respective parameter value changes in comparison with that of the Det90 Base Case scenario (see Table 3.12).

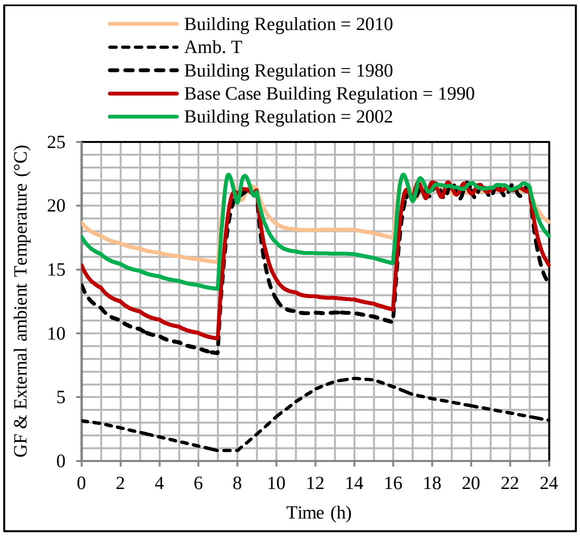


Figure 4-21. Thermal Insulation Impact: Effect of thermal insulation level on the indoor thermal condition in comparison with the Base Case averaged over 60 day simulation period.

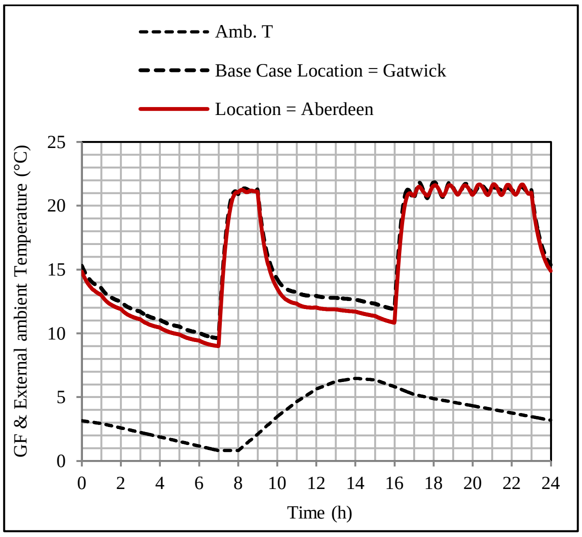


Figure 4-22. Location Impact: Effect of location on the indoor thermal condition in comparison with the Base Case averaged over 60 day simulation period.

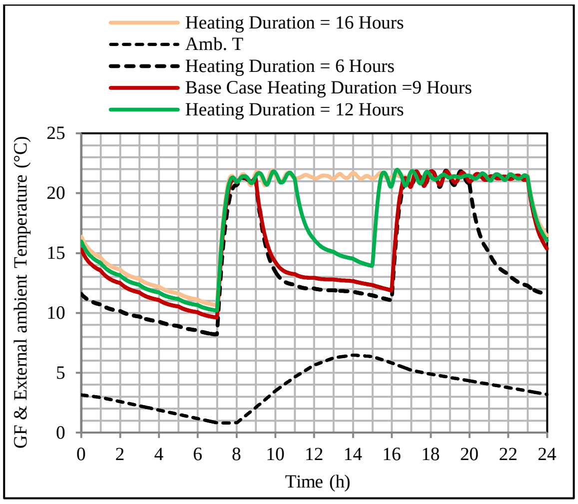


Figure 4-23. Heating Duration Impact: Effect of heating duration on the indoor thermal condition in comparison with the Base Case averaged over 60 day simulation period.

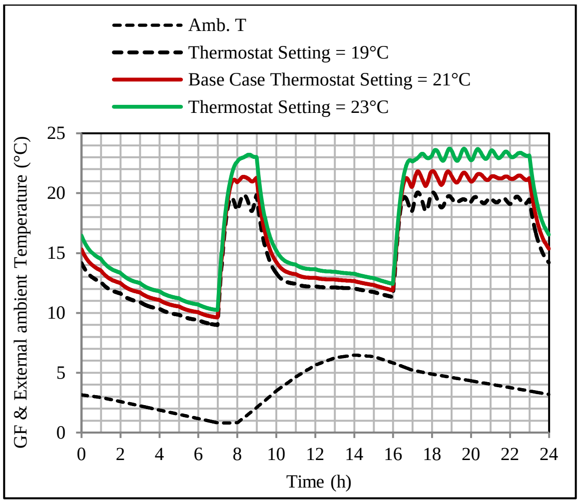


Figure 4-24. Thermostat Setting Impact: Effects of thermostat set point on the indoor space temperature in comparison with the Base Case averaged over 60 day simulation period.

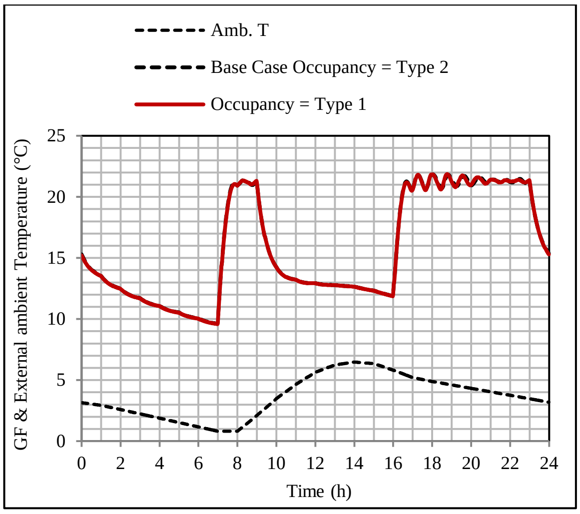


Figure 4-25. Occupancy Impact: Effect of occupancy on the indoor thermal condition in comparison with the Base Case averaged over 60 day simulation period.

The graphs in Figure 4-21 illustrate the average daily indoor space temperature profile impacts of varying thermal insulation levels. The graphs correspond to the buildings having thermal insulation levels in accordance with the 1980, 1990, 2002 and 2010 building regulation standards. As can be seen, the space temperature during the occupied heated hours stay at the thermostat set point for all insulation levels, due to the lost heat being replaced by the heating system. However, during the unheated hours it falls significantly lower for the less insulated buildings. For example, the temperature reaches a minimum value of around 8℃ at just before 7am for the building with 1980s thermal insulation and drops to around 15.5℃ for the building with the 2010s thermal insulation. This means less heat is required in better insulated buildings to raise and maintain the temperature at the set point.

Figure 4-22 shows the average daily indoor space temperature profile and how it changes with location. The difference in temperature is about 1℃ which is relatively small, and it would be interesting to see how this affects the overall energy consumption, and more importantly the DSP hour energy consumption as it will dictate the heat demand shift achievable using TES systems of different capacities.

Figure 4-23 shows the average daily indoor space temperature profile and how it changes with the heating duration. The lowest duration of 6 hours results in the lowest unheated period temperature drop. A longer heating duration means that the dwellings will have pre-heating for longer prior to any heat demand shifting which starts at 17:00. It would be interesting to see how this affects heat demand shifting achievable for different dwelling built forms, size and TES capacities which is discussed later. Figure 4-24 shows how the daily indoor space temperature profile changes with the thermostat set point. Higher thermostat settings result in a marginally higher unheated period temperatures and vice-versa. More importantly, at the start of the DSP the room temperature will be at a higher or a lower temperature for the higher or the lower thermostat set points, and thus will have a higher or lower amount of stored heat respectively. This could affect heat demand shifting ability, thermal comfort and energy consumption and is discussed later in this thesis. Figure 4-25 shows the average daily indoor space temperature profile and how it changes with the household size and occupancy profile. It can be seen that the profiles overlap each other which means that occupancy has minimal impact on the thermal comfort.

The temperature predictions for all 12 of the Base Case scenarios are summarised in Table 4-8, showing the change in the mean of the daily average (Metric 1) and the change in the mean of the daily minimum occupied space temperatures. The overall average values for all dwellings are also presented in Table 4-8 which provides a more general indication of the impacts of the five variables with respect to the Base Case conditions. The mean of the average temperatures during the heated period 17:00 to 21:00 (Metric 2) is also presented. The highlighted values are for the Base Case conditions. The remaining figures represent the differences between the Base Case temperatures and the temperatures resulting from the respective parameters changing in relation to the relevant Base Case values. For example, the space temperature for the Det70 Base Case is 16.25℃, and this changed by -0.49℃,

+0.87℃, and +1.38℃ as the thermal insulation of the building changed to be in line with the 1980, 2002 and 2010 building regulation respectively each time.

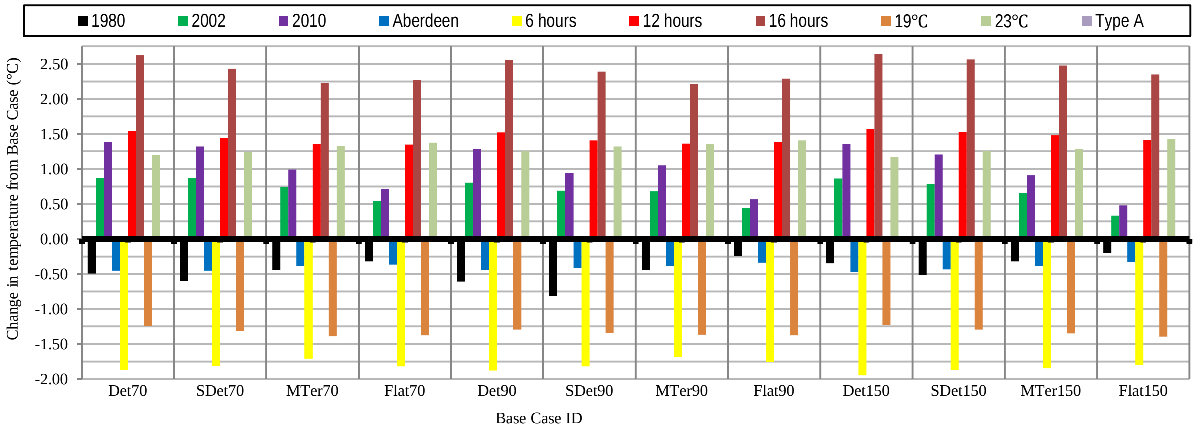


Figure 4-26. Illustration of the 60 day average of the daily mean indoor temperature change from the 12 Base Case levels due changes in thermal insulation, location, heating duration, thermostat set point and occupancy type.

The effects of the five parameter changes are highlighted in the bar chart Figure 4-26. It shows the amount by which the mean of the daily average room temperature rises or falls from the Base Case levels represented by the zero line on the X-axis. It can be seen that shorter heating duration, lower thermostat setting and poorer thermal insulation have a greater impact on reducing the room temperature levels in the same respective order. Conversely, longer heating duration, higher thermostat setting and better thermal insulation have a greater impact in keeping the room temperature higher.

As expected, occupancy (number of occupiers) has a negligible effect regardless of the dwelling built form or size, as it is not related to the thermostat set point, heating duration or heat loss in the dwellings. The relatively small influence it has is due to its impact on the internal gain and DHW use.

Location can be seen to reduce the mean room temperature in the smaller dwellings by around 0.5℃, and by around 0.65℃ in the bigger dwellings. Whilst the temperature impact is not relatively big, the energy consumption may be, and it could affect the heat demand shifting ability as discussed later in this section.

Table 4-8. Table showing All hours (00:00 to 24:00) and critical Heated hours (17:00 to 21:00) space temperature change predictions from the Base Case values due to varying thermal insulation, location, heating duration, thermostat setting and occupancy, organised by floor size and built form, and averaged over the 60 days from 2nd January. Base Case figures are highlighted.

Prediction period	Prediction type	Floor Size	Base Case ID	Thermal Insulation				Location		Heating Duration				Thermostat Setting			Occupancy	
				1980	1990	2002	2010	Gatwick	Aberdeen	6 hours	9 hours	12 hours	16 hours	19°C	21°C	23°C	Type A	Type B
All hours 00:00 to 24:00	Mean (°C) (Metric 1)	70m²	Det70	-0.49	16.25	0.87	1.38	16.25	-0.45	-1.87	16.25	1.54	2.62	-1.24	16.25	1.20	-0.03	16.25
			SDet70	-0.61	16.55	0.87	1.32	16.55	-0.45	-1.81	16.55	1.44	2.43	-1.31	16.55	1.24	-0.04	16.55
			MTer70	-0.45	17.06	0.74	0.99	17.06	-0.39	-1.71	17.06	1.35	2.23	-1.39	17.06	1.33	-0.04	17.06
			Flat70	-0.32	17.19	0.54	0.72	17.19	-0.37	-1.82	17.19	1.35	2.27	-1.38	17.19	1.37	-0.04	17.19
		90m²	Det90	-0.61	16.32	0.80	1.29	16.32	-0.44	-1.88	16.32	1.52	2.56	-1.29	16.32	1.25	-0.03	16.32
			SDet90	-0.81	16.77	0.69	0.94	16.77	-0.42	-1.82	16.77	1.41	2.39	-1.34	16.77	1.32	-0.01	16.77
			MTer90	-0.44	17.03	0.68	1.05	17.03	-0.39	-1.69	17.03	1.36	2.21	-1.37	17.03	1.35	-0.03	17.03
			Flat90	-0.24	17.28	0.44	0.57	17.28	-0.34	-1.76	17.28	1.38	2.29	-1.38	17.28	1.41	-0.02	17.28
		150m²	Det150	-0.35	15.76	0.86	1.35	15.76	-0.47	-1.95	15.76	1.57	2.64	-1.23	15.76	1.17	-0.01	15.76
			SDet150	-0.51	16.15	0.78	1.21	16.15	-0.43	-1.87	16.15	1.53	2.56	-1.29	16.15	1.26	-0.01	16.15
			MTer150	-0.32	16.43	0.66	0.91	16.43	-0.39	-1.85	16.43	1.48	2.48	-1.35	16.43	1.29	-0.01	16.43
			Flat150	-0.20	17.02	0.33	0.48	17.02	-0.33	-1.80	17.02	1.41	2.35	-1.39	17.02	1.43	0.01	17.02
	Minimum	70m²	Det70	-0.46	10.44	1.57	2.41	10.44	-0.64	-1.30	10.44	0.64	1.06	-0.74	10.44	0.72	-0.02	10.44
			SDet70	-0.72	10.79	1.64	2.34	10.79	-0.62	-1.32	10.79	0.59	1.00	-0.80	10.79	0.76	-0.04	10.79
			MTer70	-0.40	11.86	1.43	1.79	11.86	-0.55	-1.32	11.86	0.62	1.02	-0.92	11.86	0.88	-0.03	11.86
			Flat70	-0.52	12.25	0.88	1.15	12.25	-0.48	-1.41	12.25	0.75	1.27	-0.94	12.25	0.94	-0.03	12.25
		90m²	Det90	-0.70	10.47	1.47	2.31	10.47	-0.63	-1.33	10.47	0.60	0.99	-0.77	10.47	0.75	-0.02	10.47
			SDet90	-1.54	11.48	0.90	1.33	11.48	-0.58	-1.36	11.48	0.63	1.08	-0.86	11.48	0.85	-0.01	11.48
			MTer90	-0.43	11.61	1.27	1.92	11.61	-0.56	-1.31	11.61	0.58	0.94	-0.88	11.61	0.87	-0.03	11.61
			Flat90	-0.37	12.67	0.69	0.86	12.67	-0.46	-1.37	12.67	0.83	1.37	-0.97	12.67	0.99	-0.02	12.67
		150m²	Det150	0.34	8.96	2.25	2.98	8.96	-0.67	-1.28	8.96	0.41	0.69	-0.63	8.96	0.62	-0.01	8.96
			SDet150	-0.49	10.03	1.62	2.28	10.03	-0.63	-1.31	10.03	0.55	0.91	-0.74	10.03	0.72	-0.02	10.03
			MTer150	-0.16	10.69	1.40	1.74	10.69	-0.59	-1.35	10.69	0.58	0.96	-0.81	10.69	0.78	-0.01	10.69
			Flat150	-0.32	12.34	0.55	0.77	12.34	-0.45	-1.38	12.34	0.83	1.39	-0.97	12.34	0.99	0.00	12.34
Heated hours 17:00-21:00	Mean (°C) (Metric 2)	70m²	Det70	-0.14	21.30	0.07	0.13	21.30	-0.05	-0.79	21.30	0.07	0.12	-1.91	21.30	1.87	-0.02	21.30
			SDet70	-0.13	21.38	0.07	0.10	21.38	-0.06	-0.67	21.38	0.04	0.08	-1.93	21.38	1.88	-0.02	21.38
			MTer70	-0.08	21.41	0.04	0.08	21.41	-0.04	-0.55	21.41	0.03	0.04	-1.95	21.41	1.92	-0.01	21.41
			Flat70	-0.07	21.48	0.06	0.09	21.48	-0.03	-0.54	21.48	0.04	0.07	-1.93	21.48	1.91	-0.01	21.48
		90m²	Det90	-0.12	21.31	0.08	0.12	21.31	-0.05	-0.75	21.31	0.05	0.10	-1.93	21.31	1.89	-0.01	21.31
			SDet90	-0.07	21.34	0.10	0.14	21.34	-0.04	-0.57	21.34	0.09	0.13	-1.93	21.34	1.92	-0.01	21.34
			MTer90	-0.09	21.41	0.05	0.08	21.41	-0.04	-0.55	21.41	0.03	0.06	-1.95	21.41	1.91	-0.01	21.41
			Flat90	-0.07	21.48	0.05	0.06	21.48	-0.03	-0.47	21.48	0.04	0.05	-1.94	21.48	1.91	0.00	21.48
		150m²	Det150	-0.12	21.24	0.02	0.07	21.24	-0.04	-0.90	21.24	0.03	0.08	-1.94	21.24	1.89	-0.01	21.24
			SDet150	-0.08	21.25	0.04	0.10	21.25	-0.04	-0.73	21.25	0.05	0.10	-1.94	21.25	1.91	0.00	21.25
			MTer150	-0.06	21.26	0.04	0.08	21.26	-0.03	-0.69	21.26	0.06	0.09	-1.93	21.26	1.93	0.00	21.26
			Flat150	-0.04	21.31	0.02	0.05	21.31	-0.03	-0.52	21.31	0.03	0.06	-1.95	21.31	1.93	0.00	21.31
Overall average of all dwellings			Mean	-0.45	16.65	0.69	1.02	16.65	-0.41	-1.82	16.65	1.45	2.42	-1.33	16.65	1.30	-0.02	16.65
			Minimum	-0.48	11.13	1.31	1.82	11.13	-0.57	-1.34	11.13	0.63	1.06	-0.84	11.13	0.82	-0.02	11.13

Note:
Metric 1: Daily_mean_GF_T (Daily mean ground floor temperature)
Metric 2: DSP_hours_mean_GF_T (Mean ground floor temperature during the demand shift period)

The lowest daily mean temperature is produced by the shorter 6 hour heating duration option and in the detached 150m³ building and is 1.95℃ lower than the Base Case temperature of 15.76℃. The lowest daily mean temperature reached was also for the 6 hour heating duration option where it dropped by 1.28℃ from 8.96℃. The highest daily mean temperature was produced by the longer, 16 hour, heating duration option and was 2.29℃ more than the Base Case value of 17.28℃. This suggests that the room temperatures in dwellings in reality could vary considerably, and can be even worse than that suggested by this study, especially when real buildings incorporate a combination of shorter heating periods, poorer insulation, and lower thermostat setting, and are located in the north of the UK.

Options that increase the room temperature may be desirable from the thermal comfort view point, but they might not always be appropriate in terms of energy demand reduction and management through heat demand shifting. Buildings that contain these options are likely to provide the thermal comfort benefits at the expense of greater energy use, and thus may not be effective for heat demand shifting interventions. The preferred combination of options would be those that provide higher room temperatures and also reduce heat energy consumption, both in terms of benefiting both the supply side and demand side, as discussed later in this section.

4.5.2 Power demand

The power demand impact predictions for all 12 of the Base Case scenarios are summarised in Table 4-9. The results include: 1) the mean of the daily average mains supply (Metric 3), 2) the mean of the space heating only power demand in the 17:00 to 21:00 heated hours, and 3) the mean of the maximum space heating only power demand during the 17:00 to 21:00 heated hours. The highlighted values are for the Base Case conditions. The remaining figures represent the differences between the Base Case power demand and the power demand resulting from the respective parameters changing in relation to the relevant Base Case. The differences indicate the amount by which the power demand rise or fall from the Base Case values as a result of the changes made to the five corresponding parameters. For example, the power demand for the Det70 Base Case during the heated period 17:00 to 21:00 is 5.16kW, and this changed by 1.35kW, -0.93kW and -0.170kW as the thermal insulation of the building changes to be in line with the 1980, 2002 and 2010 the building regulation respectively each time.

The daily power demand values are small due to the averaging over a longer period. These figures are only useful in terms of identifying which of the five variables affect power demand. We can see that lower thermal insulation, colder location (i.e. Aberdeen), higher heating duration and higher thermostat settings have power demand increasing impact regardless of the built form and size. However, the impact is greater for higher heating durations and in the larger building. The greater impact in terms of reducing the daily average power demand is caused by the 2010 thermal insulation level. Therefore, to reduce the power demand, a combination of higher thermal insulation and lower heating duration and thermostat setting should be employed in these buildings.

Table 4-9. Mean of the daily (00:00 to 24:00) and critical Heated hours (17:00 to 21:00) space heating only and mains supply power demand for the Base Case scenario and for scenarios with varying thermal insulation, location, heating duration, thermostat setting and occupancy in relation to the base case.

				Thermal Insulation				Location		Heating Duration				Thermostat Setting			Occupancy	
Prediction period	Prediction Type	Floor Size	Base Case ID	1980	1990	2002	2010	Gatwick	Aberdeen	6 hours	9 hours	12 hours	16 hours	19°C	21°C	23°C	Type A	Type B
All hours 00:00 to 24:00	Mean Mains Supply power demand (Metric 3)	70m²	Det70	0.49	2.79	-0.37	-0.67	2.79	0.22	-0.45	2.79	0.41	0.61	-0.32	2.79	0.31	-0.18	2.79
			SDet70	0.48	2.57	-0.40	-0.64	2.57	0.20	-0.40	2.57	0.37	0.52	-0.31	2.57	0.30	-0.20	2.57
			MTer70	0.36	2.33	-0.32	-0.48	2.33	0.18	-0.32	2.33	0.31	0.42	-0.27	2.33	0.28	-0.19	2.33
			Flat70	0.25	2.19	-0.22	-0.31	2.19	0.16	-0.28	2.19	0.27	0.37	-0.23	2.19	0.25	-0.22	2.19
		90m²	Det90	0.61	3.44	-0.48	-0.81	3.44	0.27	-0.53	3.44	0.52	0.76	-0.39	3.44	0.40	-0.18	3.44
			SDet90	0.54	3.16	-0.52	-0.73	3.16	0.27	-0.45	3.16	0.45	0.65	-0.36	3.16	0.39	-0.19	3.16
			MTer90	0.46	2.89	-0.37	-0.61	2.89	0.23	-0.38	2.89	0.42	0.56	-0.34	2.89	0.37	-0.18	2.89
			Flat90	0.25	2.64	-0.22	-0.31	2.64	0.19	-0.35	2.64	0.33	0.45	-0.30	2.64	0.27	-0.23	2.64
		150m²	Det150	0.89	4.92	-0.45	-0.94	4.92	0.35	-0.80	4.92	0.82	1.16	-0.56	4.92	0.57	-0.19	4.92
			SDet150	0.74	4.71	-0.59	-1.06	4.71	0.37	-0.74	4.71	0.72	1.06	-0.54	4.71	0.56	-0.20	4.71
			MTer150	0.50	4.50	-0.51	-0.83	4.50	0.32	-0.68	4.50	0.63	0.94	-0.53	4.50	0.52	-0.21	4.50
			Flat150	0.33	3.95	-0.27	-0.45	3.95	0.29	-0.53	3.95	0.53	0.73	-0.45	3.95	0.45	-0.21	3.95
Heated hours 17:00 to 21:00	Mean Space heating only power demand (Metric 4)	70m²	Det70	1.35	5.16	-0.93	-1.70	5.16	0.52	1.63	5.16	-1.06	-1.78	-0.83	5.16	0.84	0.20	5.16
			SDet70	1.29	4.55	-0.85	-1.54	4.55	0.51	1.57	4.55	-0.91	-1.52	-0.72	4.55	0.82	0.20	4.55
			MTer70	0.94	4.05	-0.75	-1.21	4.05	0.43	1.57	4.05	-0.94	-1.51	-0.68	4.05	0.68	0.17	4.05
			Flat70	0.61	3.79	-0.53	-0.77	3.79	0.40	1.50	3.79	-0.71	-1.18	-0.57	3.79	0.59	0.13	3.79
		90m²	Det90	1.60	6.57	-1.16	-1.97	6.57	0.64	2.15	6.57	-1.27	-2.18	-1.03	6.57	1.08	0.19	6.57
			SDet90	1.33	5.91	-1.24	-1.80	5.91	0.62	2.13	5.91	-1.08	-1.92	-0.92	5.91	1.02	0.20	5.91
			MTer90	1.12	5.24	-0.91	-1.54	5.24	0.54	2.04	5.24	-1.12	-1.83	-0.85	5.24	0.83	0.16	5.24
			Flat90	0.61	4.76	-0.50	-0.74	4.76	0.40	2.01	4.76	-0.87	-1.43	-0.71	4.76	0.67	0.12	4.76
		150m²	Det150	2.64	9.62	-0.97	-2.21	9.62	0.83	3.06	9.62	-1.67	-2.78	-1.52	9.62	1.49	0.17	9.62
			SDet150	2.15	9.18	-1.20	-2.46	9.18	0.86	3.22	9.18	-1.54	-2.71	-1.32	9.18	1.44	0.19	9.18
			MTer150	1.38	8.67	-1.09	-1.94	8.67	0.76	3.21	8.67	-1.55	-2.68	-1.26	8.67	1.35	0.17	8.67
			Flat150	0.86	7.67	-0.66	-1.11	7.67	0.66	3.15	7.67	-1.28	-2.17	-1.13	7.67	1.06	0.13	7.67
	Space heating (max)	70m²	Det70	0.04	9.15	-1.17	-1.88	9.15	-0.18	2.24	9.15	-2.76	-4.87	-0.66	9.15	-0.56	-0.07	9.15
			SDet70	-0.08	8.73	-1.17	-2.64	8.73	0.03	2.46	8.73	-3.33	-4.57	-0.82	8.73	-0.56	0.19	8.73
			MTer70	0.71	8.34	-1.39	-2.08	8.34	-0.07	2.69	8.34	-4.04	-4.85	-1.17	8.34	0.55	0.20	8.34
			Flat70	0.66	16.62	-0.45	-1.48	16.62	1.00	5.59	16.62	-8.28	-9.80	-2.28	16.62	-0.03	1.04	16.62
		90m²	Det90	-0.87	12.36	-1.54	-2.22	12.36	-0.63	2.93	12.36	-3.23	-6.56	-1.55	12.36	-1.15	-0.06	12.36
			SDet90	0.66	10.85	-1.15	-2.84	10.85	0.32	4.02	10.85	-3.46	-5.57	-0.40	10.85	0.22	-0.02	10.85
			MTer90	0.27	10.95	-1.54	-3.16	10.95	0.26	3.88	10.95	-5.15	-5.93	-1.86	10.95	1.07	-0.31	10.95
			Flat90	0.80	10.17	-2.56	-2.87	10.17	0.81	4.79	10.17	-4.56	-6.07	-2.87	10.17	1.39	0.29	10.17
		150m²	Det150	-1.46	18.06	-1.54	-1.36	18.06	-0.74	4.49	18.06	-4.52	-9.57	-1.20	18.06	-2.06	-0.52	18.06
			SDet150	-0.05	16.92	-1.37	-2.11	16.92	-0.76	5.29	16.92	-3.39	-8.22	-0.89	16.92	-1.48	0.30	16.92
			MTer150	1.10	16.06	-0.11	-0.88	16.06	-0.23	5.95	16.06	-3.25	-7.90	-0.15	16.06	-0.52	-0.05	16.06
			Flat150	0.66	16.62	-0.45	-1.48	16.62	1.00	5.59	16.62	-8.28	-9.80	-2.28	16.62	-0.03	1.04	16.62

Appreciating the form of the peak space heating only power demand during the heated hours is critical to understanding the future impact it is likely to have on the grid as discussed earlier. To explore this, the effects of the five parameter changes have been analysed as illustrated in the chart in Figure 4-27. It shows how the mean of the maximum (or peak) power demand during the heated period 17:00 to 21:00 rises or falls from the Base Case levels represented by the zero line on the x-axis. The results have been categorised by floor area and built form showing the impact of the five variable changes on these categories. Contrary to daily mean power demand, the demand during the critical heated hours can be seen to reduce with longer heating duration and better thermal insulation, and have greater effect on the smaller dwelling size. The effect is significant on all four built forms although it is greater on the detached and flat built forms. Furthermore, the power demand during the critical heated hours rises for lower thermal insulation and higher thermostat set point, especially in the flats and larger buildings. Lower power demand can make heat demand shifting more effective and, therefore, need to be taken into account in selecting buildings for TES and heat demand shift interventions.

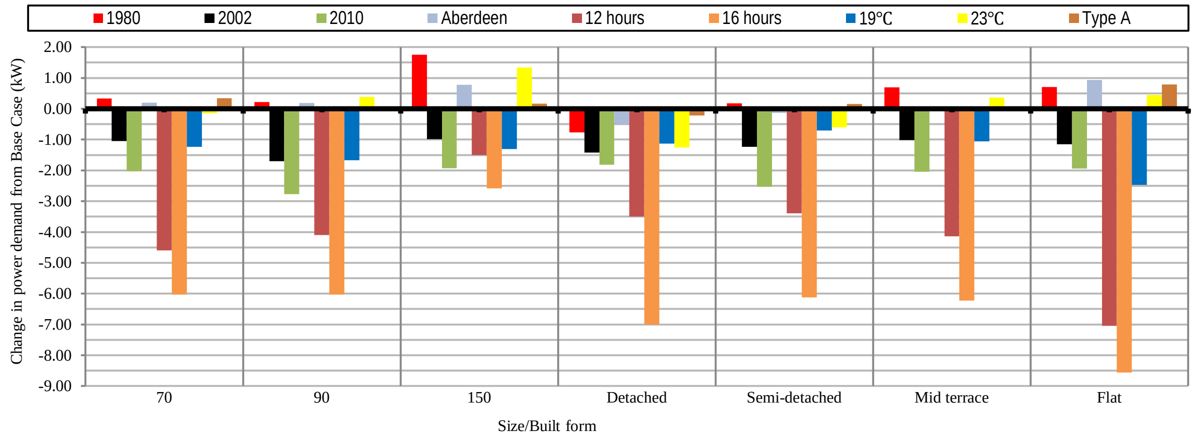


Figure 4-27. Illustration of the average power demand change during the critical heated hours (17:00 to 21:00) from the 12 Base Case levels, by building floor size and built form, due changes in thermal insulation (1980, 1990, 2002 & 2010), location, heating duration, thermostat set point and occupancy (type A).

Figure 4-28 illustrates the overall average power demand change caused by the five variables, during the critical heated period 17:00 to 21:00, with respect to the average power demand for the 12 Base Case scenarios. The results show that the greatest opportunity for minimising the peak power demands during the critical hours could be achieved by spreading the heating over a longer period, more than the other options such as increasing the thermal insulation and reducing the thermostat set points. The peak power demand rise (from the Base Case mean) is the largest (over 4kW higher) when the heating duration is the lowest at 6 hours. The thermal insulation change to the 1980 level, occupancy change to a single person (Type A) and the location change to Aberdeen have a very marginal peak power demand increasing impact. Improving thermal insulation to the 2002 and 2010 levels and reducing the thermostat setting to 19°C could provide some scope of reducing the power demand during the critical grid peak times. However, spreading the heating duration from the Base Case value of 9 hours to 16 hours reduces the peak power demand by around 7kW from the corresponding Base Case value. This could be a way of addressing any future space heating induced grid peak and off-peak load balancing challenges. It must be appreciated that this method does not imply any reduction in the space heating energy demand, but rather increases it as discussed later in this section.

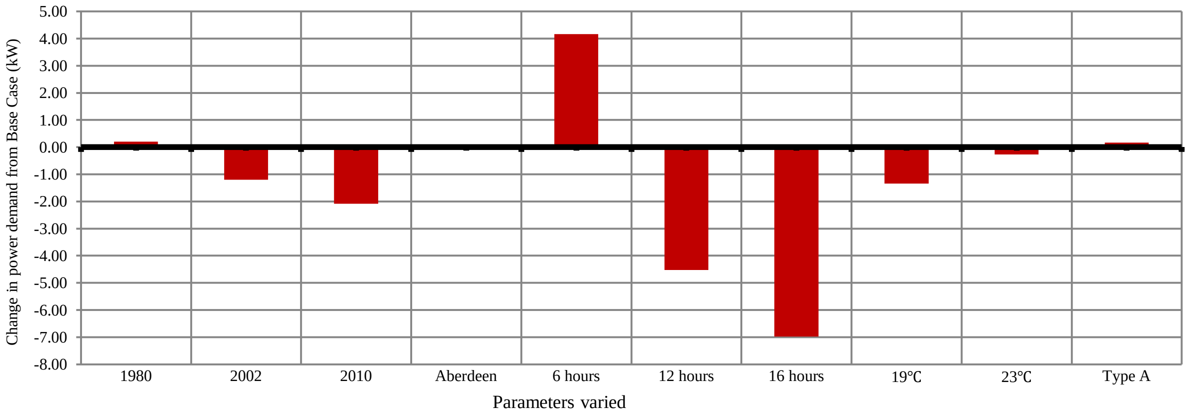


Figure 4-28. Illustration of the overall average (mean of all 12 building archetypes) power demand change during the critical heated hours (17:00 to 21:00) from the average of the 12 Base Case scenarios, due to changes in thermal insulation, location, heating duration, thermostat set point and occupancy type.

4.5.3 Energy consumption

The energy demand impacts due to changes to the thermal insulation, location, heating duration, thermostat setting and occupancy parameters for all 12 of the Base Case scenarios are summarised in Table 4-10. Results are presented for all hours (00:00 to 24:00), and the three future DSP periods which fall within the critical heated hours of 17:00 to 21:00 as discussed previously. Analysing the heat demand impact during the three DSP hours is considered important to appreciate the energy storage capacity which may be necessary in future TES systems for heat demand shifting purposes. The highlighted values are for the Base Case conditions. The remaining figures represent the difference between the Base Case energy demand and the demand resulting from the relevant parameters changing in relation to the corresponding Base Case. The differences indicate the quantity by which the daily average energy demand rise or fall from the Base Case values as a result of the changes made to the five corresponding parameters. For example, the space heating only energy consumption for the Det70 Base Case for all hours is 55.18kWh, and this value changes by +11.13kWh, -8.33kWh and -15.01kWh as the thermal insulation of the building changes to be in line with the 1980, 2002 and 2010 building regulations respectively each time.

Table 4-10. Illustration of the change in daily mean mains supply energy, daily mean space heating only energy and mean DSP energy consumption predictions for the Base Case scenarios with varying thermal insulation, built form, floor size, location, heating duration, thermostat setting and occupancy.

Prediction parameter	Prediction period	Built form	Thermal Insulation 1980	1990	2002	2010	Location Gatwick	Aberdeen	Heating Duration 6 hours	9 hours	12 hours	16 hours	Thermostat Setting 19°C	21°C	23°C	Occupancy Type A	Type B
Mains Supply	All hours 00:00 to 24:00 Mean (kWh)	Det70	11.71	66.93	-8.82	-15.95	66.93	5.35	-10.72	66.93	9.83	14.50	-7.71	66.93	7.38	-4.43	66.93
		SDet70	11.40	61.57	-9.49	-15.40	61.57	4.91	-9.53	61.57	8.81	12.38	-7.45	61.57	7.15	-4.79	61.57
		MTer70	8.53	55.92	-7.73	-11.42	55.92	4.29	-7.70	55.92	7.52	10.17	-6.55	55.92	6.70	-4.59	55.92
		Flat70	5.92	52.60	-5.25	-7.40	52.60	3.75	-6.72	52.60	6.57	8.95	-5.43	52.60	5.94	-5.27	52.60
		Det90	14.57	82.53	-11.41	-19.37	82.53	6.46	-12.61	82.53	12.43	18.31	-9.37	82.53	9.70	-4.38	82.53
		SDet90	12.99	75.67	-12.43	-17.52	75.67	6.38	-10.72	75.67	10.71	15.50	-8.72	75.67	9.25	-4.49	75.67
		MTer90	10.97	69.32	-8.92	-14.62	69.32	5.59	-9.05	69.32	9.95	13.30	-8.05	69.32	8.77	-4.43	69.32
		Flat90	6.00	63.25	-5.35	-7.53	63.25	4.53	-8.38	63.25	7.98	10.82	-7.08	63.25	6.44	-5.45	63.25
		Det150	21.40	117.81	-10.84	-22.59	117.81	8.47	-19.12	117.81	19.65	27.84	-13.43	117.81	13.54	-4.64	117.81
		SDet150	17.64	112.95	-14.15	-25.48	112.95	8.94	-17.72	112.95	17.18	25.29	-12.86	112.95	13.42	-4.70	112.95
		MTer150	11.93	107.79	-12.24	-19.92	107.79	7.56	-16.26	107.79	15.06	22.52	-12.76	107.79	12.51	-4.96	107.79
		Flat150	7.95	94.78	-6.56	-10.79	94.78	6.86	-12.62	94.78	12.63	17.50	-10.81	94.78	10.79	-5.11	94.78
Space heating	All hours 00:00 to 24:00 Mean (kWh)	Det70	11.13	55.81	-8.33	-15.01	55.81	4.47	-10.65	55.81	8.73	14.77	-7.03	55.81	6.79	1.67	55.81
		SDet70	10.57	50.79	-8.63	-14.40	50.79	4.24	-9.52	50.79	7.41	12.44	-6.79	50.79	6.42	1.58	50.79
		MTer70	7.80	45.69	-7.38	-11.11	45.69	3.79	-7.81	45.69	6.03	9.93	-6.20	45.69	5.96	1.64	45.69
		Flat70	5.43	42.72	-5.20	-7.36	42.72	3.15	-6.97	42.72	5.11	8.57	-5.37	42.72	5.35	0.98	42.72
		Det90	13.49	71.89	-10.93	-18.28	71.89	5.59	-13.33	71.89	10.70	17.96	-9.10	71.89	8.81	1.63	71.89
		SDet90	11.70	65.38	-11.63	-17.08	65.38	5.35	-11.75	65.38	8.91	15.08	-8.62	65.38	8.47	1.73	65.38
		MTer90	9.89	59.53	-8.88	-14.35	59.53	4.88	-9.80	59.53	7.84	12.65	-7.87	59.53	7.76	1.62	59.53
		Flat90	5.52	53.24	-4.75	-6.91	53.24	3.81	-8.28	53.24	6.43	10.61	-6.53	53.24	6.69	1.06	53.24
		Det150	20.48	107.07	-10.13	-21.16	107.07	7.80	-20.70	107.07	16.53	27.84	-12.97	107.07	12.38	1.67	107.07
		SDet150	16.66	102.19	-13.60	-24.30	102.19	7.98	-18.62	102.19	15.13	25.29	-12.79	102.19	12.47	1.66	102.19
		MTer150	10.62	97.06	-11.93	-18.91	97.06	7.46	-17.00	97.06	13.54	22.57	-12.37	97.06	11.81	1.70	97.06
		Flat150	7.66	85.14	-6.11	-10.06	85.14	5.74	-13.22	85.14	10.30	17.05	-10.33	85.14	10.63	1.17	85.14
	Heated hours 17:00 to 19:00 Mean (kWh)	Det70	2.72	11.71	-2.43	-3.94	11.71	1.11	4.58	11.71	-2.97	-4.77	-2.14	11.71	1.80	0.45	11.71
		SDet70	3.19	14.77	-2.77	-4.63	14.77	1.43	6.24	14.77	-3.39	-5.83	-2.30	14.77	2.36	0.38	14.77
		MTer70	1.93	9.03	-1.69	-2.59	9.03	1.09	4.63	9.03	-2.40	-3.83	-1.45	9.03	1.77	0.44	9.03
		Flat70	1.20	8.21	-1.08	-1.67	8.21	0.87	4.60	8.21	-1.85	-2.91	-1.20	8.21	1.24	0.21	8.21
		Det90	3.19	14.77	-2.77	-4.63	14.77	1.43	6.24	14.77	-3.39	-5.83	-2.30	14.77	2.36	0.38	14.77
		SDet90	2.29	13.12	-3.05	-4.17	13.12	1.35	5.83	13.12	-2.76	-5.02	-2.15	13.12	2.37	0.34	13.12
		MTer90	2.37	11.56	-2.06	-3.25	11.56	1.47	6.26	11.56	-2.88	-4.70	-1.84	11.56	2.19	0.53	11.56
		Flat90	1.30	10.07	-1.08	-1.54	10.07	0.98	5.77	10.07	-2.01	-3.31	-1.45	10.07	1.66	0.17	10.07
		Det150	4.88	21.72	-2.56	-5.35	21.72	1.92	9.61	21.72	-5.29	-7.83	-3.52	21.72	3.10	0.34	21.72
		SDet150	4.00	20.08	-3.02	-5.48	20.08	2.05	9.42	20.08	-3.95	-6.94	-2.99	20.08	3.67	0.31	20.08
		MTer150	2.34	19.20	-2.70	-4.53	19.20	1.71	9.22	19.20	-3.96	-7.02	-2.96	19.20	3.34	0.27	19.20
		Flat150	1.74	16.29	-1.62	-2.49	16.29	1.52	8.85	16.29	-3.14	-5.23	-2.65	16.29	2.55	0.20	16.29
	Heated hours 17:00 to 20:00 Mean (kWh)	Det70	4.13	16.25	-3.03	-5.25	16.25	1.63	5.70	16.25	-3.72	-6.00	-2.78	16.25	2.72	0.56	16.25
		SDet70	4.01	14.30	-2.85	-4.84	14.30	1.52	5.71	14.30	-3.07	-5.13	-2.34	14.30	2.49	0.57	14.30
		MTer70	2.77	12.68	-2.39	-3.79	12.68	1.35	5.60	12.68	-3.05	-4.98	-2.13	12.68	2.27	0.55	12.68
		Flat70	1.98	11.61	-1.45	-2.21	11.61	1.15	5.54	11.61	-2.32	-3.75	-1.62	11.61	1.90	0.36	11.61
		Det90	5.09	20.57	-3.64	-6.35	20.57	2.17	8.05	20.57	-4.28	-7.21	-3.05	20.57	3.42	0.64	20.57
		SDet90	4.02	18.36	-4.00	-5.63	18.36	1.96	7.51	18.36	-3.51	-6.39	-2.72	18.36	3.11	0.54	18.36
		MTer90	3.23	16.40	-3.01	-4.84	16.40	1.65	7.48	16.40	-3.82	-6.12	-2.73	16.40	2.64	0.55	16.40
		Flat90	1.95	14.62	-1.60	-2.30	14.62	1.33	7.16	14.62	-2.86	-4.59	-2.21	14.62	2.25	0.37	14.62
		Det150	8.06	30.11	-3.26	-7.02	30.11	2.86	11.87	30.11	-5.90	-9.57	-4.65	30.11	4.83	0.65	30.11
		SDet150	6.21	28.75	-4.28	-7.75	28.75	2.93	11.30	28.75	-5.42	-9.12	-4.32	28.75	4.88	0.66	28.75
		MTer150	4.27	27.19	-3.66	-6.15	27.19	2.68	11.40	27.19	-5.46	-9.17	-4.07	27.19	4.64	0.55	27.19
		Flat150	2.55	23.67	-2.10	-3.59	23.67	2.20	11.24	23.67	-4.46	-7.08	-3.65	23.67	3.28	0.34	23.67
	Heated hours 17:00 to 21:00 Mean (kWh)	Det70	5.39	20.71	-3.73	-6.82	20.71	2.06	6.44	20.71	-4.31	-7.21	-3.34	20.71	3.35	0.80	20.71
		SDet70	5.17	18.28	-3.40	-6.17	18.28	2.04	6.22	18.28	-3.71	-6.16	-2.87	18.28	3.27	0.81	18.28
		MTer70	3.78	16.26	-3.00	-4.83	16.26	1.70	6.25	16.26	-3.83	-6.09	-2.73	16.26	2.75	0.69	16.26
		Flat70	2.44	15.23	-2.09	-3.05	15.23	1.59	5.95	15.23	-2.93	-4.78	-2.27	15.23	2.36	0.51	15.23
		Det90	6.38	26.40	-4.66	-7.89	26.40	2.58	8.49	26.40	-5.21	-8.82	-4.14	26.40	4.33	0.77	26.40
		SDet90	5.31	23.71	-4.95	-7.24	23.71	2.50	8.42	23.71	-4.39	-7.77	-3.70	23.71	4.08	0.80	23.71
		MTer90	4.49	21.05	-3.67	-6.17	21.05	2.15	8.10	21.05	-4.59	-7.40	-3.44	21.05	3.30	0.62	21.05
		Flat90	2.42	19.11	-1.99	-2.95	19.11	1.62	8.02	19.11	-3.54	-5.81	-2.86	19.11	2.67	0.45	19.11
		Det150	10.44	38.65	-3.92	-8.85	38.65	3.33	12.12	38.65	-6.90	-11.28	-6.08	38.65	5.91	0.68	38.65
		SDet150	8.56	36.86	-4.89	-9.92	36.86	3.41	12.76	36.86	-6.29	-10.98	-5.34	36.86	5.72	0.75	36.86
		MTer150	5.53	34.79	-4.42	-7.77	34.79	3.06	12.78	34.79	-6.27	-10.81	-5.07	34.79	5.42	0.69	34.79
		Flat150	3.42	30.76	-2.64	-4.44	30.76	2.67	12.56	30.76	-5.24	-8.78	-4.50	30.76	4.26	0.53	30.76

During the critical heated hours of 17:00 to 19:00, the Base Case average heat demand is 11.71kWh for the Det70 building archetype, and this rises by 2.72kWh when the thermal insulation changes to the 1980s level. If the thermal insulation is improved to the 2010 recommended level, then the energy demand drops by 3.94kWh from the Base Case. Clearly this is a significant drop given the short duration over which it occurs. The corresponding mains supply energy consumption figures over 24 hours are: a) Base Case value of 66.93kWh; b) Base Case Value plus 11.71kWh (78.64kWh) with 1980s thermal insulation and c) Base Case minus 15.95kWh (50.98kWh) with 2010 insulation level. This shows a mains supply energy consumption impact of +17.5% and -23.8% due to the thermal insulation level changing from the Base Case level to the 1980s and 2010s level respectively.

The graphs in Figure 4-29 illustrates energy consumption impact of the five variables on buildings categorised by floor size and built form. Longer heating duration, low thermal insulation and higher thermostat setting have energy consumption increasing the impact in the same respective order. The increase varies from about 8% to 24% respectively, in relation to the Base Case values. This shows that improvements to these areas in buildings could lead to significant overall energy consumption reduction relative to the Base Case, and potentially benefitting both the supply and the demand side. The location of Aberdeen, due to relatively poorer weather conditions also results in about 4kWh to 13kWh higher energy consumption, which is around a 7% increase from the relevant Base Case level.

Figure 4-29 shows that higher insulation, shorter heating duration and lower thermostat setting reduces energy consumption from the Base Case level by about 7kWh to 20kWh. These provide a good indication as to potential energy consumption reduction significance of these options. However, as discussed previously in this section, some of these would invariably result in reduced thermal comfort and thus may cancel out the benefits.

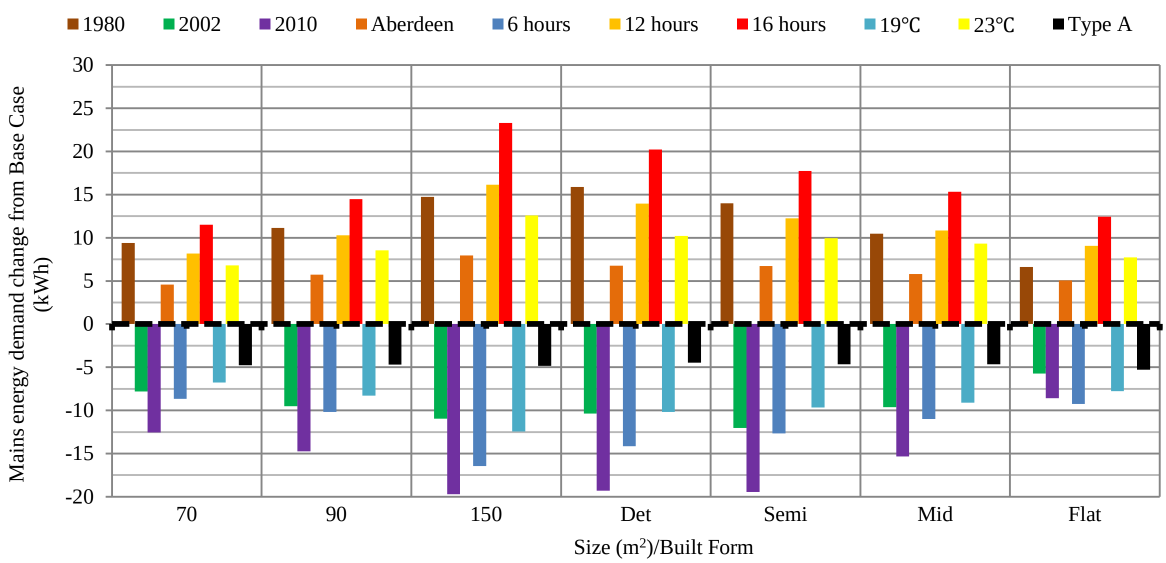


Figure 4-29. Daily mean mains supply energy consumption change from the Base Case values by floor size and built form; due to changes in thermal insulation (1980, 1990, 2002 & 2010), location, heating duration, thermostat setting and occupancy (Type A)

The five energy demand influencing factors affect the energy use during the critical heated hours as illustrated in the bar chart in Figure 4-30. It shows how the space heating only energy consumption during the three DSP periods (17:00-19:00, 17:00-20:00 and 17:00-21:00) change with respect to the mean of all Base Case scenarios, as the variables are altered. It can be seen that short heating duration, low thermal insulation, colder location, fewer occupants and higher thermostat setting all have energy demand increasing impact during the three DSPs in comparison to the same periods in the Base Case. Also longer heating duration, lower thermostat set point and higher insulation levels increase the energy consumption during the DSPs. This indicates the areas to focus on to reduce energy consumption during the DSPs. However, as mentioned before, they can also reduce the thermal comfort level. Therefore, understanding the nature and scale of the impacts is essential as it is linked to the potential ability and effectiveness of shifting the heat demand to off-peak times through the use of TES.

It can be seen that shorter heating duration results in greater energy consumption, varying from 6.77kWh to 9.01kWh, during the critical heated hours. This is because the energy use is concentrated in a relatively short time period, and thus higher energy use occurs during the three DSPs. This suggests that larger TES would be needed to shift demand from the DSP periods when short heating durations are used. Longer heating durations of 12 hours and 16 hours reduces the energy use during the DSPs, for example by 19% and 32% for the 4 hour DSP respectively from the Base Case level. The reason is the spreading of the energy use resulting in greater pre-heating of the buildings to occur before the DSPs, therefore needing less heat during the DSP to maintain the temperature at the thermostat set point. Whilst this could reduce the TES capacity requirement for heat demand shifting, the overall energy use would increase, which may not be acceptable to the household.

Lower thermal insulation (1980s level) increases the energy consumption during the three DSPs by 2.60kWh to 5.28kWh. Detailed examination shows that raising the insulation from the 1980 level to the 1990s (Base Case) level and 2010s level can reduce the energy consumption during the 4 hour DSP (17:00 to 21:00) by about 20% and 25% respectively. The thermal storage capacity need would therefore be reduced on the same scale, making it physically smaller and most likely cheaper. Also, the energy consumption reduction is unlikely to come at the expense of reduced thermal comfort, but rather due to the prevention of heat loss through the building fabric. This will make heat demand shifting using TES more effective and also reduce heating energy cost for the household.

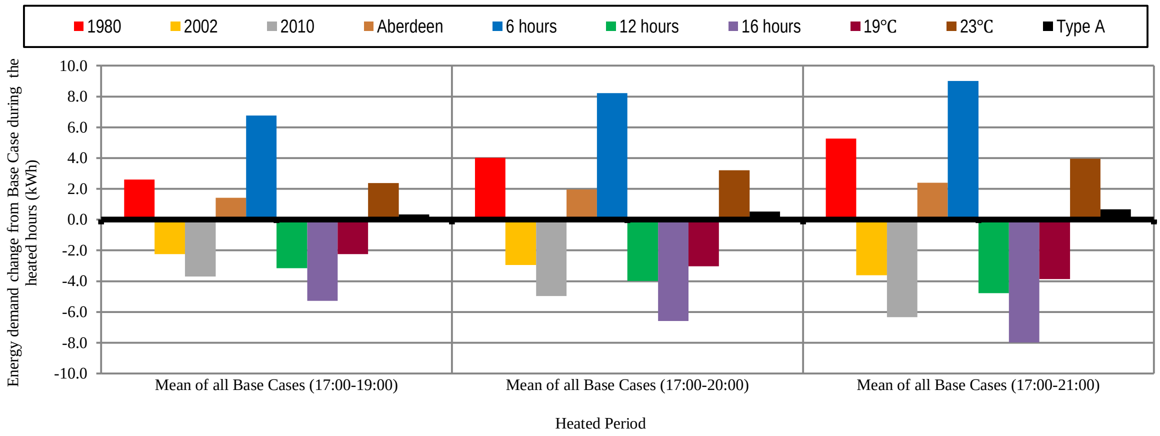


Figure 4-30. Average space heating only energy consumption change during the three DSP periods (17:00-19:00, 17:00-20:00 and 17:00-21:00) with respect to the average of the Base Case values, due to changes in thermal insulation, built form, floor size, location, heating duration, thermostat setting and occupancy.

Lower thermostat set point (19℃) reduces energy consumption during the 4 hour DSP by 3.86kWh which is a 15% reduction compared to the Base Case. Conversely, high thermostat set point (23℃) increases the energy consumption during the same DSP by 3.95kWh which is a 16% rise compared to the Base Case. Whilst low thermostat setting could reduce the TES capacity needs, it could also easily degrade thermal comfort below the commonly accepted value of 18℃ due to having a lower pre-DSP room temperature and thermal mass. This could reduce the demand shifting duration achievable whilst maintaining the room temperature above 18℃. High thermostat set point on the other hand, could lead to achieving longer heat demand shift duration whilst still keeping the room temperature above 18℃, but is likely to result in greater energy consumption. This could make it less attractive for the household.

Location of Aberdeen has a moderate energy consumption increasing impact during the DSPs, around 10% from the Base Case level for the 4 hour DSP. Thus TES systems in buildings in such locations may require correspondingly large capacity to have the same energy demand shifting effect compared to the Base Case.

As expected, reducing the occupants to a single person (Type A) has a relatively small energy consumption increasing impact during the DSPs, about 3% from the

Base Case level for the 4 hour DSP. This is because the occupant numbers only predominantly affect the DHW consumption and internal gain, both of which have relatively small connection to space heating.

The overall impact of varying the five parameters is summarised by the bar chart in Figure 4-31. It illustrates the daily 60 day average mains supply heat energy consumption prediction per unit floor area (kWh/m^2) by each built form and the mean of all four built forms, for all the variables within the five key heat energy influencing parameters investigated. This chart can be used to predict the energy consumption of matching buildings of different sizes. For example, a semi-detached dwelling of 100m^2 floor area and a thermal insulation level corresponding to the 2002s building regulation, and all other building operational and occupancy options set to the Base case, can be calculated as 70.0kWh. This is within 3% of the energy consumption measured and published for a semi-detached dwelling with similar characteristics. The average (of all four built forms) energy consumption with 98m^2 floor area and 2002 level of thermal insulation can be calculated as 68.6kWh, and this is within 2.4% of the published mean energy consumption of 36 dwellings with 98m^2 mean floor area and thermal insulation corresponding to the 2002 level as previously discussed in Sections 3.5.10 and 2.5.4. These indicate that the energy consumption predictions generated using the models are in good agreement with measured and published real world data, and the results generated are valid.

The results presented in this section show that the detached built, semi-detached, mid-terrace and flat built-forms are energy consuming in that respective order, and therefore should be targeted in that order for energy performance improving interventions. The obvious intervention should be to improve the thermal insulation as it can significantly reduce the energy per unit floor area, for example for the detached dwelling the energy consumption drops from 1.04kWh/m^2 to 0.69kWh/m^2 as the thermal insulation is changed from the 1980 to the 2010 building regulation recommendation.

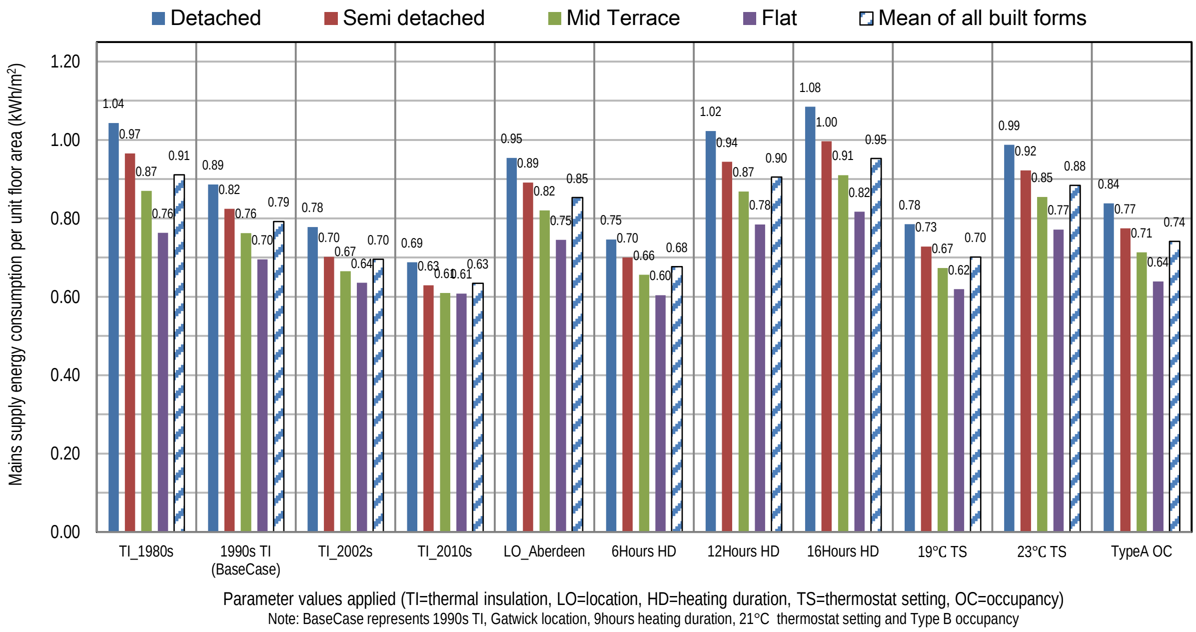


Figure 4-31. 60 day average daily mean mains supply heat energy consumption prediction per unit floor area (kWh/m^2) by built forms and the five key heat energy influencing variables investigated.

The set of graphs presented in Appendix C show the relationship between the space heating only energy consumption and floor area for the detached, semi-detached, mid terrace and flat built forms, and with thermal insulation which is the most critical of the five parameters. The graphs could be utilised to extrapolate the mean space heating only energy consumption for varying floor size.

4.6 Summary

This chapter presented the results of the simulations carried out to explore and understand the thermal performance, power and energy demand characteristics of domestic buildings. No TES and heat demand shifting was applied.

The range of outputs generated by the models and the metrics used to measure the performances are described. Demonstrations of the correct workings of the different model components were illustrated.

The thermal, power and energy demand characteristic predictions of the 12 Base Case scenarios are presented, and how the characteristic predictions change with variations in five of the key thermal and energy performance influencing parameters (thermal insulation, location, heating duration, thermostat setting, occupancy) are explored. The heating energy cost predictions, assuming that resistance element electrical heating with a COP of 1 is employed, are presented based on the electricity price tariff available from one of the six main electricity suppliers in the UK.

The thermal, power and energy demand characteristics during three future heat demand shift periods (17:00-19:00, 17:00-20:00 and 17:00-21:00) are discussed. How these characteristics could change with the varying thermal and energy performance influencing parameters, and potentially change the effects of heat demand shifting using TES are explored.

5 CHAPTER FIVE: RESULTS – IMPACTS AND BENEFITS OF DOMESTIC HDS USING SENSIBLE TES

5.1 Introduction

This chapter presents the results of the simulations carried out to determine the impacts of shifting the heat energy demand during three fixed demand shift periods using sensible TES. Simulations were carried out using the 12 Base Case building models as described previously in Section 3.4. The methodology employed during this analysis is described in Section 3.5.

This chapter is arranged as follows:

Section 5.2: Output variables and the performance analysis metrics: Provides an overview of the simulation output variables for which results are generated and the metrics used to compare the energy and thermal performance of the different building, occupancy and operational scenarios considered.

Section 5.3: TES system function and heat energy demand shift demonstration: Describes the functionality of sensible TES system model in terms of energy storage capacity, extraction and utilisation for serving the domestic space heating needs. The effect of a heat demand shift using the TES system is demonstrated.

Section 5.4: Heat demand analysis in Base Case buildings - Zero TES Case: Describes the results generated to determine the impacts on occupied space temperature, heating power demand, energy consumption and cost impacts of not heating (without any TES) the buildings during three fixed periods (2 hours, 3 hours and 4 hours) from mains grid peak period of 17:00 to 21:00.

Provides the energy cost avoidance analysis results, carried out based on the current standard electricity price tariff available from British Gas Ltd.

Section 5.5: HDS in Base Case buildings – TES Reference Case: Describes the results generated to determine the impacts on occupied space temperature, heating power demand, energy consumption and cost impacts of three fixed period heat demand shifts (2 hours, 3 hours and 4 hours) from mains grid peak period of 17:00 to 21:00 (DSP[18]) to a mains grid off-peak period of 00:00 to 07:00. TES tank sizes of 0.25m^3 and a hot water storage temperature of 75°C were used. The heating system was not permitted to draw energy from the mains grid during the DSPs and therefore the thermal condition of the occupied space was allowed to degrade below the thermostat set-point.

Provides the energy cost saving analysis results, carried out based on the potential electricity bill saving achievable if the shifted energy was purchased at the Economy7 time-of-use off-peak price tariff available from British Gas Ltd.

Section 5.6: Provides a summary of this chapter.

[18] Demand Shift Period (DSP) refers to the heat energy demand shift periods 17:00-19:00, 17:00-20:00 and 17:00-21:00.

5.2 Output variables and performance analysis metrics

The methodology and the input parameters used during this research activity was as described in Section 3.5. As per activity 2 (see chapter 4), the performance prediction data was generated for nine output variables as were shown in Table 5.1. These relate to temperature of the occupied space, power demand and energy demand, which are usually affected by space heating and DHW consumption.

Table 5-1. Performance analysis variables used and the corresponding data generated, recorded and analysed for extracting the relevant heat demand and thermal comfort information.

Performance analysis	Output variable name	Variable description	Performance analysis metrics
Space temperature	GF_T	Ground floor air temperature	7. DSP_minimum_GF_T 8. %DSP_T>18℃
	FF_T	First floor air temperature	
	Amb_T	External air temperature	
Power demand	Mains_supply_load_kW	Whole building power demand	
	Heating_load_kW	Space heating only power demand	
	DHW_load_kW	DHW only power demand	
Energy demand	Mains_supply_kWh	Mains supply daily energy demand	9. TES_tank_energy_kWh
	Space_heating_only_kWh	Heating only daily energy demand	10. Energy_cost_saving/day
	DHW_only_kWh	DHW only daily energy demand	

To enable comparison of the performance of the different simulation scenarios considered, four further metrics were used in addition to the 6 metrics described previously in Section 4.2 (See Table 5-1). Metrics 7 (*DSP_minimum_GF_T*) represents the absolute minimum ground floor air temperature reached during the DSP periods. Metric 8 *(%DSP_T>18℃*) represents the percentage of time of the DSP the air temperature remains above the thermal comfort threshold of 18℃. A temperature of 18℃ is usually taken as a value above which space temperatures should remain in order to ensure thermal comfort. Metric 9 *(TES_tank_energy_kWh)* represents the heat energy supplied by the TES tank for DHW and space heating during the DSP and is the amount of energy shifted in time. Metric 10 *(Energy_cost_saving/day)* represents the potential energy bill saving due to buying the energy shifted in time at the discounted price equivalent to the currently available Economy7 electricity price tariff.

5.3 TES system function and heat energy demand shift demonstration

TES Operation

Figure 5-1 illustrates the charging and discharging of a TES system of 0.25m^3 volume applied to the Det70 Base Case building on a sample day in January. The system is setup to provide 21°C occupied space temperature as shown by the 'Thermostat_Set' trace. Energy from the supply is allowed to be drawn during all times except the DSP (17:00 to 21:00). The 'T_Top' and 'T_Bottom' represent the water temperature at the top and bottom of the TES tank respectively. This is caused by the temperature stratification in the stored water, and also due to the hot and cold water entering and leaving the tank to and from the top and bottom respectively. The Mains_supply_load_kW represents the power demand from the mains electricity grid. It can be seen that the water temperature rises (during charging from the mains supply) at 00:00 hours reaching the maximum set-point of 95°C, and remains at this level until 07:00. It starts to drop after this time due to the heat loss through the tank surface area, and because the mains supply is not allowed to replenish the lost heat. The mains supply power demand rises as energy is drawn during the morning heating period (07:00 to 09:00). During the evening heating period (16:00 to 23:00) the mains supply power demand again rises until it is prevented from being used during the DSP. As the mains supply stops at 17:00 water temperature drops rapidly as the stored water is circulated around the heating loop and the stored heat is pumped into the occupied space. The stored water continues to be circulated until the end of the DSP. The mains supply power demand rises again at 21:00 at the end of the DSP, when the heating system is again allowed to draw energy from the mains supply.

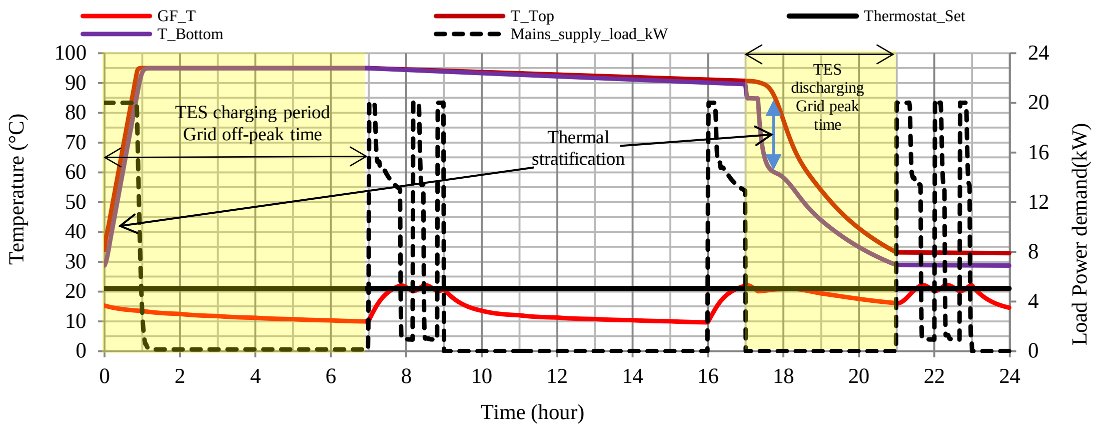


Figure 5-1. Illustration of the stored water temperature profiles (T_Top, T_bottom), mains supply power demand (Mains_supply_load_W) for a sample winter day with a 4 hour heat energy demand shift using a 0.25m³ TES system.

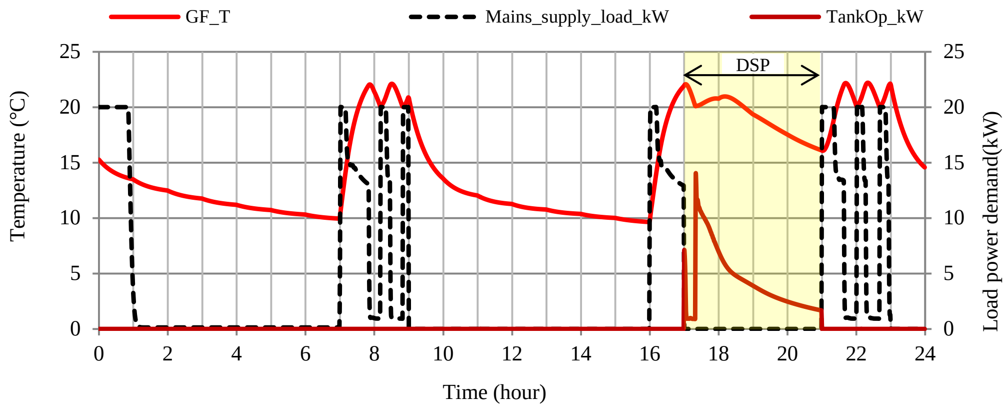


Figure 5-2. Illustration of the occupied space temperature response (GF_T), and power demand from the mains supply (Mains_supply_load_kW) and a 0.25m^3 TES system (TankOp_kW), with a 4 hour heat energy demand shift during a winter day in January.

The effect of the heat demand shifting arrangement on the thermal conditions of the occupied space is illustrated in Figure 5-2. The 'Mains_supply_load_kW' trace illustrates the power demand from the mains supply. The shaded region represents the DSP during which energy from the mains supply is prevented from being drawn, and heat is supplied from the TES system. This is represented by the 'TankOp_kW' trace'. It can be seen that during the DSP the space temperature 'GF_T' drops below 20℃ just before 19:00 and reaches a minimum value of about 16℃ at 21:00 as a result of the TES store being depleted. At 21:00 the heating system was able to draw power from the mains supply again and restore the space temperature to the thermostat set point.

The cumulative mains supply energy consumption predictions (Total_Q_Mains_kWh), the DHW energy use and the space heating energy use (Total_Q_DHW_kWh and Total_Q_SpaceHeating_kWh) and the energy supplied by the TES tank (Total_TES_tank_energy_kWh) are illustrated in Figure 5-3. The Total_Q_Mains_kWh which represents the load applied to the grid, has a zero gradient part during the DSP, from 17:00 to 21:00, and a positive gradient part from 00:00 to about 01:00. This simulated heat energy demand shift in time from the grid peak time of 17:00 to 21:00 to an off-peak time of 00:00 to about 01:00. The Total_Q_tank_energy_kWh profile, which did not exist in the Base Case, represents the energy supplied from the TES system, and was only active during the heat demand shift period. This flattens out towards the end of the DSP as the stored heat gets depleted. The Total_Q_SpaceHeating_kWh and the Total_Q_DHW_kWh had positive gradients during the DSP periods resulting from the energy supply from the TES tank.

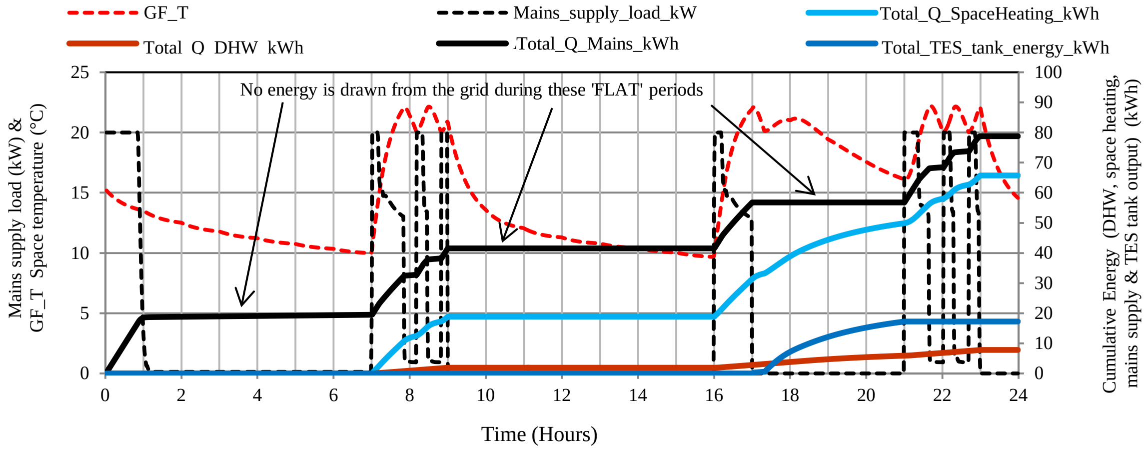


Figure 5-3. Illustration of the heat demand shift impact on mains supply energy draw , space heating energy consumption, DHW energy consumption and TES tank energy supply for a sample day in January when heating is prevented for 4 hours (17:00 to 21:00) during the evening occupied hours and a 0.25m^3 TES applied.

5.4 Heat demand analysis in Base Case buildings - Zero TES Case

This section presents the results generated to determine the impacts of not heating the buildings on the occupied space thermal conditions, power and energy demands and the heating energy cost of not heating (without any TES) the buildings for three fixed heat demand shift periods (2 hours, 3 hours and 4 hours) from mains grid peak period beginning at 17:00. The model configuration, variable settings and the methodology utilised in generating these results is described in Section 3.7.

5.4.1 Space temperature

Figure 5-4 illustrates the ground floor room temperature, mains supply power demand, and the energy draw profile for a sample day in January for the dwelling represented by the Base Case Det70. In this example, the heating system is inhibited for four hours from 17:00 to 21:00. As a result, the mains grid power demand and thus the energy consumption in this period is zero. This form of load profiles may benefit the supply side in future scenarios where the grid load peaks unsustainably during this period due greater electrification of heating, and daily grid load balancing becoming problematic. However, it comes at the expense of the thermal comfort in the living space as shown in Figure 5-4. The room temperature (T_GF) declines from 17:00 and reaches a minimum value of about 12℃ at 21:00 before rising towards the thermostat set point as the heating system is able to operate again. In this example, the room temperature remains below the thermal comfort threshold of 18℃ for around three and half hours, and may be unacceptable to many households.

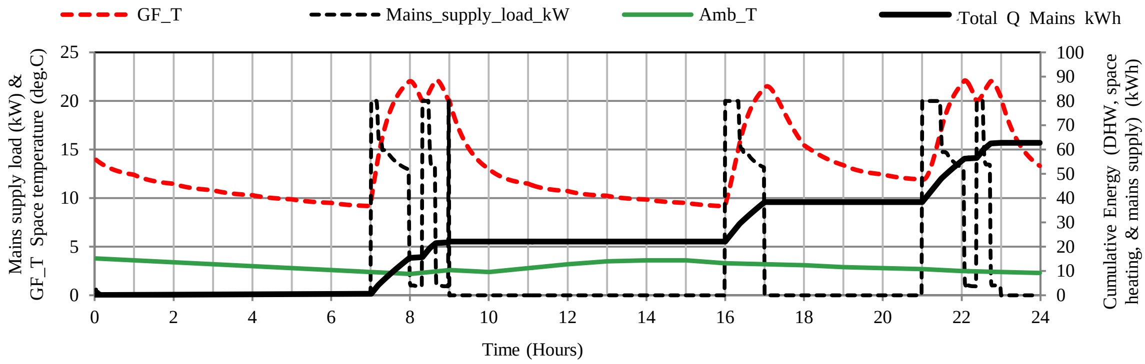


Figure 5-4. Daily profile of the ground floor (GF_T) & external ambient (Amb_T) temperatures, mains supply power demand (Mains_supply_load_kW) and the mains supply energy draw profile (Total_Q_Mains_kWh) for a sample day in January when heating is prevented for 4 hours (17:00 to 21:00) during the evening occupied hours and without using TES.

Table 5-2 provides a summary of the ground floor air temperature impact of not heating for the three DSPs during the occupied hours, averaged over the 60 winter days. The table shows the mean of the daily average (Metric 1), the mean of the daily maximum and the mean of the daily minimum room temperatures. The mean of the daily average (Metric 2) temperature and the mean of the minimum temperatures during the respective heating inhibited periods are shown. Percentage of the inhibited period which remains at 18℃ or higher (Metric 8) are also provided. The difference between the Base Case results, as discussed in Chapter 4, and those obtained with heat demand shifting with Zero TES, is also shown, indicating the room temperature impact predictions. The results are categorised by floor area, as before, to allow comparisons to be made.

It can be seen that inhibiting heating during the occupied hours has a reducing impact on the daily mean temperature (Metric 1), dropping it by around 1.2℃ in larger dwellings and about 1℃ in the smaller dwellings compared to the Base Case values. The 60 day minimum temperature was lowest for the larger 150m^2 detached dwelling at 4.39℃, and is a 4.57℃ reduction from the corresponding Base Case value. The minimum temperatures occur during the unheated hours and therefore not directly linked to the occupied heated hour thermal comfort.

The room temperatures during the three DSPs (heating inhibited periods) are of particular interest, and we can see that the 60 day mean (Metric 6) and 60 day minimum (Metric 7) values vary from 14.59℃ to 18.63℃ and 7.36℃ to 13.23℃ respectively. As expected, the mean and the minimum room temperatures were the lowest during the longest of the three DSPs.

Table 5-2. Summary of the 60 day average, minimum and maximum temperature predictions with the main heating system inhibited for three periods during the evening occupied hours and when no TES is applied.

			All hours 00:00-24:00			DSP/Heating 'Inhibited' hours 17:00-19:00			DSP/Heating 'Inhibited' hours 17:00-20:00			DSP/Heating 'Inhibited' hours hours 17:00-21:00		
	Size	Base Case ID	Mean (Metric 1) (℃)	Max. (℃)	Min. (℃)	Mean (Metric 2) (℃)	Min (Metric7) (℃)	%DSP_T>18°C (Metric 8) (%)	Mean (Metric 2) (℃)	Min (Metric7) (℃)	%DSP_T>18°C (Metric 8) (%)	Mean (Metric 2) (℃)	Min (Metric7) (℃)	%DSP_T>18°C (Metric 8) (%)
HDS with Zero TES	70m²	Det70	15.10	22.21	5.93	17.16	11.02	27%	16.19	9.88	18%	15.42	8.88	13%
		SDet70	15.51	22.35	6.48	17.79	11.78	34%	16.83	10.68	22%	16.04	9.69	16%
		MTer70	16.12	22.44	8.02	18.28	13.09	40%	17.45	12.07	27%	16.75	11.12	19%
		Flat70	16.23	22.54	8.57	18.61	13.18	48%	17.54	11.95	31%	16.61	10.80	22%
	90m²	Det90	15.18	22.23	6.00	17.22	11.01	28%	16.18	9.82	19%	15.34	8.83	14%
		SDet90	15.66	22.33	7.45	17.68	12.09	33%	16.70	10.96	22%	15.92	9.95	16%
		MTer90	16.10	22.43	7.72	18.24	12.86	40%	17.35	11.71	27%	16.62	10.77	20%
		Flat90	16.31	22.54	9.09	18.63	13.23	50%	17.52	11.81	31%	16.58	10.85	22%
	150m²	Det150	14.58	22.18	4.39	16.57	9.77	24%	15.45	8.46	16%	14.59	7.36	12%
		SDet150	14.97	22.20	5.54	16.99	10.46	27%	15.85	9.16	18%	14.99	8.19	13%
		MTer150	15.29	22.24	6.47	17.29	11.32	30%	16.22	10.00	20%	15.37	9.00	14%
		Flat150	15.95	22.31	8.77	18.02	12.60	39%	16.88	11.38	26%	15.91	10.26	18%
Change from Base Case Buildings	70m²	Det70	-1.15	-0.25	-4.51	-3.93	-8.94	-73%	-5.11	-10.09	-82%	-5.89	-11.08	-87%
		SDet70	-1.05	-0.25	-4.31	-3.41	-8.23	-66%	-4.55	-9.33	-78%	-5.34	-10.31	-84%
		MTer70	-0.94	-0.24	-3.85	-2.95	-6.92	-60%	-3.95	-7.93	-73%	-4.67	-8.89	-81%
		Flat70	-0.96	-0.19	-3.69	-2.73	-6.84	-52%	-3.94	-8.06	-69%	-4.88	-9.21	-78%
	90m²	Det90	-1.15	-0.21	-4.48	-3.92	-8.99	-72%	-5.12	-10.17	-81%	-5.97	-11.16	-86%
		SDet90	-1.11	-0.19	-4.03	-3.50	-7.93	-67%	-4.62	-9.05	-78%	-5.41	-10.05	-84%
		MTer90	-0.93	-0.22	-3.89	-2.98	-7.16	-60%	-4.04	-8.31	-73%	-4.79	-9.24	-80%
		Flat90	-0.97	-0.17	-3.58	-2.70	-6.79	-50%	-3.95	-8.20	-69%	-4.90	-9.16	-78%
	150m²	Det150	-1.18	-0.16	-4.57	-4.48	-10.21	-76%	-5.76	-11.51	-84%	-6.65	-12.61	-88%
		SDet150	-1.18	-0.16	-4.48	-4.07	-9.55	-73%	-5.38	-10.85	-82%	-6.25	-11.81	-87%
		MTer150	-1.14	-0.16	-4.22	-3.82	-8.70	-70%	-5.03	-10.01	-80%	-5.89	-11.01	-86%
		Flat150	-1.07	-0.13	-3.57	-3.15	-7.42	-61%	-4.43	-8.63	-74%	-5.40	-9.75	-82%

Note
Metric 1: Daily_mean_GF_T (daily mean ground floor space temperature averaged over 60 days)
Metric 2: DSP_hours_mean_GF_T (DSP mean temperature averaged over 60 days where: a=17:00-19:00, b=17:00-20:00, c=17:00-19:00)
Metric 7: DSP_minimum_GF_T (DSP overall minimum temperature of 60 days)
Metric 8: %DSP_T>18°C (% DSP temperature above thermal comfort level of 18℃ averaged over 60 days)

The thermal comfort impact is illustrated by Metric 8 (%DSP_T>18℃) showing the percentage of the DSP during which the temperature remains higher than 18℃. The preferred thermal comfort is 100%, which means that the temperature does not drop below 18°C during the DSP. We can see that when the DSP is 2 hours, the room temperature stays higher than 18℃ for only 24% of that period, or only 29 minutes out of 120, for the Det150 building. It improves to 50%, or 60 minutes out of 120, for the Flat90 archetype. The 60 day minimum temperatures during the same periods are 9.77℃ and 13.23℃. But, when the DSP increases to 4 hours, the room temperature stays higher than 18℃ for only 12% of that period, or only 29 minutes out of 240 minutes, for the Det150 building, and improves to only 22%, or 53 minutes out of 240 minutes, for the Flat90 archetype. The corresponding 60 day minimum temperature during the same period varies from 7.36℃ to 10.85℃. Clearly, as the DSP duration increases, the thermal condition degrades as well. Compared to the Base Case, the degradation is very significant. For example, the room temperature staying higher than 18℃ in Flat70 for the 2 hour and 4 hour DSPs reduces by 52% and 78% respectively, from the Base Case value. The results show that Built form and Size affect thermal comfort as mentioned above.

Table 5-3. Summary of the 60 day average thermal condition predictions with the main heating system inhibited for three periods during the evening occupied hours and when no TES is applied.

			All hours (mean) 00:00-24:00			Heated hours 17:00-19:00			Heated hours 17:00-20:00			Heated hours 17:00-21:00		
TES intervention	Category	Sub category	Mean (°C)	Max. (°C)	Min. (%)	Mean (°C)	Min (°C)	%DSP_T>18°C (%)	Mean (°C)	Min (°C)	%DSP_T>18°C (%)	Mean (°C)	Min (°C)	%DSP_T>18°C (%)
none	Size	70m²	15.74	22.38	7.25	17.96	12.27	37.2%	17.00	11.14	24.6%	16.20	10.12	17.5%
		90m²	15.81	22.38	7.56	17.93	12.30	38.0%	16.93	11.08	24.9%	16.11	10.10	17.8%
		150m²	15.20	22.23	6.29	17.22	11.04	29.9%	16.10	9.75	20.0%	15.22	8.70	14.5%
	Built form	Detached	14.95	22.20	5.44	16.98	10.60	26.4%	15.94	9.39	17.7%	15.11	8.36	12.7%
		Semi detached	15.38	22.29	6.49	17.49	11.44	31.4%	16.46	10.26	21.0%	15.65	9.28	15.2%
		Mid terrace	15.84	22.37	7.40	17.93	12.42	36.7%	17.01	11.26	24.7%	16.24	10.30	17.7%
		Flat	16.16	22.46	8.81	18.42	13.00	45.6%	17.31	11.72	29.4%	16.36	10.64	20.7%
	All	Overall average	15.58	22.33	7.04	17.70	11.87	35.0%	16.68	10.66	23.2%	15.84	9.64	16.6%

A summary of the temperatures are provided in Table 5-3, showing the mean of the 60 days, categorised by floor sizes and the built forms considered. An overall mean of all 12 Base Case scenarios is also provided. As shown, the predicted lowest minimum room temperature average of all 12 buildings during the three heating inhibited periods is 9.64℃ and occurs for the 4 hour DSP. This figure remains marginally higher for the 2 and 3 hour DSP. The lowest and the highest percentage of the heating inhibited period during which the room temperature average of all 12 buildings remaining higher than 18℃ is 16.6% and 35.0% respectively. This implies, for example, that on average if the heating is inhibited for 2 hours then the room temperature would remain below the normally accepted temperature for thermal comfort for around 78 minutes out of 120 minutes. This worsens to over 200 minutes out of 240 minutes when a 4 hour DSP is considered. These indicate that heating inhibition during the occupied hours could degrade the thermal comfort level in the occupied space significantly and, therefore, may be harmful for the health and wellbeing of the occupants.

5.4.2 Power demand

The daily mains supply heating load profile which results from the lack of use of heat during the heated hours is relatively simple as shown previously in Figure 5-4. It shows that no loading of the mains supply occurs during the inhibited period and therefore would not add to the grid peak (See Section 2.2.3). Therefore, this form of load profiles may benefit the supply side in future scenarios where the grid load peak demand and supply becomes challenging to match due to greater uptake of, for example, electric heating and electric vehicles. However, this is achieved without meeting the heating service needs, and most likely to be unacceptable to the occupants.

5.4.3 Energy consumption

Table 5-4 summarises the space heating energy consumption predictions resulted from the three inhibited heating periods for the 12 building archetypes. Differences between the energy consumption values for simulations with heating inhibition and the Base Case (without heating inhibition) for the three DSP has been presented, showing the mean of the daily average, the 60 day maximum and the 60 day minimum values. The results are organised by dwelling size to enable easier comparison.

Table 5-4 also shows the daily mean energy use avoided and the corresponding energy cost saving incurred as a result of the heating inhibition. The daily mean mains supply energy consumption reduces from the Base Case figure as shown. For example, for the Det70 building the mains supply energy consumption reduces by 4.92kWh, 9.64kWh and 14.67kWh respectively for the three DSPs compared to the Base Case values. These increase to 7.75kWh, 16.26kWh and 24.52kWh respectively for the larger Det150 building. Size clearly affects the energy consumption reduction achieved. Likewise, built form also affect the energy consumption reduction, for example the reduction in the mean mains supply energy consumption varies from 12.29kWh, 13.21kWh, 14.13kWh and 16.95kWh respectively for the Flat90, MTer90, SDet90 and the Det90 buildings.

The daily mean energy cost saving can vary from £1.24/day to £5.83/day depending on the building size, built form and the DSP for which the heating has been inhibited. The cost saving, however, is achieved without meeting the heating service needs.

Table 5-4. Prediction of the 60 day average daily maximum, minimum and mean space heating only energy consumption change during the three heating inhibited periods (or DSPs). The Base Case space heating energy consumption is shown for comparison purposes.

		Floor Size	Building Archetype	Space heating energy only			Mains Supply energy			Energy use avoided			Energy Saving per day		
				Heated hours 17:00-19:00 (kWh)	Heated hours 17:00-20:00 (kWh)	Heated hours 17:00-21:00 (kWh)	Heated hours 2hDSP (kWh)	Heated hours 3hDSP (kWh)	Heated hours 4hDSP (kWh)	Heated hours 17:00-19:00 (kWh)	Heated hours 17:00-20:00 (kWh)	Heated hours 17:00-21:00 (kWh)	Heated hours 17:00-19:00 (£)	Heated hours 17:00-20:00 (£)	Heated hours 17:00-21:00 (£)
TES Base Case	Mean	70m²	Det70	2.97	3.02	3.02	62.01	57.29	52.26	11.71	16.25	20.71	1.77	2.45	3.12
			SDet70	2.91	2.98	3.02	57.34	52.84	48.62	10.24	14.30	18.28	1.54	2.16	2.76
			MTer70	2.72	2.82	2.87	52.38	48.54	44.81	9.03	12.68	16.26	1.36	1.91	2.45
			Flat70	2.72	2.79	2.78	49.47	45.80	42.18	8.21	11.61	15.23	1.24	1.75	2.30
		90m²	Det90	3.71	3.76	3.75	77.28	70.94	65.58	14.77	20.57	26.40	2.23	3.10	3.98
			SDet90	3.42	3.53	3.60	71.18	65.91	61.54	13.12	18.36	23.71	1.98	2.77	3.58
			MTer90	3.35	3.45	3.52	65.39	60.59	56.10	11.56	16.40	21.05	1.74	2.47	3.18
			Flat90	3.24	3.34	3.38	59.72	55.04	50.96	10.07	14.62	19.11	1.52	2.20	2.88
		150m²	Det150	4.36	4.41	4.41	110.06	101.55	93.29	21.72	30.11	38.65	3.28	4.54	5.83
			SDet150	4.42	4.50	4.53	105.44	97.21	90.18	20.08	28.75	36.86	3.03	4.34	5.56
			MTer150	4.32	4.44	4.50	100.91	92.94	87.03	19.20	27.19	34.79	2.90	4.10	5.25
			Flat150	4.02	4.17	4.26	89.37	82.91	76.31	16.29	23.67	30.76	2.46	3.57	4.64
	Maximum	70m²	Det70	3.43	3.51	3.55	81.48	74.50	65.31	18.25	25.63	31.93	2.75	3.86	4.81
			SDet70	3.37	3.45	3.48	75.79	69.99	63.90	16.57	22.64	28.73	2.50	3.41	4.33
			MTer70	3.27	3.34	3.37	70.04	64.12	59.77	14.35	20.02	24.99	2.16	3.02	3.77
			Flat70	3.10	3.28	3.31	66.77	61.19	56.63	12.55	17.21	22.99	1.89	2.60	3.47
		90m²	Det90	4.24	4.34	4.38	102.13	93.46	83.72	23.20	31.86	40.43	3.50	4.80	6.10
			SDet90	4.16	4.26	4.29	93.97	85.89	79.56	20.45	28.39	36.11	3.08	4.28	5.45
			MTer90	4.09	4.19	4.21	88.66	81.37	74.49	17.64	25.27	32.58	2.66	3.81	4.91
			Flat90	3.85	3.94	3.98	77.90	69.37	65.44	15.29	22.39	29.17	2.31	3.38	4.40
		150m²	Det150	5.17	5.29	5.32	142.77	132.67	119.44	33.40	46.02	58.72	5.04	6.94	8.85
			SDet150	5.11	5.23	5.26	140.42	129.01	117.53	31.78	44.53	56.63	4.79	6.71	8.54
			MTer150	5.03	5.15	5.19	132.98	125.33	111.35	30.20	41.99	52.87	4.55	6.33	7.97
			Flat150	4.64	4.74	4.98	117.94	110.83	101.95	24.78	35.51	45.77	3.74	5.35	6.90
	Minimum	70m²	Det70	2.31	2.26	2.33	46.08	42.52	40.66	6.77	9.50	12.19	1.02	1.43	1.84
			SDet70	1.94	2.05	2.27	39.79	36.13	34.28	5.19	7.86	10.48	0.78	1.19	1.58
			MTer70	2.30	2.30	2.32	36.74	33.75	32.59	4.77	7.16	9.29	0.72	1.08	1.40
			Flat70	1.45	1.39	1.45	34.93	31.62	30.51	4.19	5.39	7.81	0.63	0.81	1.18
		90m²	Det90	2.85	2.97	2.89	55.55	50.98	48.78	8.14	11.61	15.18	1.23	1.75	2.29
			SDet90	2.73	2.73	2.76	49.96	46.93	46.46	7.45	10.50	13.64	1.12	1.58	2.06
			MTer90	2.60	2.57	2.70	44.26	43.12	40.65	6.46	9.15	12.49	0.97	1.38	1.88
			Flat90	1.99	1.93	1.99	41.58	40.14	36.58	6.07	9.06	12.02	0.91	1.37	1.81
		150m²	Det150	3.29	3.29	3.33	79.47	74.04	69.21	11.19	16.95	23.88	1.69	2.56	3.60
			SDet150	3.38	3.39	3.42	78.20	72.14	66.83	10.93	15.62	21.59	1.65	2.36	3.26
			MTer150	3.39	3.39	3.43	74.55	70.09	65.28	10.51	14.86	21.76	1.58	2.24	3.28
			Flat150	3.33	3.46	3.39	64.65	60.83	58.40	10.66	16.58	21.14	1.61	2.50	3.19
Change from Base Case Buildings	Mean	70m²	Det70	-8.74	-13.23	-17.68	-4.92	-9.64	-14.67	11.71	16.25	20.71	1.77	2.45	3.12
			SDet70	-7.33	-11.32	-15.26	-4.22	-8.73	-12.95	10.24	14.30	18.28	1.54	2.16	2.76
			MTer70	-6.32	-9.86	-13.38	-3.54	-7.38	-11.11	9.03	12.68	16.26	1.36	1.91	2.45
			Flat70	-5.50	-8.82	-12.44	-3.12	-6.80	-10.41	8.21	11.61	15.23	1.24	1.75	2.30
		90m²	Det90	-11.06	-16.81	-22.64	-5.25	-11.59	-16.95	14.77	20.57	26.40	2.23	3.10	3.98
			SDet90	-9.70	-14.83	-20.11	-4.48	-9.76	-14.13	13.12	18.36	23.71	1.98	2.77	3.58
			MTer90	-8.21	-12.94	-17.54	-3.93	-8.72	-13.21	11.56	16.40	21.05	1.74	2.47	3.18
			Flat90	-6.83	-11.28	-15.73	-3.53	-8.21	-12.29	10.07	14.62	19.11	1.52	2.20	2.88
		150m²	Det150	-17.36	-25.70	-34.25	-7.75	-16.26	-24.52	21.72	30.11	38.65	3.28	4.54	5.83
			SDet150	-15.66	-24.25	-32.33	-7.50	-15.74	-22.77	20.08	28.75	36.86	3.03	4.34	5.56
			MTer150	-14.88	-22.76	-30.29	-6.88	-14.85	-20.77	19.20	27.19	34.79	2.90	4.10	5.25
			Flat150	-12.27	-19.50	-26.51	-5.41	-11.87	-18.48	16.29	23.67	30.76	2.46	3.57	4.64
	Maximum	70m²	Det70	-14.83	-22.11	-28.38	-7.75	-14.74	-23.92	18.25	25.63	31.93	2.75	3.86	4.81
			SDet70	-13.20	-19.19	-25.25	-8.11	-13.91	-20.01	16.57	22.64	28.73	2.50	3.41	4.33
			MTer70	-11.07	-16.68	-21.62	-5.97	-11.89	-16.24	14.35	20.02	24.99	2.16	3.02	3.77
			Flat70	-9.45	-13.93	-19.68	-2.78	-8.36	-12.92	12.55	17.21	22.99	1.89	2.60	3.47
		90m²	Det90	-18.96	-27.51	-36.05	-8.98	-17.65	-27.39	23.20	31.86	40.43	3.50	4.80	6.10
			SDet90	-16.29	-24.13	-31.82	-10.07	-18.14	-24.47	20.45	28.39	36.11	3.08	4.28	5.45
			MTer90	-13.54	-21.09	-28.37	-6.21	-13.49	-20.37	17.64	25.27	32.58	2.66	3.81	4.91
			Flat90	-11.44	-18.45	-25.19	-6.60	-15.13	-19.06	15.29	22.39	29.17	2.31	3.38	4.40
		150m²	Det150	-28.23	-40.74	-53.40	-16.89	-26.99	-40.23	33.40	46.02	58.72	5.04	6.94	8.85
			SDet150	-26.67	-39.29	-51.37	-14.72	-26.12	-37.60	31.78	44.53	56.63	4.79	6.71	8.54
			MTer150	-25.16	-36.84	-47.68	-10.73	-18.38	-32.36	30.20	41.99	52.87	4.55	6.33	7.97
			Flat150	-20.14	-30.76	-40.78	-8.64	-15.75	-24.63	24.78	35.51	45.77	3.74	5.35	6.90
	Minimum	70m²	Det70	-4.47	-7.24	-9.85	-1.94	-5.50	-7.36	6.77	9.50	12.19	1.02	1.43	1.84
			SDet70	-3.25	-5.81	-8.21	-2.19	-5.85	-7.70	5.19	7.86	10.48	0.78	1.19	1.58
			MTer70	-2.47	-4.85	-6.96	-2.95	-5.94	-7.10	4.77	7.16	9.29	0.72	1.08	1.40
			Flat70	-2.74	-4.01	-6.36	-1.87	-5.18	-6.29	4.19	5.39	7.81	0.63	0.81	1.18
		90m²	Det90	-5.29	-8.64	-12.29	-4.53	-9.10	-11.30	8.14	11.61	15.18	1.23	1.75	2.29
			SDet90	-4.72	-7.77	-10.88	-3.78	-6.81	-7.28	7.45	10.50	13.64	1.12	1.58	2.06
			MTer90	-3.86	-6.58	-9.80	-5.47	-6.60	-9.08	6.46	9.15	12.49	0.97	1.38	1.88
			Flat90	-4.07	-7.13	-10.03	-3.69	-5.14	-8.70	6.07	9.06	12.02	0.91	1.37	1.81
		150m²	Det150	-7.90	-13.67	-20.55	-3.67	-9.09	-13.93	11.19	16.95	23.88	1.69	2.56	3.60
			SDet150	-7.55	-12.23	-18.18	-0.46	-6.52	-11.84	10.93	15.62	21.59	1.65	2.36	3.26
			MTer150	-7.12	-11.47	-18.33	-2.29	-6.75	-11.57	10.51	14.86	21.76	1.58	2.24	3.28
			Flat150	-7.33	-13.12	-17.75	-2.71	-6.53	-8.96	10.66	16.58	21.14	1.61	2.50	3.19

When the daily minimum and maximum energy consumption are analysed, we can see that the reduction from the Base Case level can vary from 1.87kWh (for Flat70 with a 2 hour DSP) to 40.23kWh (for the Det150 with a 4 hour DSP). The corresponding energy cost avoidance varies from £0.63/day to £8.85/day. These illustrate the range of heat demand reduction possible and the range of energy cost saving possibilities, based on the current price of electricity, but achievable at the expense of thermal comfort if TES was not used. These also indicate the range of heat energy values that can be shifted to off-peak times through the use of TES and the potential cost savings possible.

5.5 HDS in Base Case buildings – TES Reference Case

This section presents the results of the temperature, power and energy demand characteristic predictions of the Base Case scenarios when heat demand shifting from the grid peak time to a grid off peak time is implemented using sensible TES. All 12 Base Case archetypes models were upgraded to include a 0.25m^3 cylindrical hot water storage tank simulating a sensible heat store at 75℃. The size of the TES was selected such that it could be retrofitted into existing buildings and heating systems relatively easily. DSPs of 2, 3 and 4 hours, from 17:00 hours, were simulated with the TES supplying stored heat during these periods. The heating energy cost predictions are presented which are based on the electricity price tariff available from British Gas Ltd. (one of the six main electricity suppliers in the UK). The model configuration, variable settings and the methodology utilised in generating these results is described in Section 3.7.

5.5.1 Space temperature

Figure 5-5 illustrates daily mean occupied space temperature (GF_T), mains supply load (Mains_supply_load_kW), space heating power demand (Heating_load_kW) and the TES tank power demand (TES_load_kW) profiles simulated for the Det70 built form for a sample day in January. This simulation attempted to shift the heat demand for 4 hours from 17:00 to 21:00. The ‘Mains_supply_load_kW’ trace indicates the power demand between 00:00 to about 01:00 for charging the TES system (see point A). During the morning occupied period the air temperature behaves as expected as power is drawn from the mains supply to meet the heat demand. However, during the evening occupied period the indoor air temperature begins to rise at 16:00 and reaches 21℃ (thermostat set point) drawing power from the mains supply. At 17:00 the DSP period kicks in and no power is allowed to be drawn from the mains supply until 21:00, and instead heat from the TES is used. This is illustrated by trace ‘TES_tank_load_kW’ which is active during the DSP period (see point B). As the stored heat is depleted just after 18:00 the occupied space temperature begins to drop reaching a minimum of 16℃ at 21:00 (see point C). At 21:00 the heating system draws power from the mains supply and the space temperature rises again towards the thermostat set point.

In this example, the impact of the heat demand shift is that the space temperature remains below the recommended minimum room temperature for thermal comfort 18℃ for a period of approximately 1.5 hours during the occupied hours. This means the room temperature stays within the acceptable value for around 62% of the 4 hour DSP, thus having a thermal comfort (Metric 8) figure of 62%. Given that the minimum temperature drops only to 16℃ and that the room temperature remains higher than 18℃ for most of the DSP, the degradation in thermal comfort may be acceptable to most of the households and also unacceptable to some households. The deciding factor could be the financial gains available to the households by avoiding higher peak time energy prices, thus providing an incentive to accept the lower thermal comfort level in return.

The levels of thermal comfort decline will vary depending on the external weather conditions and the building types. To explore this, predictions were generated for all twelve building archetypes and over a 60 winter day simulation period from 2nd January. The graphs in Figure 5-6 illustrates the 60 day average room temperature, TES tank load, mains supply load and the space heating load profiles for the Det70 built form. It can be seen that the 60 day average minimum temperature during the DSP, for this particular building, is just below 17℃, and that the room temperature during this period will remain below 18℃ for around 80 minutes.

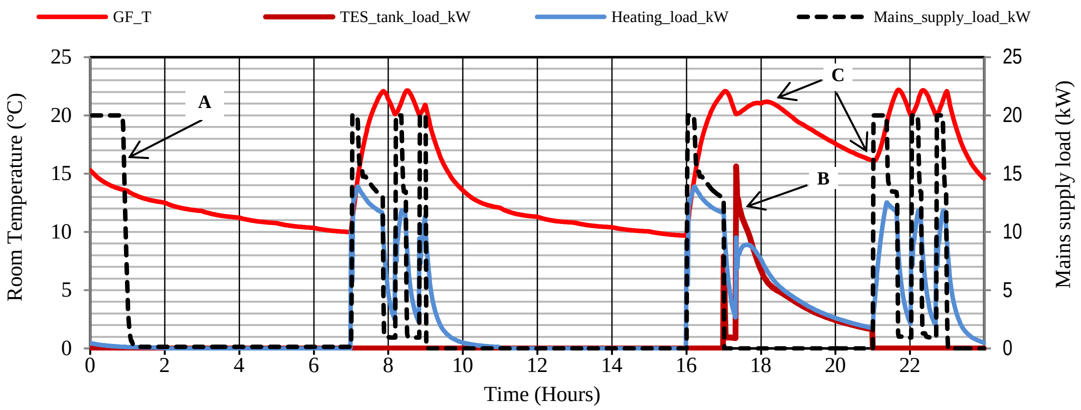


Figure 5-5. Illustration of the heat demand shift impact on room temperature (GF_T), mains supply load (Mains_supply_load_kW), space heating power demand (Heating_load_kW) and the TES tank power demand (TES_load_kW) profiles for a sample day in January when heating is prevented for 4 hours (17:00 to 21:00) during the evening occupied hours and a 0.25m³ TES applied.

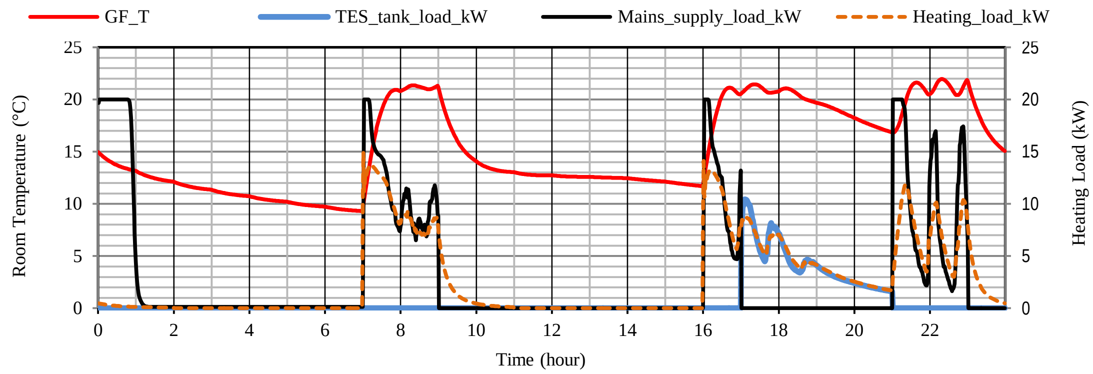


Figure 5-6. Illustration of the 60 day average heat demand shift impact on room temperature (GF_T), mains supply load (Mains_supply_load_kW), space heating power demand (Heating_load_kW) and the TES tank power demand (TES_load_kW) profiles when heating is prevented for 4 hours (17:00 to 21:00) during the evening occupied hours and a 0.25m^3 TES applied.

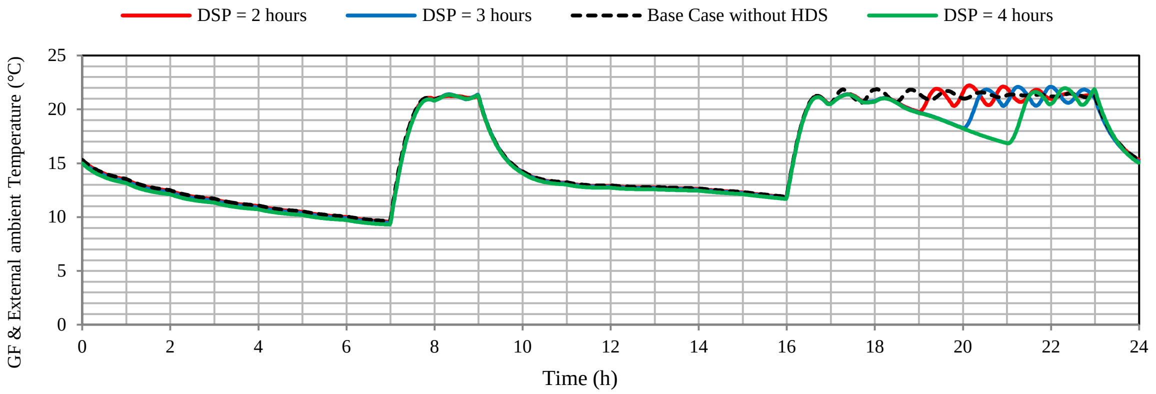


Figure 5-7. Illustration of the 60 day average thermal response with a 2 hour, 3 hour and 4 hour heat demand shift simulation, and the Base case response, for the Det70 dwelling with a 0.25m^2 TES tank with 70°C water storage temperature.

As mentioned above, the thermal comfort, power and energy demand would vary with the length of the DSP. The graphs in Figure 5-7 illustrate the impact of varying DSP on the room temperature. It starts reducing just after 18:00 as the heat store in the TES tank is depleted. The 2 hour DSP ends at 19:00 and so the room temperature is restored back to the thermostat set point using energy from the grid. Similarly for 3 and 4 hour DSP, the room temperature is restored to the thermostat set point as the DSPs end at 20:00 and 21:00 respectively.

The space temperature during the DSP, and how it is affected by the different variables such as built form and DSP duration, is important as it could indicate the potential effectiveness and acceptability of heat demand shifting interventions. Heat demand shifts that do not degrade thermal comfort level and still shifts large amounts of energy to off-peak times are likely to be more acceptable. As seen and discussed earlier, two factors which can affect thermal comfort during the DSP are the built form and the DPS duration, for any given TES size. A better understanding of the impact of these is necessary and can be gained by examining the resulting room temperatures, during the DSP, in all 60 winter days considered in this work. To do this, the frequency distribution curves with 1°C class intervals, using the minutely recorded DSP period temperature data, can be plotted and analysed, as shown in Figure 5-8 and Figure 5-9 for the sample buildings as shown. The temperature limit (18°C) for ensuring thermal comfort is shown in the frequency distribution graphs. Figure 5-8 shows the frequency distribution of the room temperature during a 4 hour DSP (from 17:00 to 21:00) for the four built forms of the same physical size. It can be seen that the frequency of the temperature below 18°C is highest for the detached dwelling and lowest for the flat. This suggests that the thermal comfort in the Flat is better in comparison with the detached building for the given TES capacity and heat demand shift duration. Nevertheless, a significant portion of the temperature measurements for all four built forms remains below 18°C, and the minimum value drops as low as 12°C to 14°C. Similarly, the graphs in Figure 5-9 shows the frequency distribution during the DSPs of 2 hours (17:00 to 19:00), 3 hours (17:00 to 20:00) and 4 hours (17:00 to 21:00), for the Det90 building. We can see the temperature measured at 18°C or higher increases as the DSP duration reduces from 4 hours to 2 hours, thus showing an improvement in the thermal comfort. However, as before, a significant portion of the measurements remains below 18°C and the minimum values reaching as low as 12°C. These suggest that for the above example cases, the thermal comfort may degrade beyond the occupant acceptability threshold, at least on some of the 60 days. Appreciating the problems, therefore, allows other option to be considered such as further reducing the DSP, for example to 1 hour, so that the space temperature does not decrease as much during that period. But that would reduce the amount of heat shifted to off-peak times, and make it less attractive for the households in terms of the energy bill savings possible, and therefore could prevent greater uptake.

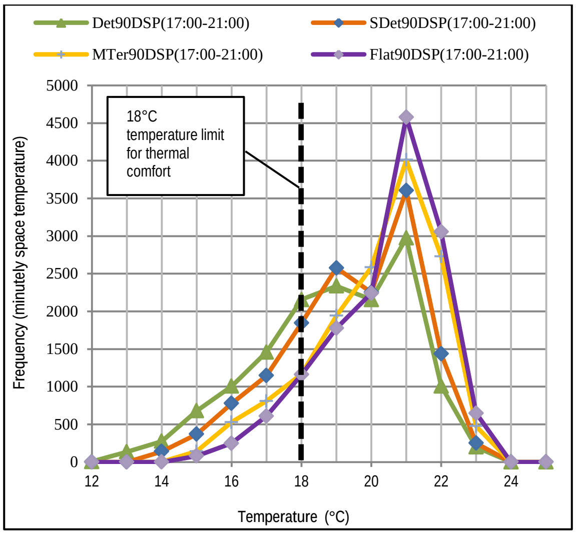


Figure 5-8. Frequency distribution of one minutely recorded space temperature over 60 days during the DSP of 17:00 to 21:00 for four building archetypes corresponding to the four built forms each with a floor size of 90m^2.

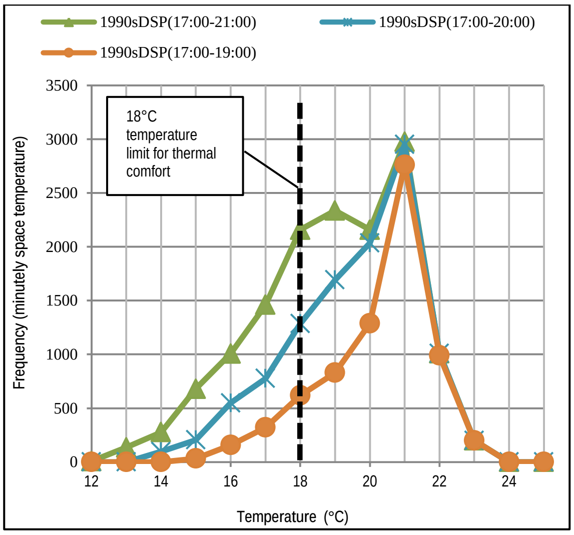


Figure 5-9. Frequency distribution of one minutely recorded space temperature over 60 days for the three DSPs (17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00), for the Det90 archetype.

The results of the room temperature analysis for all the twelve Base Case building archetypes are summarised in Table 5-5, showing the daily 60 day mean and minimum room temperature values during the three DSP periods. The 60 day mean percentage of the DSP duration during which the room temperature remains higher than the acceptable thermal comfort limit of 18℃ (Metric 8) are shown. The changes in the temperatures due to the heat demand shifting compared to the Base Case simulations are also shown for comparison purposes. The results are categorised by floor size to enable easier like for like comparison.

The effect on the daily average temperature is that it reduced marginally, by around 0.3℃ for the larger dwellings and around 0.1℃ for the smaller dwellings. The daily minimum reduced by around 2.5℃ to 3.8℃. During the more important DSPs, the worst case mean temperature reduction is 10℃ from the Base Case level to a value of 9.93℃, occurring for the Det150 archetype and a 4 hour DSP. For this archetype and a 4 hour DSP the 60 day mean thermal comfort (Metric 8) value is 37% which means that the temperature would remain above the 18℃ limit for just 82 minutes out of the 240 minutes. For the same dwelling, the percentage of time the temperature remains higher than 18℃ improves to 51% and 80% for the 3 and 4 hour DSP respectively. The minimum thermal comfort over 60 days is considerably worse at about 18%, 12% and 8% respectively for 2, 3 and 4 hour DSPs, indicating that the temperature could remain below 18℃ limit for almost the entire 4 hour DSP.

Table 5-5. 60 day average thermal condition predictions with active sensible TES tank sizes of 0.25m³, 75°C water storage temperature (TES Reference Case) and change from Base Case predictions for all hours and the three DSPs.

			TES Reference Case and change from the Base Case room temperature predictions											
			All hours 00:00-24:00			Heated hours 17:00-19:00			Heated hours 17:00-20:00			Heated hours 17:00-21:00		
			Mean Metric 1	Max.	Min.	Mean (Metric 2)	Min (Metric7)	%DSP_T>18°C (Metric 8)	Mean (Metric 2)	Min (Metric7)	%DSP_T>18°C (Metric 8)	Mean (Metric 2)	Min (Metric7)	%DSP_T>18°C (Metric 8)
	Size	Base Case ID	(°C)	(°C)	(°C)	(°C)	(°C)	(%)	(°C)	(°C)	(%)	(°C)	(°C)	(%)
TES Reference Case	70m²	Det70	16.11	22.43	6.82	19.99	15.34	100%	19.49	13.87	95%	18.83	12.57	66%
		SDet70	16.44	22.57	7.34	20.42	16.19	100%	20.04	14.73	100%	19.47	13.39	83%
		MTer70	16.97	22.66	8.85	20.67	17.49	100%	20.46	16.05	100%	20.00	14.76	100%
		Flat70	17.13	22.72	9.43	20.89	17.78	100%	20.72	16.21	100%	20.21	14.85	100%
	90m²	Det90	16.13	22.41	6.80	19.73	14.82	100%	19.39	13.28	77%	18.58	11.85	55%
		SDet90	16.63	22.49	8.34	20.41	15.95	100%	19.80	14.26	93%	19.07	12.91	66%
		MTer90	16.94	22.60	8.52	20.75	16.92	100%	20.34	15.23	100%	19.71	13.83	87%
		Flat90	17.25	22.68	10.00	21.06	17.80	100%	20.68	15.73	100%	20.00	14.19	89%
	150m²	Det150	15.52	22.28	5.03	19.33	13.20	80%	18.39	11.38	51%	17.45	9.93	37%
		SDet150	15.87	22.33	6.26	19.24	13.75	86%	18.43	12.01	55%	17.57	10.62	39%
		MTer150	16.18	22.37	7.23	19.47	14.51	100%	18.74	12.84	62%	17.93	11.46	44%
		Flat150	16.88	22.41	9.55	20.18	15.77	100%	19.44	14.10	79%	18.54	12.69	55%
Change from Base Case Buildings	70m²	Det70	-0.14	-0.03	-3.62	-1.10	-4.62	0%	-1.82	-6.09	-5%	-2.47	-7.39	-34%
		SDet70	-0.12	-0.03	-3.45	-0.78	-3.82	0%	-1.35	-5.27	0%	-1.91	-6.61	-17%
		MTer70	-0.09	-0.03	-3.01	-0.56	-2.52	0%	-0.94	-3.95	0%	-1.42	-5.24	0%
		Flat70	-0.06	-0.02	-2.83	-0.45	-2.24	0%	-0.75	-3.81	0%	-1.27	-5.16	0%
	90m²	Det90	-0.19	-0.03	-3.68	-1.41	-5.18	0%	-1.90	-6.71	-23%	-2.72	-8.14	-45%
		SDet90	-0.15	-0.02	-3.14	-0.76	-4.07	0%	-1.52	-5.75	-7%	-2.27	-7.10	-34%
		MTer90	-0.09	-0.05	-3.09	-0.47	-3.10	0%	-1.05	-4.79	0%	-1.70	-6.18	-13%
		Flat90	-0.03	-0.03	-2.67	-0.27	-2.22	0%	-0.79	-4.28	0%	-1.48	-5.82	-11%
	150m²	Det150	-0.24	-0.06	-3.93	-1.72	-6.78	-20%	-2.82	-8.59	-49%	-3.79	-10.04	-63%
		SDet150	-0.28	-0.03	-3.77	-1.83	-6.26	-14%	-2.79	-7.99	-45%	-3.67	-9.38	-61%
		MTer150	-0.25	-0.03	-3.47	-1.64	-5.51	0%	-2.50	-7.17	-38%	-3.33	-8.55	-56%
		Flat150	-0.14	-0.02	-2.79	-0.99	-4.25	0%	-1.87	-5.92	-21%	-2.77	-7.32	-45%

Note
Metric 1: Daily_mean_GF_T (daily mean ground floor space temperature averaged over 60 days)
Metric 2: DSP_hours_mean_GF_T (DSP mean temperature averaged over 60 days where: a=17:00-19:00, b=17:00-20:00, c=17:00-19:00)
Metric 8: %DSP_T>18°C (% DSP temperature above thermal comfort level of 18°C averaged over 60 days)

Built form has a significant impact on the effects of heat demand shifting as illustrated in Table 5-5. For example, when a 3 hour DSP is used the space temperature remains higher than 18℃ for 51%, 55%, 62% and 79% respectively for the Det150, SDet150, MTer150 and Flat150 dwellings. This is better illustrated in Table 5-6 and Figure 5-10 which shows the results of the 60 day average for all dwelling sizes and all dwelling built forms. The overall average of all dwellings is also shown. As can be seen, thermal comfort varies from 93.2% to 100% for 2 hour DSP, 74.4% to 93.0% and 52.7% to 81.5% respectively for the detached, semi-detached, mid terrace and the flat built forms. Obviously dwelling floor size affects the room temperature, and its magnitude can be seen in Table 5-5, Table 5-6 and Figure 5-11. It can be seen that a 2 hour heat demand shift can be achieved in the 70m² dwellings without degrading the 60 day average thermal comfort (Metric 8 remaining at 100%), whilst for the 150m² dwellings the temperature drops and Metric 8 falls to 91.5%. Similarly, for a 4 hour DSP Metric 8 is at 87.4% for the 70m² dwellings, and it drops to 43.2% for the 150m² dwellings.

Table 5-6. Room temperature summary of the 60 day mean of all buildings with heat demand shifting using active sensible TES tank sizes of 0.25m³, 75°C water storage temperature and three DSP period.

			All hours (mean) 00:00-24:00			Heated hours 17:00-19:00			Heated hours 17:00-20:00			Heated hours 17:00-21:00		
TES intervention	Category	Sub category	Mean (°C)	Max. (°C)	Min (%)	Mean (°C)	Min (°C)	%DSP_T>18°C (%)	Mean (°C)	Min (°C)	%DSP_T>18°C (%)	Mean (°C)	Min (°C)	%DSP_T>18°C (%)
TES Reference Case 0.25m² 75°C water temperature	Size	70m²	16.66	22.59	6.82	20.49	15.34	100.0%	20.18	13.87	98.6%	19.63	12.57	87.4%
		90m²	16.74	22.55	6.80	20.49	14.82	100.0%	20.05	13.28	92.6%	19.34	11.85	74.2%
		150m²	16.11	22.35	5.03	19.55	13.20	91.5%	18.75	11.38	61.8%	17.87	9.93	43.8%
	Built form	Detached	15.92	22.37	5.03	19.68	13.20	93.2%	19.09	11.38	74.4%	18.29	9.93	52.7%
		Semi detached	16.31	22.46	6.26	20.02	13.75	95.4%	19.43	12.01	82.6%	18.71	10.62	62.9%
		Mid terrace	16.70	22.54	7.23	20.29	14.51	100.0%	19.85	12.84	87.3%	19.21	11.46	76.9%
		Flat	17.08	22.60	9.43	20.71	15.77	100.0%	20.28	14.10	93.0%	19.58	12.69	81.5%
	All	Overall average	16.50	22.50	5.03	20.18	13.20	97.2%	19.66	11.38	84.3%	18.95	9.93	68.5%

If the overall average of all dwellings over the 60 days is considered, it can be seen that the mean daily temperature remains at 16.50°C with a daily maximum and minimum values of 22.50°C and 5.03°C respectively. During the three DSPs, the mean temperature varies from 20.18°C to 18.95°C whilst the minimum value varies from 13.20°C to 9.93°C. The thermal comfort figures are 97.2% for a 2 hour DSP, 84.3% for a 3 hour DSP and 68.5% for a 4 hour.

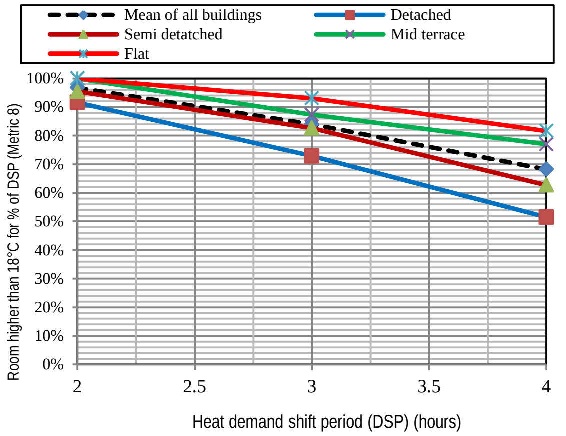


Figure 5-10. Percentage of the DSP for which the room temperature remains higher than 18°C against the DSPs of 2 hour, 3 hour and 4 hour, categorised by built form, when a 0.25m³ TES tank with 75°C water storage temperature is used.

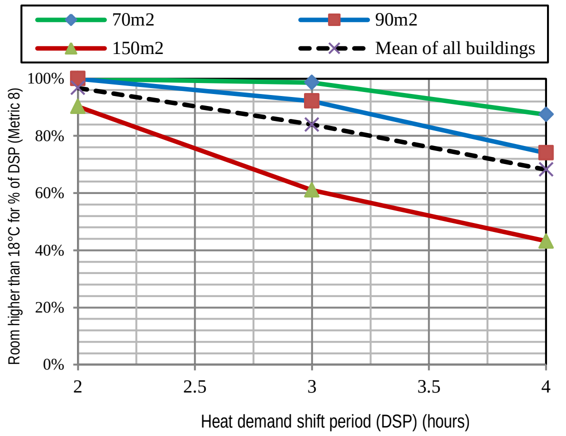


Figure 5-11. Percentage of the DSP for which the room temperature remains higher than 18°C against the DSPs of 2 hour, 3 hour and 4 hour, categorised by building size, when a 0.25m³ TES tank with 75°C water storage temperature is used.

The result indicate that temperature is significantly affected in larger detached dwelling built forms when longer DSPs, particularly 3 and 4 hours, are implemented with the TES Reference Case level of thermal storage. However in the smaller semi-detached, mid terrace and flat built forms a two hour heat demand shift can be achieved with virtually no or minimal thermal comfort impact. This is particularly encouraging given the large quantity of such buildings in the housing stock (See Chapter 3, Section 3.2), which could be equipped with the TES Reference Case level of thermal storage relatively easily. These dwellings could provide options for shaving off two hours' worth of peak grid load in future energy systems, caused by wide-spread electric heating that coincide with the 2 hour DSP used in this study.

5.5.2 Power demand

The graphs in Figure 5-12 illustrate the impact of varying DSP on the power demand profiles for the Det70 building. It shows the daily mean mains power demand profile averaged over the 60 days. As can be seen, no loading occurs from 17:00 to 19:00, 17:00 to 20:00 and 17:00 to 21:00 for the 2, 3 and 4 hour DSPs respectively as opposed to the Base Case. There is a power demand from 00:00 to about 01:00 when the TES tank is charged up. It can be seen, interestingly, that during the charging period of the TES, from 00:00 to 01:00, the mains supply load for the longer DSP simulation remains marginally longer compared to the simulation of the shorter ones. This is due to the TES tank, in attempting to supply heat into the space for a longer period, loses more of its stored heat. Therefore, at the start of the re-charge period it begins from a lower temperature thus taking marginally longer to reach the maximum storage temperature.

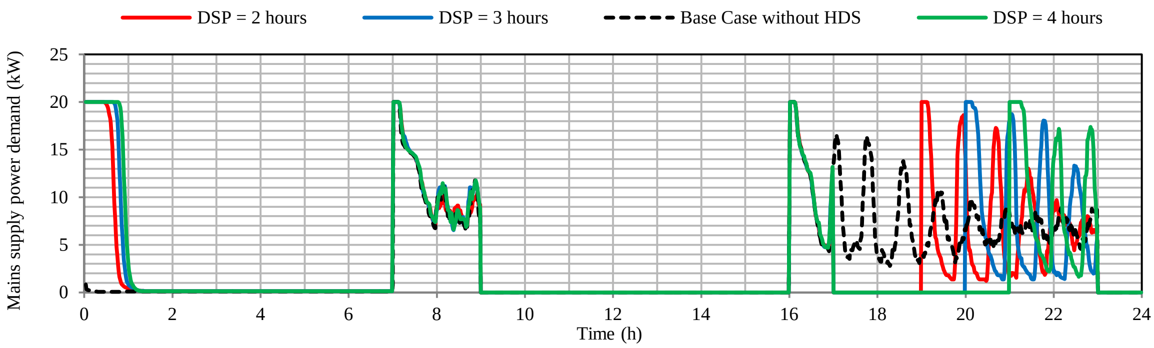


Figure 5-12. Illustration of the 60 day average mains supply power demand response with a 2 hour, 3 hour and 4 hour heat demand shift simulation, and the Base case response, for the Det70 dwelling with a 0.25m^3 TES tank with 70°C water storage temperature.

Table 5-7 provides a summary of the power demand impact for the 12 building archetypes averaged over 60 days. It shows the power demand of the 12 building archetypes, organised by floor size. The mean, maximum and minimum values are provided for the daily mains supply (00:00 to 24:00), and the DSP period space heating only power demand. The DSP period power demand is the power provided by the TES tank to the radiators and is independent of the mains supply. As before, the mean power demand values in the table are averages of the relevant time periods, and are not the instantaneous power demand, which can be as high as the power rating of the water heater. Therefore, it may be more appropriate to use the average power demand data to appreciate the general direction the power demand takes as a result of applying heat demand shifting. Obviously, the archetypes which have higher average power demand with the heat demand shifting intervention are likely to have higher overall heating energy consumption, which could reduce acceptability. The difference between these and the Base Case values are also shown in Table 5-7. We can see that the mean mains supply power reduces slightly compared with the Base Case. This is because the DSP time power is set to zero, and in its place only the power needed for charging the TES is registered. A full TES charge is not always sufficient for providing all the heat needed to maintain the temperature at the thermostat set point, for example on colder days, thus registering a lower power use compared to the Base Case. For the same reason, the power provided by TES to the radiators during the DSPs is lower compared to the power provided to the radiators in the Base Case scenarios. But, as can be seen, the reduction is considerably greater for the larger and high energy consuming dwellings. For example, the Det150 archetype mean power during the 4 hour DSP reduces by 5.53kW from the Base Case, whereas it only reduces by 0.99kW for the Flat70 archetype. It must be noted that the power predictions from the heating system during the DSP do not directly affect the mains supply in the same time period, as the heat is supplied from the TES tank which is charged at a different earlier time. The resulting form of the power demand profile, which would transfer over to the mains grid (See Figure 5-12), could benefit the supply side in future scenarios where the grid load peak demand and supply becomes challenging to match due to greater uptake of electric heating.

Table 5-7. Daily mean of the mean, mean of the maximum and mean of the minimum radiator heat load with heat demand shift during three DSP periods using a 0.25m³ TES tank storing water at 75°C, for the 12 Base Case buildings.

			Mains supply demand			Space heating only power demand								
			All hours 00:00-24:00			Heated hours 17:00-19:00			Heated hours 17:00-20:00			Heated hours 17:00-21:00		
			Mean	Max.	Min	Mean	Max.	Min	Mean	Max.	Min	Mean	Max.	Min
			Metric 3			Metric 4			Metric 4			Metric 4		
	Size	Base Case ID	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)
TES Reference Case	70m²	Det70	2.68	20.00	0.00	4.40	8.53	2.76	3.66	8.52	1.72	3.11	8.46	1.14
		SDet70	2.49	20.00	0.00	4.13	7.14	2.81	3.50	7.21	1.77	3.01	7.35	1.16
		MTer70	2.28	20.00	0.00	3.80	6.37	2.23	3.32	6.40	1.79	2.86	6.46	1.18
		Flat70	2.16	20.00	0.00	3.56	7.12	1.93	3.20	7.14	1.88	2.80	7.18	1.23
	90m²	Det90	3.28	25.00	0.00	5.15	10.50	3.01	4.22	10.37	1.79	3.53	10.56	1.13
		SDet90	3.05	25.00	0.00	4.86	7.75	3.05	4.05	7.67	1.80	3.42	8.18	1.13
		MTer90	2.80	25.00	0.00	4.65	8.37	3.11	3.91	8.39	1.85	3.31	8.19	1.15
		Flat90	2.56	25.00	0.00	4.27	7.62	2.11	3.73	7.73	1.96	3.21	7.78	1.20
	150m²	Det150	4.57	30.00	0.00	6.32	14.78	3.10	5.00	15.02	1.73	4.09	14.51	1.05
		SDet150	4.40	30.00	0.00	6.20	13.59	3.18	4.95	14.02	1.77	4.07	14.34	1.06
		MTer150	4.22	30.00	0.00	6.09	13.19	3.19	4.88	13.09	1.74	4.03	13.83	1.04
		Flat150	3.75	30.00	0.00	5.82	11.79	3.25	4.70	11.75	1.78	3.90	11.94	1.05
Change from Base Case Buildings	70m²	Det70	-0.11	0.00	0.00	-1.42	-0.61	-0.93	-1.72	-0.63	-1.18	-2.05	-0.69	-1.77
		SDet70	-0.08	0.00	0.00	-0.96	-1.60	-0.40	-1.24	-1.52	-1.02	-1.55	-1.38	-1.63
		MTer70	-0.05	0.00	0.00	-0.69	-1.97	-0.10	-0.89	-1.94	-0.54	-1.18	-1.88	-1.15
		Flat70	-0.03	0.00	0.00	-0.51	-0.44	0.34	-0.65	-0.42	0.29	-0.99	-0.38	-0.36
	90m²	Det90	-0.17	0.00	0.00	-2.18	-1.86	-0.97	-2.61	-1.98	-2.19	-3.04	-1.80	-2.85
		SDet90	-0.10	0.00	0.00	-1.66	-3.10	-0.62	-2.05	-3.18	-1.88	-2.49	-2.66	-2.54
		MTer90	-0.09	0.00	0.00	-1.10	-2.59	0.29	-1.53	-2.56	-0.97	-1.93	-2.77	-1.54
		Flat90	-0.08	0.00	0.00	-0.73	-2.54	0.27	-1.12	-2.44	0.12	-1.55	-2.39	-0.64
	150m²	Det150	-0.34	0.00	0.00	-4.45	-3.28	-2.38	-5.00	-3.04	-3.75	-5.53	-3.55	-4.43
		SDet150	-0.31	0.00	0.00	-3.76	-3.33	-1.70	-4.60	-2.90	-3.11	-5.10	-2.58	-3.82
		MTer150	-0.27	0.00	0.00	-3.43	-2.87	-1.60	-4.16	-2.97	-3.00	-4.64	-2.22	-3.71
		Flat150	-1.17	0.00	0.00	-4.95	-6.27	-2.23	-5.30	-6.31	-3.70	-5.72	-6.12	-4.43

[a] Metric 3: Whole building daily mean mains supply power demand (Daily_mean_MS_power_kW)
[b] Metric 4: Space heating only mean power demand during the occupied hours from 17:00 to 19:00, 17:00 to 20:00 and 17:00 and 21:00.

5.5.3 Energy consumption

The energy consumption impact of heat demand shifting using sensible TES is illustrated in Figure 5-13. It shows the energy draw profiles for the Det70 buildings averaged over the 60 days, showing the cumulative mains supply energy draw (Total_Q_Mains_kWh), space heating energy consumption (Total_Q_SpaceHeating_kWh), DHW energy consumption (Total_Q_DHW_kWh) and the TES tank energy supply (Total_TES_tank_energy_kWh) profiles. The mains supply load and room temperature profiles are also shown for reference purposes. It can be seen that the mains supply energy draw graph is flat, i.e. has a zero gradient, during the period 17:00 to 21:00 indicating that no load was applied during this period thus avoiding the peak time electricity price. Instead it occurred during 00:00 to 01:00 in charging up the TES, at off-peak or discounted electricity price, and the stored energy is fed into the space during the period 17:00 to 21:00. As discussed previously, the flat parts of the draw profile indicate times when no loading of the mains grid occurs, and the diagonally rising positive gradient parts indicate loading of the mains grid. This is in contrast to the Base Case energy draw profile shown previously in Section 4.3 which showed that the mains supply energy draw begins at 07:00 and ends at 23:00, and it has a relatively high gradient during 17:00 to 21:00, indicating loading of the mains supply during this period. Avoiding this, by having a flat draw profile, during this period could prevent the unsustainable peaking of the grid in the future due to wider use of electric heating. Also, shifting the corresponding heat demand for this period to an off peak time could provide grid balancing options as discussed previously and further discussed later in this section.

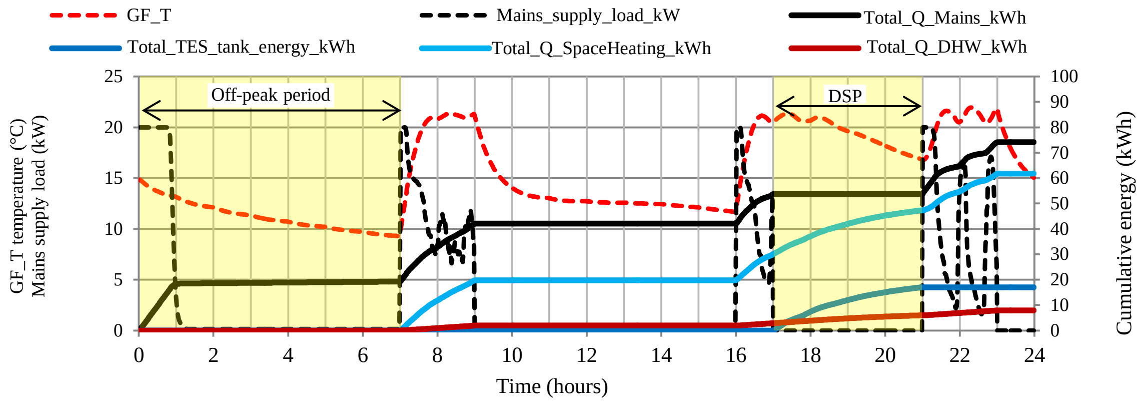


Figure 5-13. Illustration of the 60 day average heat demand shift impact on mains supply energy draw , space heating energy consumption, DHW energy consumption and TES tank energy supply profiles when heating is prevented for 4 hours (17:00 to 21:00) during the evening occupied hours and a 0.25m^3 TES applied.

The effect of heat demand shifting over different periods is illustrated in Figure 5-14, showing the mains supply energy draw profile for the three DSPs considered. The energy draw profile for the Base Case building is also shown for comparison purposes. Firstly, we can see that during the three DSPs the energy draw profiles are flat or have zero gradients, for the respective durations, indicating no loading of the mains supply in these DSPs. Further, we can see that the draw profiles have positive gradient between 00:00 to about 01:00 indicating grid loading during this period. The energy drawn in the ‘DSP=4 hours’ simulation is marginally higher compared to the others due to the TES tank beginning its re-charging cycle from a lower temperature as discussed earlier.

It could be argued that a wide scale charging of TES systems during the period 00:00 to 01:00 could result in a new grid peak during that period. However, the current grid load during the period is considerably lower compared to the grid peak load, as discussed previously in Chapter 3, Section 2.2.3. The water heater could be controlled to operate at a lower power level, so that the charging of the TES takes longer, thereby spreading the load over the entire off-peak period. Other control strategies such as proportional control, as discussed in Section 3.5.7., could also be used. These could avoid concentration of energy consumption in any particular time period and thus prevent new grid peaks being created.

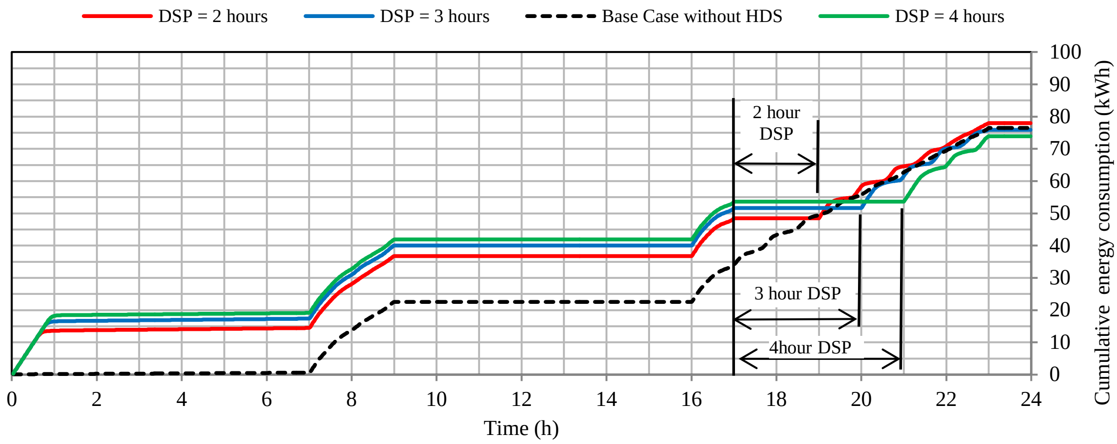


Figure 5-14. Illustration of the 60 day average mains supply energy draw response with a 2 hour, 3 hour and 4 hour heat demand shift simulation, and the Base case response, for the Det70 dwelling with a 0.25m³ TES tank with 70°C water storage temperature.

The energy consumption predictions for the twelve Base Case building archetypes are provided in Table 5-8. The table shows: 1) Daily space heating only energy use with the 3 DSPs; 2) DSP hour space heating energy use; 3) mains supply energy use for the 3 DSPs; 4) The energy supplied from the TES tank for heat demand shifting (energy shifted in time – Metric 9) for the 3 DSPs, and 4) the amount to energy bill saving per day (Metric 10) for the 3 DSPs, based on the currently available discounted Economy 7 electricity price. Results are organised by floor size, showing the 60 day average of the mean, maximum and minimum values. For example, for the Det70 building archetype the daily mean space heating only energy consumption are 55.03kWh, 53.74kWh and 51.06kWh when heat demand shifts of 2, 3 and 4 hours are implemented respectively. The energy consumption figure reduces for longer DSPs due to the TES, with a fixed amount of stored heat, attempting to supply it into the occupied space for longer time periods without resorting to the mains supply. The overall energy consumed (Mains supply energy) for the three respective DSPs are 66.81kWh, 64.91kWh and 62.05kWh. These are higher as they also incorporate the DHW energy and the energy losses[19] associated with the TES tank

[19] TES and pipe losses are internal gains to the heated space

and the pipe work. The energy supplied by the radiators into the space during the three DSP in the respective order was 8.91kWh, 11.12kWh and 12.57kWh. These are marginally high compared to the heat output by the TES tank during the same DSP periods which were 8.50kWh, 10.89kWh and 12.51kWh. The differences are most probably due to the thermal mass effect of the radiators caused by the pre-heating of the room prior to the DSPs. The energy bill saving prediction for the Det70 building archetype are £0.83/day, £1.07/day and £1.23/day for the three DSP respectively. These are determined by working out the difference between the cost of the TES output energy, based on standard electricity price of 15.08p/kWh, and the cost of the same TES output energy at the Economy7 discounted price. The Economy7 discounted energy price used is 5.28p/kWh, which is discounted by 65% from the standard price tariff.

Table 5-8 also shows the difference between the values predicted with the TES Reference case level of thermal storage and the corresponding Base Case values as discussed in Chapter 4.

It is common sense to believe that heat demand shifting, without thermal comfort degradation, would have an overall energy consumption increasing effect due to the heat loss from the TES tank. However, the results show that for some buildings archetypes and DSP hours, where the room temperature remained above 18℃ for 100% of the DSP, for example the Flat70 with a 2 hour DSP, the mean mains supply energy consumption increases marginally (by 0.44kWh for Flat70 with a 2 hour DSP) compared to the Base Case values. Also, for most building archetypes, even in those where no significant thermal comfort degradation occurs such as the MTer70 with 3 hour DSP (See Table 5.5), the mains supply mean energy consumption reduced marginally (by 0.88kWh for MTer70 with 3 hour DSP) compared to the Base Case values. The explanation for this is that during the DSPs, a lower space temperature (18℃) is used to define thermal comfort cut-off, as opposed to the thermostat set point of 21℃. Overall, based on the TES tank capacity and storage loss factor considered in this research activity, it can be said that heat demand shifting without thermal comfort degradation in all built forms of 70m^2 and 90m^2 floor areas, and DSPs of 2 and 3 hours, do not have any significant energy consumption increasing impact. This of course assumes that an 18℃ temperature during the DSP is acceptable instead of the thermostat set point.

Table 5-8. Summary of the 60 day average change in Mains supply and space heating only energy consumption from the Base Case figures due to heat demand shifting from three DSPs, using a 0.25m³ TES and a water storage temperature of 75°C.

				Space heating only						Mains supply energy			TES (shifted) energy			Energy Saving per day		
				Daily energy consumption with DSP hours of:			Radiator output energy in DSP hours of:			Daily energy consumption with DSP hours of:			(Metric 9) (With DSP hours of:			(Metric 10) With DSP hours of:		
		Floor Size	Building Archetype	2hDSP (kWh)	3hDSP (kW)	4hDSP (kW)	2hDSP (kWh)	3hDSP (kWh)	4hDSP (kWh)	2hDSP (kWh)	3hDSP (kWh)	4hDSP (kWh)	2hDSP (kWh)	3hDSP (kWh)	4hDSP (kWh)	2hDSP (£)	3hDSP (£)	4hDSP (£)
TES Reference Case	Mean	70m²	Det70	55.03	53.74	51.60	8.91	11.12	12.57	66.81	64.91	62.05	8.50	10.89	12.51	0.83	1.07	1.23
			SDet70	50.17	49.19	47.61	8.34	10.61	12.15	61.42	60.15	58.15	8.10	10.54	12.22	0.79	1.03	1.20
			MTer70	45.25	44.70	43.63	7.67	10.04	11.56	56.13	55.04	53.74	7.65	10.19	11.90	0.75	1.00	1.17
			Flat70	42.48	42.18	41.29	7.20	9.70	11.31	53.04	52.56	51.01	7.19	9.86	11.66	0.70	0.97	1.14
		90m²	Det90	70.54	68.59	65.52	10.44	12.82	14.30	81.68	79.31	75.96	9.26	11.65	13.22	0.91	1.14	1.30
			SDet90	64.14	62.66	60.21	9.82	12.26	13.81	75.73	74.03	71.14	9.02	11.45	13.01	0.88	1.12	1.27
			MTer90	58.97	58.04	56.33	9.41	11.86	13.39	69.25	67.65	65.48	8.59	11.12	12.73	0.84	1.09	1.25
			Flat90	53.03	52.30	50.92	8.62	11.31	12.97	63.35	62.04	59.98	8.05	10.75	12.49	0.79	1.05	1.22
		150m²	Det150	104.13	100.81	95.23	12.87	15.25	16.64	115.05	110.66	104.60	10.79	13.03	14.42	1.06	1.28	1.41
			SDet150	99.41	96.18	91.18	12.61	15.09	16.57	110.07	106.26	101.60	10.54	12.85	14.28	1.03	1.26	1.40
			MTer150	94.73	92.01	87.45	12.38	14.86	16.37	105.26	102.38	97.49	10.41	12.75	14.17	1.02	1.25	1.39
			Flat150	84.15	81.93	78.54	11.82	14.31	15.80	93.78	90.69	86.64	10.05	12.45	13.91	0.99	1.22	1.36
	Max.	70m²	Det70	74.06	71.17	67.00	10.16	12.55	14.17	86.49	83.97	78.75	9.36	11.81	13.49	0.92	1.16	1.32
			SDet70	68.71	66.64	61.88	9.93	12.27	13.86	80.76	78.62	73.67	9.18	11.60	13.27	0.90	1.14	1.30
			MTer70	62.15	60.03	57.23	9.63	11.89	13.42	74.06	71.81	68.70	9.08	11.32	12.96	0.89	1.11	1.27
			Flat70	58.01	56.13	54.04	9.24	11.36	12.80	69.18	66.65	64.80	9.05	11.29	12.86	0.89	1.11	1.26
		90m²	Det90	95.29	90.47	84.91	11.86	14.38	16.05	108.46	101.83	97.30	10.18	12.62	14.24	1.00	1.24	1.40
			SDet90	86.58	83.11	79.70	11.60	14.06	15.67	99.65	94.89	90.90	10.04	12.40	13.99	0.98	1.22	1.37
			MTer90	80.97	77.63	74.17	11.37	13.81	15.37	92.17	89.80	84.52	9.94	12.22	13.78	0.97	1.20	1.35
			Flat90	71.13	68.16	65.43	10.92	13.23	14.62	81.84	78.44	76.28	9.84	12.15	13.63	0.96	1.19	1.34
		150m²	Det150	138.32	132.14	121.56	14.50	17.14	18.78	149.15	143.70	132.69	11.65	14.05	15.53	1.14	1.38	1.52
			SDet150	133.59	125.47	119.43	14.31	16.94	18.55	146.54	136.63	131.40	11.52	13.91	15.38	1.13	1.36	1.51
			MTer150	127.21	122.40	112.67	14.09	16.66	18.25	137.14	135.45	123.56	11.36	13.72	15.18	1.11	1.34	1.49
			Flat150	111.12	107.62	102.35	13.22	15.55	16.92	119.69	116.31	112.31	11.28	13.39	14.74	1.11	1.31	1.44
	Min..	70m²	Det70	38.38	38.87	38.61	5.86	8.70	10.43	51.82	50.56	49.90	5.82	8.97	11.01	0.57	0.88	1.08
			SDet70	32.69	32.83	32.74	4.75	7.00	8.90	44.62	44.77	43.74	5.41	7.55	10.24	0.53	0.74	1.00
			MTer70	29.63	29.59	28.70	4.34	6.47	7.84	42.30	40.41	40.05	4.27	7.15	9.23	0.42	0.70	0.90
			Flat70	27.39	27.33	26.61	3.59	4.78	7.25	38.36	39.38	37.22	5.19	6.62	9.72	0.51	0.65	0.95
		90m²	Det90	49.28	49.61	49.82	7.31	10.24	12.03	60.79	60.12	59.37	6.75	9.85	11.85	0.66	0.97	1.16
			SDet90	43.28	43.60	43.93	6.65	9.50	11.59	56.54	53.88	53.69	6.85	9.92	11.62	0.67	0.97	1.14
			MTer90	39.55	37.88	38.49	5.80	7.75	9.88	51.32	48.07	48.95	5.33	9.18	11.14	0.52	0.90	1.09
			Flat90	36.52	35.12	35.38	5.67	7.47	9.69	46.54	45.33	44.91	6.29	9.02	11.27	0.62	0.88	1.10
		150m²	Det150	73.88	73.45	72.87	10.84	13.41	14.80	82.56	81.63	80.24	9.39	11.80	13.33	0.92	1.16	1.31
			SDet150	70.13	69.66	68.89	10.62	13.12	14.62	79.24	77.84	78.91	9.11	11.69	13.21	0.89	1.15	1.30
			MTer150	68.57	68.32	67.15	10.54	12.92	14.47	79.10	76.29	75.63	9.16	11.75	13.19	0.90	1.15	1.29
			Flat150	60.60	61.39	59.74	10.33	12.70	14.20	68.95	69.37	67.01	9.22	11.67	13.18	0.90	1.14	1.29
Change from Base Case Buildings	Mean	70m²	Det70	-0.78	-2.07	-4.21	-2.79	-5.13	-8.13	-0.12	-2.03	-4.88	8.50	10.89	12.51	0.83	1.07	1.23
			SDet70	-0.62	-1.60	-3.18	-1.90	-3.69	-6.13	-0.15	-1.42	-3.42	8.10	10.54	12.22	0.79	1.03	1.20
			MTer70	-0.44	-0.99	-2.06	-1.36	-2.64	-4.70	0.21	-0.88	-2.17	7.65	10.19	11.90	0.75	1.00	1.17
			Flat70	-0.23	-0.54	-1.43	-1.01	-1.91	-3.92	0.44	-0.04	-1.59	7.19	9.86	11.66	0.70	0.97	1.14
		90m²	Det90	-1.35	-3.30	-6.37	-4.33	-7.75	-12.09	-0.85	-3.22	-6.58	9.26	11.65	13.22	0.91	1.14	1.30
			SDet90	-1.24	-2.72	-5.16	-3.30	-6.10	-9.90	0.06	-1.63	-4.53	9.02	11.45	13.01	0.88	1.12	1.27
			MTer90	-0.56	-1.48	-3.20	-2.15	-4.54	-7.66	-0.07	-1.67	-3.83	8.59	11.12	12.73	0.84	1.09	1.25
			Flat90	-0.21	-0.94	-2.32	-1.45	-3.31	-6.14	0.11	-1.21	-3.27	8.05	10.75	12.49	0.79	1.05	1.22
		150m²	Det150	-2.94	-6.26	-11.83	-8.85	-14.86	-22.01	-2.76	-7.15	-13.21	10.79	13.03	14.42	1.06	1.28	1.41
			SDet150	-2.78	-6.01	-11.01	-7.46	-13.66	-20.29	-2.88	-6.68	-11.35	10.54	12.85	14.28	1.03	1.26	1.40
			MTer150	-2.33	-5.05	-9.60	-6.82	-12.33	-18.42	-2.54	-5.41	-10.30	10.41	12.75	14.17	1.02	1.25	1.39
			Flat150	-0.99	-3.22	-6.60	-4.47	-9.36	-14.96	-1.00	-4.09	-8.14	10.05	12.45	13.91	0.99	1.22	1.36
	Maximum	70m²	Det70	-3.38	-6.27	-10.44	-8.10	-13.07	-17.76	-2.75	-5.27	-10.49	9.36	11.81	13.49	0.92	1.16	1.32
			SDet70	-3.44	-5.50	-10.26	-6.63	-10.37	-14.87	-3.15	-5.29	-10.23	9.18	11.60	13.27	0.90	1.14	1.30
			MTer70	-1.95	-4.07	-6.87	-4.72	-8.12	-11.57	-1.95	-4.20	-7.31	9.08	11.32	12.96	0.89	1.11	1.27
			Flat70	-1.25	-3.14	-5.22	-3.31	-5.85	-10.19	-0.37	-2.90	-4.75	9.05	11.29	12.86	0.89	1.11	1.26
		90m²	Det90	-4.12	-8.94	-14.49	-11.35	-17.48	-24.38	-2.65	-9.28	-13.82	10.18	12.62	14.24	1.00	1.24	1.40
			SDet90	-4.34	-7.81	-11.22	-8.85	-14.32	-20.44	-4.38	-9.14	-13.14	10.04	12.40	13.99	0.98	1.22	1.37
			MTer90	-2.21	-5.55	-9.02	-6.27	-11.46	-17.21	-2.69	-5.06	-10.34	9.94	12.22	13.78	0.97	1.20	1.35
			Flat90	-1.72	-4.68	-7.42	-4.38	-9.16	-14.55	-2.67	-6.06	-8.23	9.84	12.15	13.63	0.96	1.19	1.34
		150m²	Det150	-9.60	-15.79	-26.37	-18.90	-28.88	-39.94	-10.51	-15.96	-26.98	11.65	14.05	15.53	1.14	1.38	1.52
			SDet150	-8.38	-16.50	-22.53	-17.47	-27.59	-38.07	-8.59	-18.50	-23.73	11.52	13.91	15.38	1.13	1.36	1.51
			MTer150	-4.98	-9.80	-19.52	-16.11	-25.33	-34.62	-6.57	-8.27	-20.16	11.36	13.72	15.18	1.11	1.34	1.49
			Flat150	-5.28	-8.79	-14.06	-11.56	-19.96	-28.84	-6.89	-10.27	-14.27	11.28	13.39	14.74	1.11	1.31	1.44
	Minimum	70m²	Det70	0.16	0.65	0.39	-0.92	-0.80	-1.76	3.80	2.54	1.88	5.82	8.97	11.01	0.57	0.88	1.08
			SDet70	0.15	0.29	0.19	-0.44	-0.86	-1.58	2.65	2.80	1.76	5.41	7.55	10.24	0.53	0.74	1.00
			MTer70	-0.36	-0.40	-1.29	-0.43	-0.68	-1.44	2.61	0.73	0.37	4.27	7.15	9.23	0.42	0.70	0.90
			Flat70	-0.15	-0.21	-0.93	-0.60	-0.61	-0.56	1.56	2.58	0.42	5.19	6.62	9.72	0.51	0.65	0.95
		90m²	Det90	-0.44	-0.11	0.10	-0.83	-1.37	-3.15	0.71	0.04	-0.71	6.75	9.85	11.85	0.66	0.97	1.16
			SDet90	-0.66	-0.34	-0.01	-0.80	-1.01	-2.05	2.80	0.13	-0.05	6.85	9.92	11.62	0.67	0.97	1.14
			MTer90	-0.63	-2.30	-1.69	-0.65	-1.40	-2.61	1.60	-1.66	-0.77	5.33	9.18	11.14	0.52	0.90	1.09
			Flat90	-0.10	-1.49	-1.24	-0.40	-1.59	-2.33	1.26	0.05	-0.37	6.29	9.02	11.27	0.62	0.88	1.10
		150m²	Det150	-0.52	-0.95	-1.54	-0.35	-3.55	-9.07	-0.58	-1.51	-2.90	9.39	11.80	13.33	0.92	1.16	1.31
			SDet150	-0.19	-0.66	-1.43	-0.31	-2.50	-6.97	0.58	-0.82	0.25	9.11	11.69	13.21	0.89	1.15	1.30
			MTer150	0.04	-0.22	-1.38	0.03	-1.94	-7.29	2.25	-0.55	-1.21	9.16	11.75	13.19	0.90	1.15	1.29
			Flat150	0.92	1.72	0.07	-0.33	-3.89	-6.94	1.59	2.01	-0.35	9.22	11.67	13.18	0.90	1.14	1.29

Note
Metric 9: TES_tank_energy_kWh (amount of heat provided by the TES store during the DSP or potentially shifted to off-peak time)
Metric 10: Energy_cost_saving/day (potential electricity bill saving based on current Economy7 price tariff and heat shifted to off peak time)

The lowest (mean of the minimum) and the highest (mean of the maximum) energy delivered into the heated space from the TES Tank (or energy shifted in time) were 4.27kWh and 15.53kWh with a mean value of 10.94kWh. The energy shifted as percentage of the Base Case mains supply energy varies from 7.3% to 26.4% with a mean value of 14.5%. These figures are dependent upon the duration of the DSP, building archetype and the external weather conditions. It must be noted that the difference is due to the amount of heat required by the buildings and the period over which it is drawn from the TES tank, and that the heat content in the tank remained the same for all buildings and DSP options. The larger Det150 building resulted in the largest amount of TES energy delivery, whilst the smaller SDet70 building resulted in the smallest amount. Assuming that the TES is charged at an electricity price equivalent to the current Economy7 off-peak price as mentioned above, then the potential energy bill savings predictions, based on the minimum and the maximum energy supplied by the TES, varies from £0.42/day to £1.52/day with a mean value of £1.07/day. These are equivalent to 4.7% to 17.2% of the Base Case energy cost with a mean value of 9.4%.

It is important to appreciate the relationship between the amount heat shifted and the thermal comfort impact, as it could provide an indication as to which buildings are more suitable for HDS interventions. This can be explored by examining the graphs in Figure 5-15, which show the daily mean heat energy shifted (Energy shifted) using the three DSPs in the twelve building archetypes. The corresponding thermal impact (Metric 8) in the buildings for the three DSPs is also shown. For example, at one extreme (see the yellow traces), a 4 hour DSP and energy shifts of 11.66kWh and 11.90kWh without thermal comfort degradation (i.e. Metric 8 is at 100%) is only possible in the Flat70 and the MTer70 archetypes. The thermal comfort degrades for all other archetypes with the Det150 being the worst, where 14.42kWh is shifted but with thermal comfort of only 34%. At the other extreme (See the purple traces), a 2 hour DSP shifting energy from 7.19kWh to 10.41kWh without thermal comfort degradation is possible for all archetypes except SDet150 and Det150. This indicates that, in terms of the amount of energy shifted, larger buildings and longer DSPs are more effective, but they have a thermal comfort reducing effect. However, for shorter DSPs and smaller dwellings thermal comfort is not affected as much but the quantity of heat energy shifted reduces, which may not be effective in terms of demand shifting and/or energy bill reduction as discussed below.

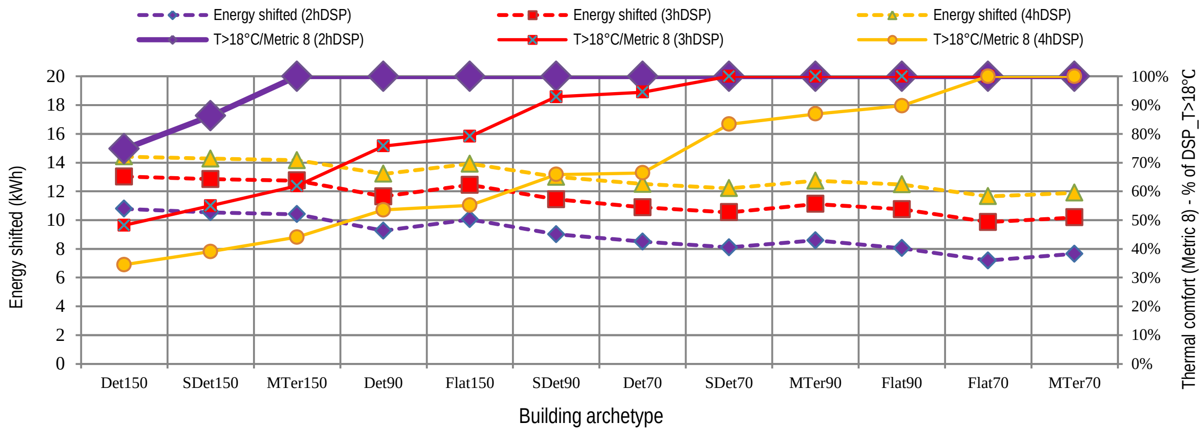


Figure 5-15. Prediction of the mean energy supplied by the TES (or energy shifted) and the corresponding thermal comfort impact by building archetype.

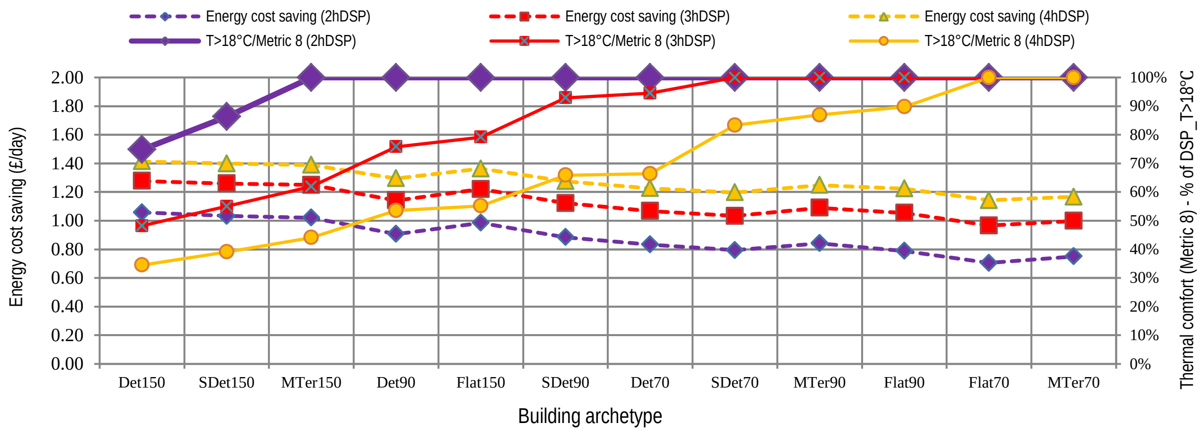


Figure 5-16. Prediction of the energy bill saving based on the Economy7 off-peak electricity price and the corresponding thermal comfort impact by building archetype.

The financial benefit which may be available to the households in comparison with the thermal comfort impact may be a factor that decides the uptake of heat demand shifting in buildings with TES. The charts in Figure 5-16 can be used to explore this, where it shows the daily mean energy bill saving (Metric 10) achievable for the 12 building archetypes if the heat energy shifted from the three DSPs were purchased at the existing Economy7 off-peak electricity price. The corresponding thermal impact (Metric 8) in the buildings for the three DSPs is also shown. For example, a 4 hour DSP in the Flat70 and the MTer70 archetypes, shifting 11.66kWh and 11.90kWh, without thermal comfort impact could yield savings of £1.14/day and £1.09/day respectively. These represent 14.4% and 13.8% reduction in daily energy cost compared to the Base Case scenarios without heat demand shifting. The same DSP in the larger Det150 building shifts 14.42kWh, giving an energy bill saving of £1.41/day (7.9% compared to Base Case), but at the expense of reduced thermal comfort of 34%. A 2 hour DSP results in energy bill saving from £1.06/day to £0.70/day. The range of energy shifted by this option is relatively small due to the shorter DSP and so the energy bill saving is also small, but is achieved in most archetypes without affecting thermal comfort. Therefore, in terms of the energy shifted per household this option may not be very effective, and may not be economically attractive to the households. However, the lower energy shifting means smaller TES capacity needs, which could make it relatively cheaper to install and thus encourage greater uptake.

The energy consumption prediction averaged and organised by floor size and built form are summarised in Table 5-9. The 60 day Mean, Maximum and the Minimum space heating only, mains supply, TES tank supplied energy (heat shifted, Metric 9) and the corresponding energy bill saving per day (Metric 10) are presented. The average of all 12 building archetypes is also shown. The bar chart in Figure 5-17 illustrates the 60 day mean showing: 1) the space heating energy consumption (all built-forms averaged) by floor size, 2) the space heating energy consumption (all floor sizes averaged) by built-form, and 3) the space heating energy consumption average of all 12 building archetypes (all built-forms and floor sizes). As before, the space heating energy consumption can be seen to vary considerably with floor size, for example the mean value for a 2 hour DSP varying from 48.23kWh for 70m^2 dwellings to 95.60kWh for the 150m^2 dwellings. For the larger DSP values, the energy use by the bigger 150m^2 dwelling falls slightly, from 95.60kWh for a 2 hour DSP to 88.10kWh for a 4 hour DSP. This is due to the mains supply being 'substituted' by a fixed and limited capacity TES for a longer DSP and unsuccessfully relied upon to supply the heat needed to ensure the required room temperature. The differences in mean energy consumption due to built-form are comparatively small, varying from 76.57kWh for the detached built form to 59.89kWh for the flat. Again, longer DSP duration reduces energy use for the reasons as explained above. It can be seen that the energy consumption average of all 12 building archetypes are 68.50kWh, 66.86kWh and 64.13kWh for the 2, 3 and 4 hour DSP respectively. These are marginally lower than the average value predicted for the Base Case simulation (69.71kWh) where no TES and heat demand shifting was applied, for the reasons as discussed earlier.

Table 5-9. Summary of the 60 day average energy consumption predictions resulting from heat demand shifting from three DSPs, using a 0.25m³ and water storage temperature of 75°C, organised by floor size and built form.

				Space heating energy only						Mains Supply energy			TES (shifted) energy			Energy Saving per day		
				Daily energy consumption with DSP hours of:			Radiator output during the DSP hours of:			Daily energy consumption with DSP hours of:			(Metric 9) (With DSP hours of:			(Metric 10) With DSP hours of:		
		Floor Size	Building Archetype	17:00-19:00 (kWh)	17:00-20:00 (kW)	17:00-21:00 (kWh)	17:00-19:00 (kWh)	17:00-20:00 (kWh)	17:00-21:00 (kWh)	17:00-19:00 (kWh)	17:00-20:00 (kWh)	17:00-21:00 (kWh)	17:00-19:00 (kWh)	17:00-20:00 (kWh)	17:00-21:00 (kWh)	17:00-19:00 (£)	17:00-20:00 (£)	17:00-21:00 (£)
TES Reference Case 0.25m³ 75°C water temperature	Mean	Size	70m²	48.23	47.45	46.03	8.03	10.37	11.90	59.35	58.16	56.24	7.86	10.3	12.0	0.77	1.02	1.18
			90m²	61.67	60.40	58.25	9.57	12.06	13.62	72.50	70.76	68.14	8.73	11.2	12.8	0.86	1.10	1.26
			150m²	95.60	92.73	88.10	12.42	14.88	16.34	106.04	102.50	97.58	10.45	12.7	14.2	1.02	1.25	1.39
		Built form	Detached	76.57	74.38	70.78	10.74	13.06	14.51	87.85	84.96	80.87	9.51	11.8	13.3	0.93	1.16	1.31
			Semi detached	71.24	69.34	66.33	10.26	12.65	14.17	82.40	80.15	76.96	9.22	11.6	13.1	0.90	1.14	1.29
			Mid terrace	66.31	64.92	62.47	9.82	12.25	13.77	76.88	75.02	72.24	8.88	11.3	12.9	0.87	1.11	1.27
			Flat	59.89	58.80	56.92	9.21	11.77	13.36	70.06	68.43	65.88	8.43	11.0	12.6	0.83	1.08	1.24
		Overall average		68.50	66.86	64.13	10.01	12.44	13.95	79.30	77.14	73.99	9.01	11.4	13.0	0.88	1.12	1.28
	Maximum	Size	70m²	65.73	63.49	60.04	9.74	12.02	13.56	77.62	75.26	71.48	9.17	11.5	13.1	0.90	1.13	1.29
			90m²	83.49	79.84	76.05	11.43	13.87	15.43	95.53	91.24	87.25	10.00	12.3	13.9	0.98	1.21	1.36
			150m²	127.56	121.91	114.00	14.03	16.57	18.13	138.13	133.02	124.99	11.45	13.7	15.2	1.12	1.35	1.49
		Built form	Detached	102.56	97.93	91.16	12.17	14.69	16.33	114.70	109.84	102.91	10.40	12.8	14.4	1.02	1.26	1.41
			Semi detached	96.29	91.74	87.00	11.95	14.42	16.03	108.98	103.38	98.66	10.25	12.6	14.2	1.00	1.24	1.39
			Mid terrace	90.11	86.69	81.35	11.69	14.12	15.68	101.13	99.02	92.26	10.13	12.4	13.9	0.99	1.22	1.37
			Flat	80.09	77.30	73.94	11.12	13.38	14.78	90.24	87.14	84.47	10.05	12.2	13.7	0.99	1.20	1.35
		Overall average		92.26	88.41	83.36	11.73	14.15	15.71	103.76	99.84	94.57	10.21	12.5	14.0	1.00	1.23	1.38
	Minimum	Size	70m²	32.02	32.15	31.66	4.64	6.74	8.61	44.28	43.78	42.73	5.17	7.57	10.0	0.51	0.74	0.99
			90m²	42.16	41.55	41.90	6.36	8.74	10.80	53.80	51.85	51.73	6.31	9.49	11.4	0.62	0.93	1.12
			150m²	68.30	68.21	67.16	10.58	13.04	14.52	77.46	76.28	75.45	9.22	11.7	13.2	0.90	1.15	1.30
		Built form	Detached	53.85	53.98	53.77	8.00	10.78	12.42	65.06	64.10	63.17	7.32	10.2	12.0	0.72	1.00	1.18
			Semi detached	48.70	48.70	48.52	7.34	9.87	11.70	60.14	58.83	58.78	7.12	9.72	11.6	0.70	0.95	1.15
			Mid terrace	45.92	45.26	44.78	6.89	9.05	10.73	57.57	54.92	54.88	6.26	9.36	11.1	0.61	0.92	1.10
			Flat	41.50	41.28	40.57	6.53	8.31	10.38	51.28	51.36	49.71	6.90	9.10	11.3	0.68	0.89	1.12
		Overall average		47.49	47.30	46.91	7.19	9.50	11.31	58.51	57.30	56.63	6.90	9.60	11.5	0.68	0.94	1.14

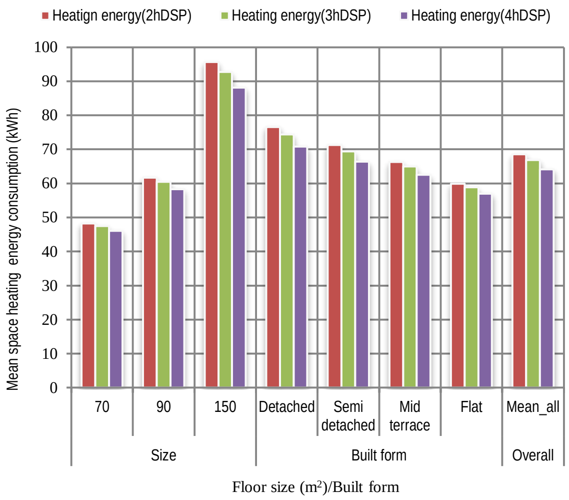


Figure 5-17. Mean of the 60 days daily space heating only energy consumption predictions for the three DSPs, averaged over floor size and building archetype, and the overall average of all archetypes

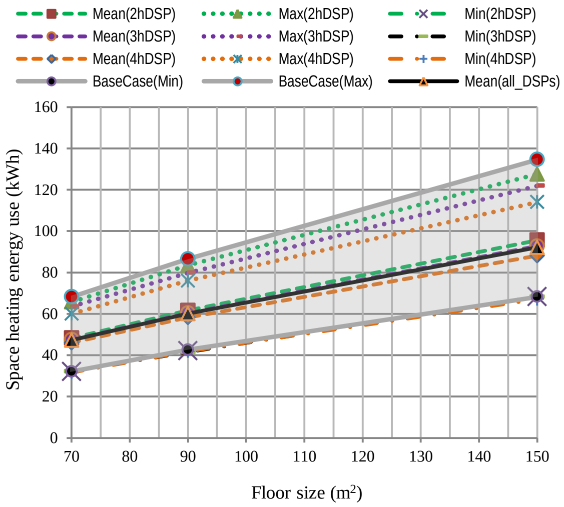


Figure 5-18. Built form averaged 60 day mean, maximum and minimum daily space heating energy consumption predictions for the three DSPs by floor size. Base Case daily maximum and minimum energy consumption variation over the 60 days shown by the grey shaded region. .

The graphs in Figure 5-18, which is based on data in Table 5-9, show the relationship between the daily maximum, minimum and mean space heating energy consumption over the 60 winter days, and the floor area for the three DSPs. The Base Case (See Chapter 4) 60 day maximum and minimum daily energy demand variation predicted for ensuring 21℃ room temperature (see grey shaded area) is also shown in Figure 5-18. These graphs illustrate the difference between the heat actually used with the demand shifting intervention, and that used by the Base Case models (without demand shifting) to achieve the required space temperature. It can be seen that the 'Maximum' energy used, on the 'colder' days, for all DSPs are lower compared to the maximum energy required for the 'colder' days in the Base Case simulation. Also, the difference becomes greater for larger floor area. The 60 day mean energy use was also lower compared to the Base Case (see Figure 4-15 in Chapter 4). These suggest that on the 'colder' days less heat was available, during the DSP hours, compared to the amount used in Base Case, therefore having a thermal comfort reducing effect. This is confirmed by the graphs in Figure 5-19 which show the mean energy used/shifted by floor area, during the three DSPs and over the 60 days. The corresponding thermal comfort values are also shown. The mean energy use/shifted graph in Figure 5-19 can be compared with the corresponding mean energy use graph for the Base Case (See Figure 4-20). It can be realised that the energy used with the demand shifting intervention is relatively less compared to the Base Case. For example, the 150m^2 buildings in the Base Case consumed 21.95kWh during the 2 hour DSP, compared with only 12.42kWh with the demand shifting intervention, and its impact is the reduced thermal comfort figure (Metric 8) of 90% as shown. It can also be seen that for the same DSP, the 70m^2 buildings in the Base Case consumed 11.22kWh compared with 8.03kWh with the demand shifting intervention. However, this time, the thermal comfort figure (Metric 8) remained at 100%, even though the energy reduced, and the reason for this is that a space temperature equal to or above 18℃ has been considered to provide an acceptable thermal comfort as discussed previously.

As explained above, the graphs in Figure 5-19 can be used to gain an appreciation of the effects of weather variation (over the 60 day simulation period) on the heat used/shifted and the resulting thermal comfort impact during the DSPs, and how these vary with different building sizes. Similarly, the graphs in Figure 5-20 can be used to gain an appreciation of the effects of weather variation on the potential electricity bill savings, and the resulting thermal comfort impact during the DSPs, and how these vary with different building sizes. For example, a 2 hour heat demand shifting in 70m^2 buildings could provide an energy cost saving of £0.77/day whilst still maintaining thermal comfort (Metric 8) of 100%. But it only enables 8.03kWh to be shifted to an off-peak time. However, for 150m^2 buildings the cost saving and the heat shifted increases to £1.02/day and 12.42kWh respectively, but the thermal comfort degrades to 90%.

Both Figure 5-19 and Figure 5-20 could be used to determine the effectiveness of heat demand shifting using TES in buildings of different sizes. They could aid future policy implementation such as targeting the right type of buildings for heat demand management using TES. Households could use these graphs to help them decide what the financial benefits and thermal comfort impacts are like to be, which may or may not influence acceptability and/or uptake.

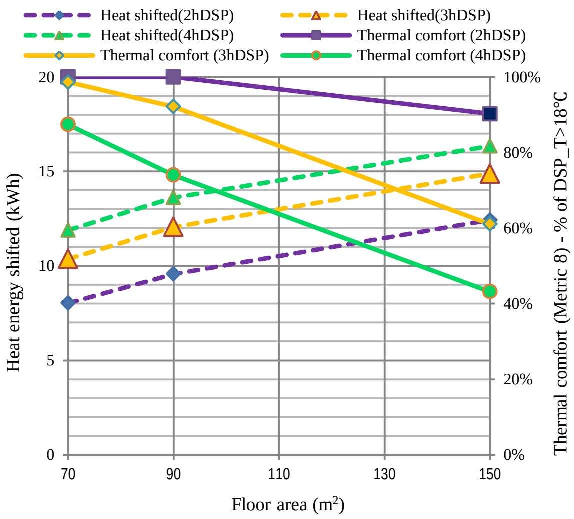


Figure 5-19. Mean (of all built forms and 60 winter days) energy shifted (or consumed) during the three DSPs by floor size, and the corresponding thermal comfort impact.

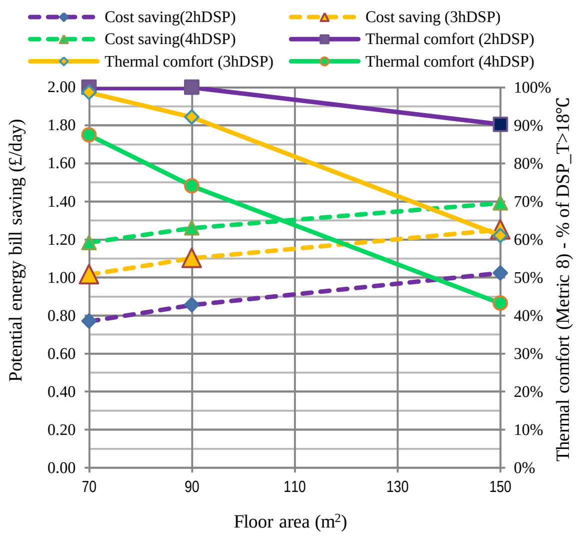


Figure 5-20. Mean (of built forms and 60 winter days) energy bill reduction achieved (based on the energy shifted and purchased at an Economy7 off-peak price) for the three DSPs by floor size, and the corresponding thermal comfort impact.

5.6 Summary

This chapter presented the results of simulations carried out to explore and understand the thermal performance, power and energy demand characteristics in domestic buildings when the heat energy demand within three fixed future DSPs, from the grid peak period of 17:00 to 21:00 hours, is shifted in time through the use of active sensible TES.

The range of outputs generated by the models and the metrics used to measure the performances are described. Demonstrations of the correct workings of the TES system model components were illustrated.

The temperature, power and energy demand characteristic predictions of the 12 Base Case models with the heating system inhibited for three DSPs, and without the use of TES are presented. The impact of this on the thermal comfort, power demand and energy demand are discussed.

The temperature, power and energy demand characteristic predictions, resulting from heat demand shifting from the mains grid peak time to off-peak time by three DSPs, in the 12 Base Case models with the a 'TES Reference Case' level of thermal storage are presented. The impact of this on the thermal comfort, power demand and energy demand are discussed, and the heating bill saving which could be achieved if the shifted energy was purchased at a price based on the currently available Economy7 off-peak price tariff is explored.

6 CHAPTER SIX- RESULTS: PARAMETRIC ANALYSIS OF TES CAPACITY, BUILDING FABRIC, OCCUPANCY AND OPERATIONAL CONDITIONS

6.1 Introduction

This chapter presents the results of the simulations carried out to determine how the impacts of HDS change with varying TES capacity, and building insulation, occupancy and operational conditions.

This chapter is arranged as follows:

Section 6.2:	**Output variables and the performance analysis metrics:** Provides an overview of the simulation output variables for which results are generated, and the metrics used to compare the energy and thermal performance characteristics.
Section 6.3:	**Impacts of TES capacity variation:** Describes the results generated to explore the impacts of varying TES capacity by way of increasing the physical size of the TES tank and the temperature of the hot water stored.
Section 6.4:	**Impacts of thermal insulation, thermostat setting, location, heating duration and occupancy variation:** Describes the results generated to determine the impacts of varying the building thermal characteristics, occupancy and operational parameters.
Section 6.5:	Provides a summary of this chapter.

6.2 Output variables and performance analysis metrics

The methodology and the input parameters used during this research activity was as described in Section 3.8. As per tasks 2 and 3 (see chapter 4 and chapter 5), the performance prediction data was generated for nine output variables as previously shown in Tables 4.1 and 5.1. Also as before, 10 metrics were used to enable the results to be compared with the TES Reference Case and the Base Case results as described previously in Sections 4.2 and 5.2.

6.3 Impact of TES capacity variation

Overview

This section presents the predictions of the space temperature, power and energy consumption impacts of varying TES capacity from those used in the TES Reference Case, as discussed in Chapter 5. Five building archetypes (Det150, Det90, SDet90, MTer90 and Flat90) were used. The thermal insulation, occupancy and operational parameters used were as described in Table 3.14. The floor size used is the UK housing stock average of 90m^2 with the exception of the Det70 and Det150, which had 70m^2 and 150m^2 floor areas. These archetypes have been considered to include into the simulations small and large buildings with low and high energy consumption and low and high energy efficient as can be found in the housing stock. The TES capacity variations included: 1) changing the TES tank sizes from 0.25m^3 to 0.5m^3 and 0.75 m^3, and 2) increasing the hot water storage temperature from 75℃ to 95℃. As before, four fixed DSPs were used (2, 3 and 4 hours during the mains grid peak period of 17:00 to 21:00) to shift the peak-time demand to the off-peak period (00:00 to 07:00). All other variables were as per the TES Reference Case values as previously described in Section 3.8.

6.3.1 Space temperature

The effects of varying TES capacity in relation to TES Reference Case (see Chapter 3, Section 3.7) on the occupied space temperature is illustrated in Figure 6-1 and Figure 6-2 for the Det90 building archetype. Figure 6-1 shows the occupied space temperature profile averaged over 60 days, simulated to achieve a 4 hour demand shift from 17:00 to 21:00 with TES sizes of 0.25m^3, 0.5m^3 and 0.75m^3. Similarly, the mean space temperature profile utilising hot water storage temperatures of 75°C and 95°C are shown in Figure 6-2. The profile for heat demand shifting with no (or 'Zero') TES is also shown for comparison. The Base Case space temperature profile (when no heat demand shift is applied) and the external ambient air temperature profile are also shown for reference. As can be seen, both sets of graphs show that the space temperature during the DSP improves as the TES capacity is enhanced. In these examples, increasing the TES size from 0.25m^3 to 0.5m^3 raises the minimum DSP temperature (Metric 7) by about 3°C, whilst changing the water storage temperature from 75°C to 95°C increases minimum DSP temperature by about 1°C. This indicates that increasing the TES capacity by either or both of the methods mentioned will improve thermal comfort during the DSP, and also increase the energy shifted in time as discussed later, therefore potentially benefitting both the demand and the supply sides. Appreciating the magnitude of these benefits could provide informed decision making in terms of, for example, TES sizing and future energy bill saving, which may or may not influence uptake. To do this, each of the five building archetypes selected were simulated to provide 2 hour, 3 hour and 4 hour heat demand shift using 8 different TES capacity options. An example of a TES capacity option is a TES size of 0.25m³ and a water storage temperature of 75°C.

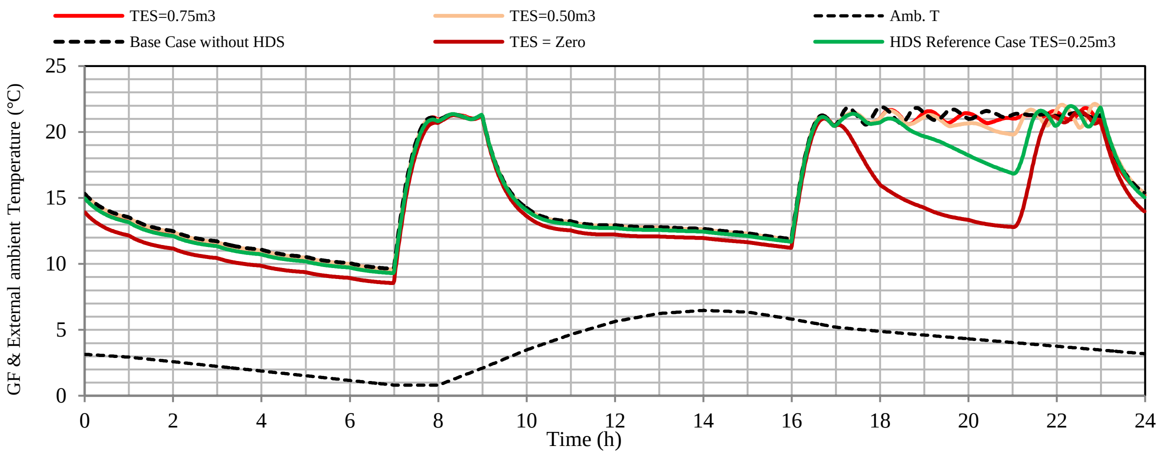


Figure 6-1. Illustration of the 60 day average thermal response impacts for TES size options of: Zero TES (no TES applied), 0.25m³, 0.5m³ and 0.75m³ used to simulate a 4 hour heat demand shift from 17:00 to 21:00. The Base Case response and the external ambient temperature are shown for comparison.

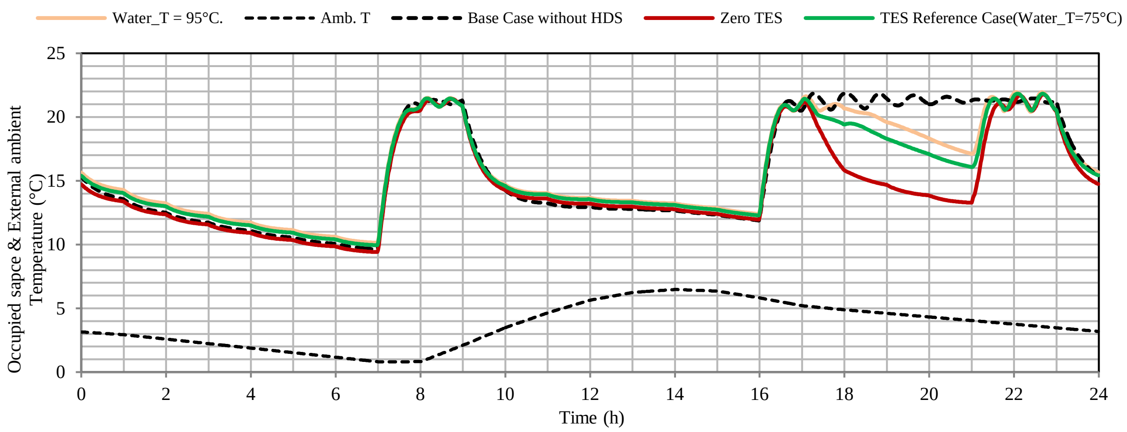


Figure 6-2. Illustration of the 60 day average thermal response impacts for TES hot water storage temperature options of: Zero TES (no TES applied), 75°C and 95°C, used to achieve a 4 hour heat demand shift. The Base Case response and external ambient temperature are shown for comparison.

The occupied space temperature predictions are summarised in Table 6-1 for the different TES size and water storage temperature options. It shows the 60 day mean DSP temperature (Metric 2), the absolute minimum DSP temperature over 60 days (Metric 7) and the 60 day average thermal comfort (Metric 8) recorded for each of the three DSPs considered. The changes in these values from the respective TES Reference Case figures (shown in the highlighted rows) are also shown.

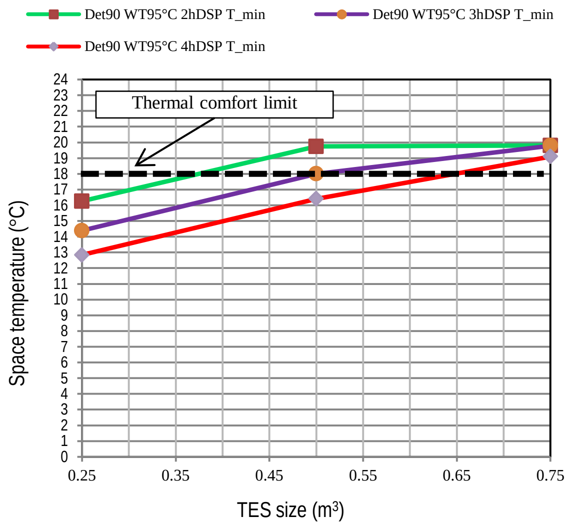
It can be seen that larger TES size and hot water storage temperature options provide higher mean space temperatures and greater thermal comfort (Metric 8) values in all archetypes. The 60 day mean DSP temperature predictions stay higher than 18°C thermal comfort level for all archetypes except Det150 provided that the TES size is 0.5m^3 or higher. But the absolute minimum DSP temperature does drop below 18°C as shown. As expected, the temperature is worse for the detached built form (Det90) and are 14.82°C, 13.28°C and 11.85°C for the 2, 3 and 4 hour DSP respectively, for a 0.25m^3 TES and a 75°C water storage temperature. These are all below 18°C thermal comfort level. When the TES size is increased to 0.75m^3 and a 95°C water storage is used, the minimum temperature increases to 19.80°C, 19.79°C and 19.10°C for the same respective DSPs. This time the temperature remains higher than 18°C thermal comfort level for all three DSPs. This indicates that with a combination of TES sizes (up to 0.75m^3) and water storage temperatures (up to 95°C), up to 4 hours' worth of heat demand shift can be achieved in all four built forms with floor size up to 90m^2 without degrading thermal comfort. In the Det150 building with a 150m^2 floor area, a 3 hour heat demand shift could be achieved without degrading thermal comfort.

The relationship between the TES size with a 95°C water storage temperature and the minimum space temperature is illustrated in Figures 6-3 (a-d) for the three DSPs and the four building archetypes with UK housing stock average or 90m^2 floor sizes (Det90, SDet90, MTer90 and Flat90). Figures 6-3 (e) shows the same relationship for the large detached dwelling (Det150) which require more energy, and in which the impact of heat demand shifts are more likely to be magnified. The minimum temperature limit for thermal comfort (18°C) is illustrated by the black horizontal dashed lines.

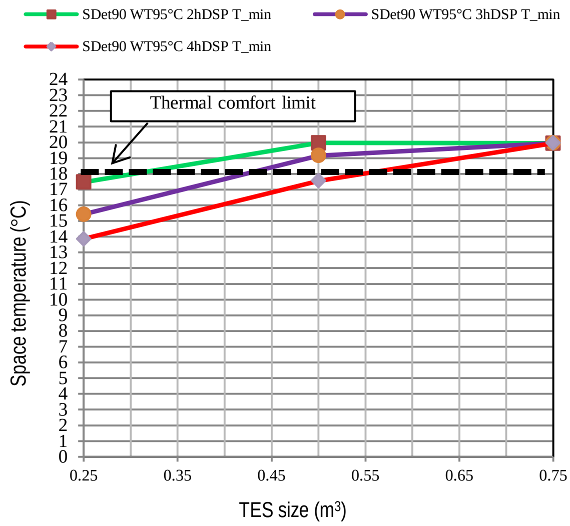
Table 6-1. Summary of the 60 day mean and minimum occupied space temperature impacts in four building archetypes due to varying TES tank sizes and a hot water storage temperature of 75°C.

TES water storage temper-ature	Arche-type	TES Size (m^3)	DSP hours 17:00-19:00 Mean (Metric 2) (°C)	DSP hours 17:00-19:00 Min (Metric7) (°C)	DSP hours 17:00-19:00 %DSP_T>18° (Metric 8) (%)	DSP hours 17:00-20:00 Mean (Metric 2) (°C)	DSP hours 17:00-20:00 Min (Metric7) (°C)	DSP hours 17:00-20:00 %DSP_T>18°C (Metric 8) (%)	DSP hours 17:00-21:00 Mean (Metric 2) (°C)	DSP hours 17:00-21:00 Min (Metric7) (°C)	DSP hours 17:00-21:00 %DSP_T>18° (Metric 8) (%)
TES Capacity impact 75°C	Det90	0.25	20.10	14.82	100%	19.39	13.28	77%	18.58	11.85	55%
		0.50	20.81	17.28	100%	20.65	15.85	100%	20.21	14.49	100%
		0.75	21.00	18.74	100%	21.04	17.61	100%	20.86	16.45	100%
	Det150	0.25	19.33	13.20	80%	18.39	11.38	51%	17.45	9.93	37%
		0.50	20.42	15.59	100%	19.93	13.81	100%	19.23	12.30	72%
		0.75	20.74	17.14	100%	20.61	15.64	100%	20.19	14.23	100%
	SDet90	0.25	20.41	15.95	100%	19.80	14.26	93%	19.07	12.91	66%
		0.50	20.94	18.38	100%	20.87	16.87	100%	20.54	15.49	100%
		0.75	21.09	19.80	100%	21.14	18.60	100%	21.03	17.39	100%
	MTer90	0.25	20.75	16.92	100%	20.34	15.23	100%	19.71	13.83	87%
		0.50	21.07	19.35	100%	21.07	17.92	100%	20.90	16.65	100%
		0.75	21.13	19.95	100%	21.26	19.67	100%	21.19	18.58	100%
	Flat90	0.25	21.06	17.80	100%	20.68	15.73	100%	20.00	14.19	89%
		0.50	21.19	19.96	100%	21.23	18.72	100%	21.08	17.10	100%
		0.75	21.23	19.96	100%	21.32	19.96	100%	21.28	19.25	100%
Change from TES Reference Case 75°C	Det90	0.25	0.00	0.00	0%	0.00	0.00	0%	0.00	0.00	0%
		0.50	0.71	2.34	0%	1.26	2.57	23%	1.63	2.64	45%
		0.75	0.90	3.81	0%	1.64	4.33	23%	2.28	4.60	45%
	Det150	0.25	0.00	0.00	0%	0.00	0.00	0%	0.00	0.00	0%
		0.50	1.09	2.40	20%	1.54	2.43	49%	1.78	2.37	35%
		0.75	1.41	3.94	20%	2.23	4.26	49%	2.74	4.30	63%
	SDet90	0.25	0.00	0.00	0%	0.00	0.00	0%	0.00	0.00	0%
		0.50	0.53	2.43	0%	1.06	2.61	7%	1.47	2.58	34%
		0.75	0.68	3.86	0%	1.33	4.34	7%	1.96	4.49	34%
	MTer90	0.25	0.00	0.00	0%	0.00	0.00	0%	0.00	0.00	0%
		0.50	0.32	2.42	0%	0.73	2.70	0%	1.19	2.82	13%
		0.75	0.39	3.02	0%	0.92	4.45	0%	1.48	4.75	13%
	Flat90	0.25	0.00	0.00	0%	0.00	0.00	0%	0.00	0.00	0%
		0.50	0.13	2.16	0%	0.55	2.99	0%	1.09	2.91	11%
		0.75	0.17	2.16	0%	0.65	4.22	0%	1.28	5.06	11%
TES Capacity impact 95°C	Det90	0.25	20.77	16.25	100%	20.35	14.38	100%	19.64	12.84	78%
		0.50	21.15	19.74	100%	21.20	18.00	100%	21.02	16.41	100%
		0.75	21.17	19.80	100%	21.32	19.79	100%	21.30	19.10	100%
	Det150	0.25	20.21	14.32	100%	19.39	12.24	72%	18.44	10.66	52%
		0.50	20.97	17.67	100%	20.86	15.60	100%	20.41	13.85	100%
		0.75	21.07	19.35	100%	21.17	18.13	100%	21.05	16.45	100%
	SDet90	0.25	20.97	17.47	100%	20.67	15.43	100%	20.05	13.86	92%
		0.50	21.18	19.96	100%	21.29	19.16	100%	21.19	17.56	100%
		0.75	21.19	19.95	100%	21.35	19.96	100%	21.35	19.96	100%
	MTer90	0.25	21.11	18.46	100%	20.96	16.55	100%	20.54	14.98	100%
		0.50	21.25	19.93	100%	21.37	19.93	100%	21.32	18.88	100%
		0.75	21.26	19.93	100%	21.42	19.93	100%	21.41	19.95	100%
	Flat90	0.25	21.27	19.68	100%	21.19	17.34	100%	20.80	15.44	100%
		0.50	21.36	19.99	100%	21.48	19.99	100%	21.42	19.73	100%
		0.75	21.37	20.00	100%	21.52	20.00	100%	21.50	20.00	100%
Change from TES Reference Case 95°C	Det90	0.25	0.67	1.32	0%	0.96	1.10	23%	1.05	0.98	23%
		0.50	1.05	4.81	0%	1.81	4.72	23%	2.44	4.56	45%
		0.75	1.07	4.87	0%	1.92	6.51	23%	2.71	7.25	45%
	Det150	0.25	0.88	1.12	20%	1.00	0.86	21%	1.00	0.73	15%
		0.50	1.64	4.47	20%	2.48	4.22	49%	2.97	3.93	63%
		0.75	1.74	6.15	20%	2.78	6.75	49%	3.61	6.52	63%
	SDet90	0.25	0.56	1.52	0%	0.86	1.17	7%	0.99	0.95	26%
		0.50	0.77	4.01	0%	1.49	4.90	7%	2.12	4.65	34%
		0.75	0.78	4.00	0%	1.55	5.70	7%	2.28	7.05	34%
	MTer90	0.25	0.37	1.54	0%	0.62	1.33	0%	0.83	1.15	13%
		0.50	0.51	3.00	0%	1.04	4.70	0%	1.61	5.05	13%
		0.75	0.52	3.01	0%	1.08	4.70	0%	1.71	6.12	13%
	Flat90	0.25	0.21	1.88	0%	0.52	1.60	0%	0.80	1.25	11%
		0.50	0.30	2.19	0%	0.80	4.25	0%	1.42	5.54	11%
		0.75	0.31	2.20	0%	0.84	4.27	0%	1.50	5.81	11%

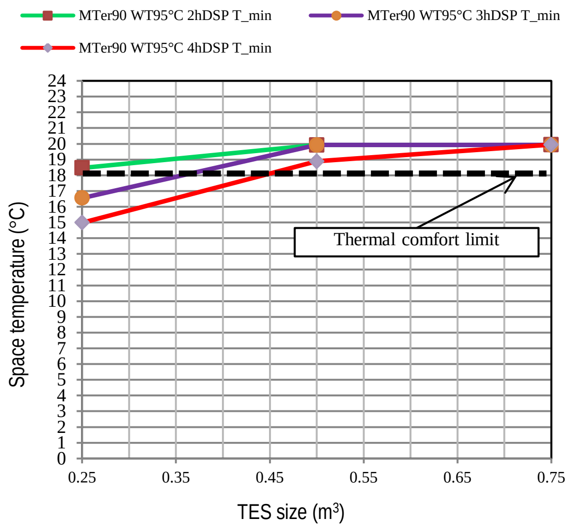
Note:
Metric 2: DSP_hours_mean_GF_T (DSP mean temperature averaged over 60 days)
Metric 7: DSP_minimum_GF_T (DSP overall minimum temperature of 60 days)
Metric 8: %DSP_T>18°C (% DSP temperature above thermal comfort level of 18°C averaged over 60 days)



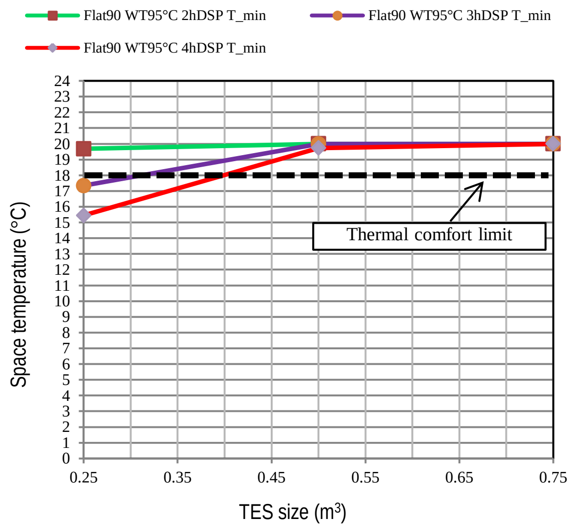
a) Det90



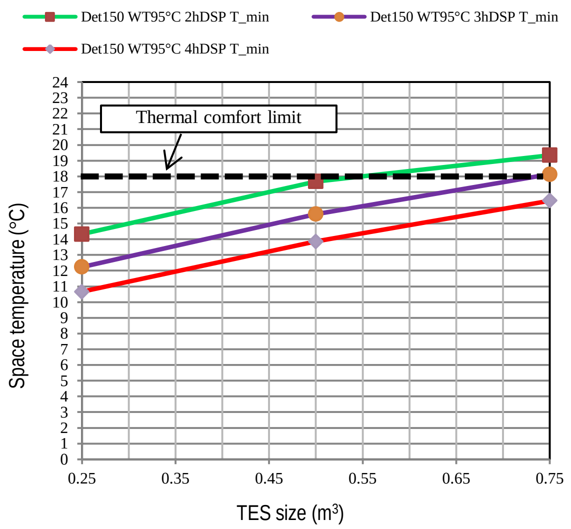
b) SDet90



c) MTer90



d) Flat90

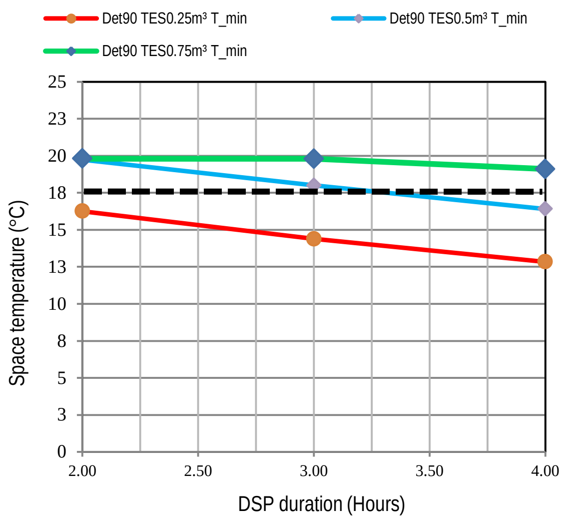


e) Det150

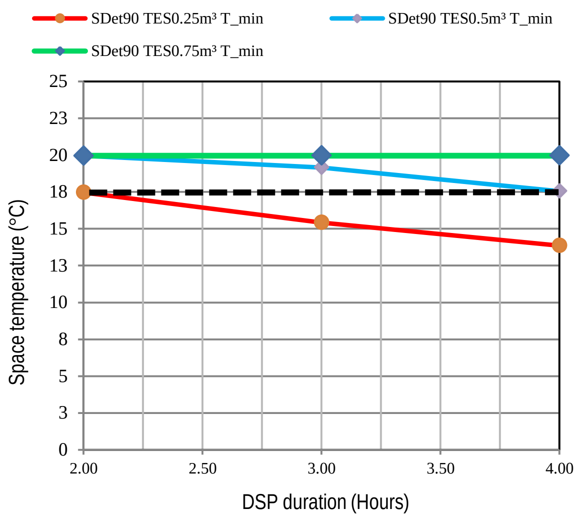
Figures 6-3 (a-e). Impact of TES size with a 95°C water storage temperatures on 60 day minimum space temperature (Metric 7) for 2, 3 and 4 hour DSP for: **a)** Det90, **b)** SDet90, **c)** MTer90, **d)** Flat90 and **e)** Det150 building archetypes.

These graphs are useful in that they can be used to determine the worst case temperature that could exist in the respective building archetypes when heat demand shifts using TES sizes in the range 0.25m³ to 0.75m³ and water storage temperature of 95°C is implemented. For example, it can be extrapolated from Figures 6-3 (a) that to achieve a 2 hour demand shift in the Det90 archetype without degrading space temperature below 18°C a TES size of approximately 0.37m³ and a water temperature of 95°C would be required. Similarly, Figures 6-3 (d) can be used to determine that a TES size of around 0.4m³ and a water temperature of 95°C could provide a 4 hour demand shift in a Flat90 archetype whilst ensuring that the space temperature does not drop below 18°C.

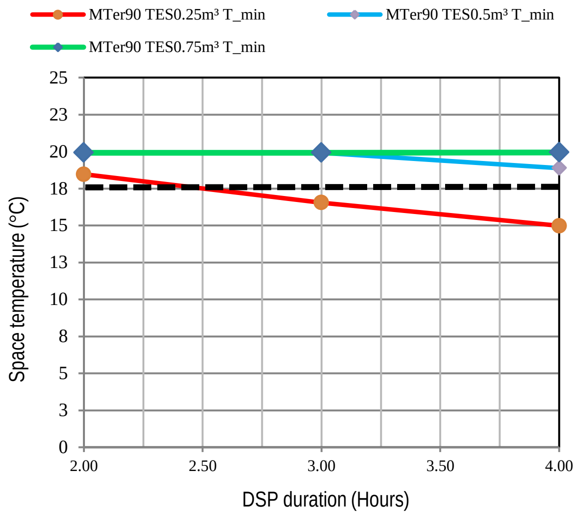
The set of graphs in Figure 6-4 (a-e) illustrate the relationship between the DSP duration achieved in the same five building archetypes and the 60 day minimum space temperature when TES sizes of 0.25m³, 0.50m³ and 0.75m³ are used with a water storage temperature of 95°C. The minimum temperature limit for thermal comfort (18°C) is also illustrated by the black horizontal dashed lines. For example, it can be determined from Figure 6-4 (a) a 0.5m³ TES with a 95°C water storage temperature could be used to achieve up to 3.25 hours HDS in a Det90 archetype without degrading the space temperature below the 18°C thermal comfort limit. The same TES option could provide about 2 hours HDS without degrading space temperature below 18°C in the Det150 archetype as shown in Figure 6-4 (e).



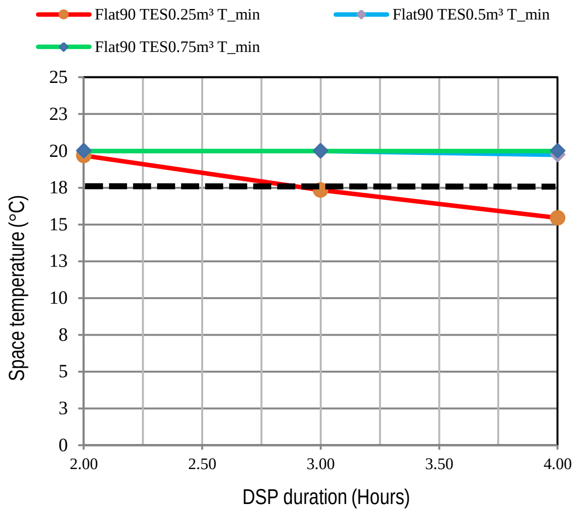
a) Det90



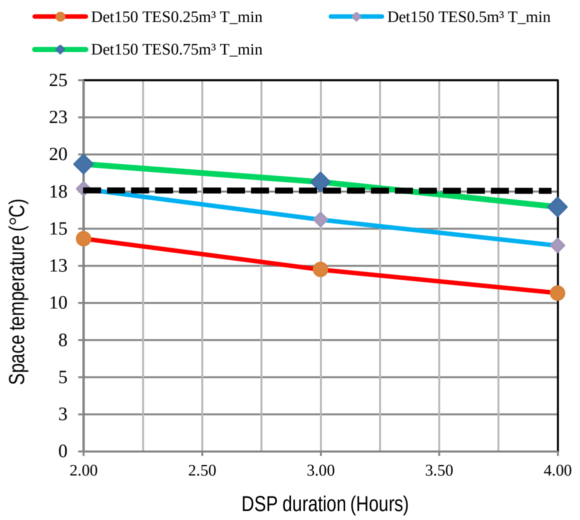
b) SDet90



c) MTer90



d) Flat90



e) Det150

Figure 6-4(a-e). Relationship between heat demand shift duration and the 60 day minimum space temperature with TES sizes of 0.25m³, 0.50m³ and 0.75m³ and a water storage temperature of 95°C are used in the archetypes: a) Det90, b) SDet90, c) MTer90, d) Flat90 and e) Det150.

The link between the floor area of the dwellings and the 60 day minimum space temperature for the DSPs and the TES size and water storage temperature options could be very useful. This is illustrated in Figure 6-5, showing how the 60 day minimum space temperature change with floor area for the detached built form. Results are shown for the three DSPs, three TES sizes and a water storage temperature of 95°C. Only the detached built form with floor sizes of 70m², 90m² and 150m² have been used as it is the most energy consuming. This required simulations to be performed on the Det70 in addition to the 5 archetypes mentioned earlier in this section. The minimum temperature limit for thermal comfort (18°C) is also illustrated. It can be seen that a 0.25m³ TES option in all sizes of detached dwellings and for all three DSP is predicted to degrade the space temperature below the thermal comfort threshold. However, a 3 hour DSP could be achieved with a 0.75m3 TES in all sizes up to 150m2 without lowering space temperature below 18°C.

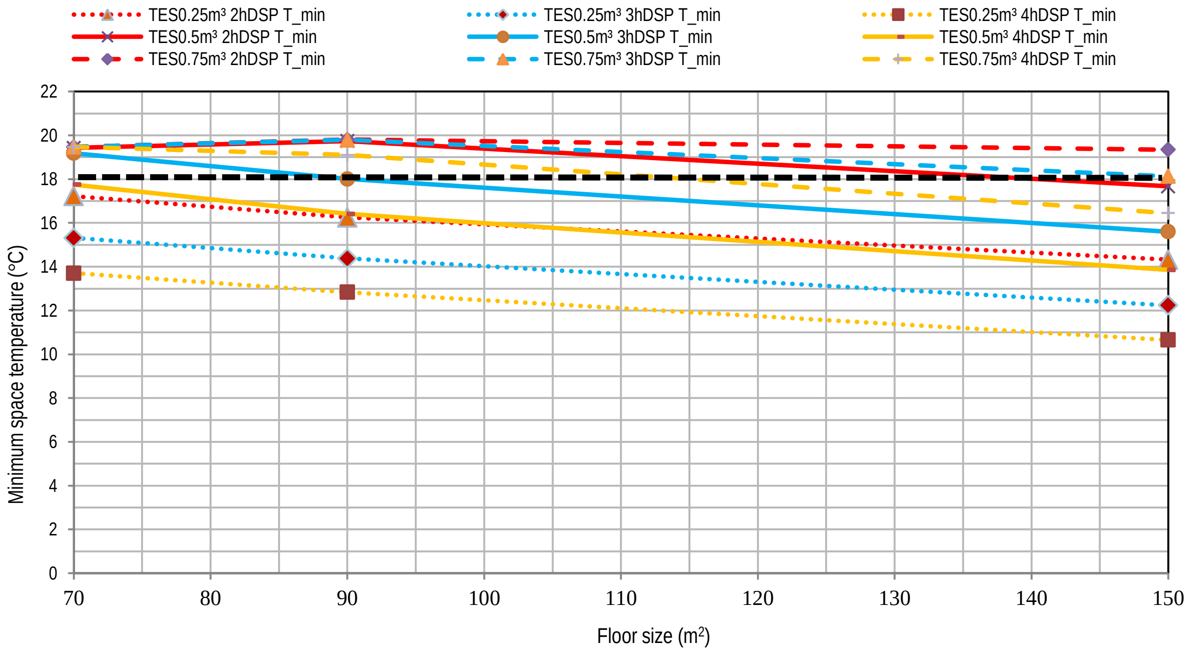


Figure 6-5. Relationship between the detached dwelling floor area (70m² to 150m²) and the 60 day minimum space temperature for TES sizes of 0.25m³, 0.50m³ and 0.75m³ with a water storage temperature of 95°C.

6.3.2 Power demand

Figure 6-6 and Figure 6-7 illustrate the 60 day mean power demand profile prediction for the Det90 archetype, simulated to achieve a 4 hour DSP from 17:00 to 21:00, utilising TES sizes of 0.25m³, 0.5m³ and 0.75m³, and water storage temperatures of 75°C and 95°C. For comparison, the temperature profiles for the Base Case (without heat demand shifting), Zero TES (heat demand shifting with zero TES) and the external ambient air temperature profiles are also shown. It can be seen that the power demand during the DSP period is zero. It peaks to 25kW from the period 00:00 to around 00:30, as per the water heater power rating, when the TES devices are charged up. The duration of the peak power demand varies for larger TES capacity options, from 00:00 to about 01:30. These indicate a power demand shift in time, from the grid peak period to the grid off-peak period.

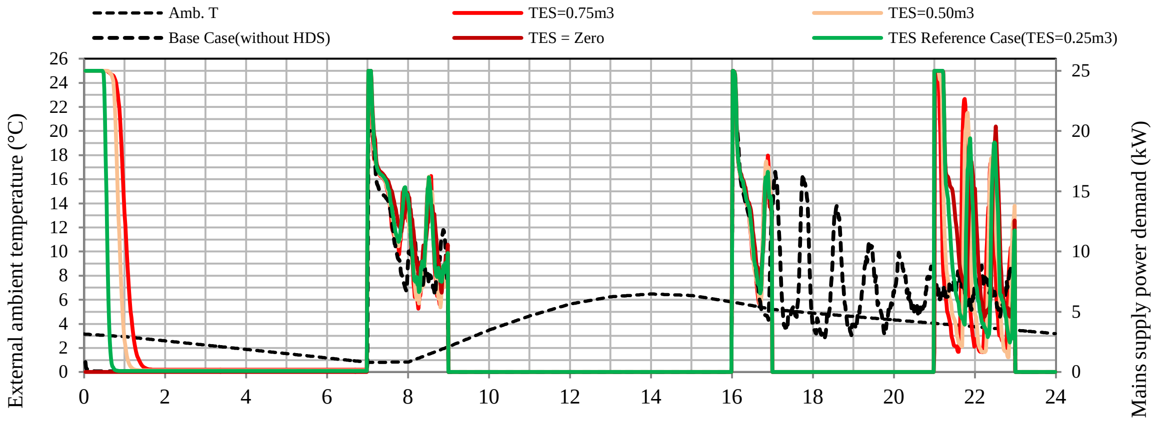


Figure 6-6. 60 day mean mains supply power demand impacts for TES tank sizes of: Zero (No TES), 0.25m³, 0.5m³ and 0.75m³; simulating a 4 hour heat demand shift in a Det90 archetype.

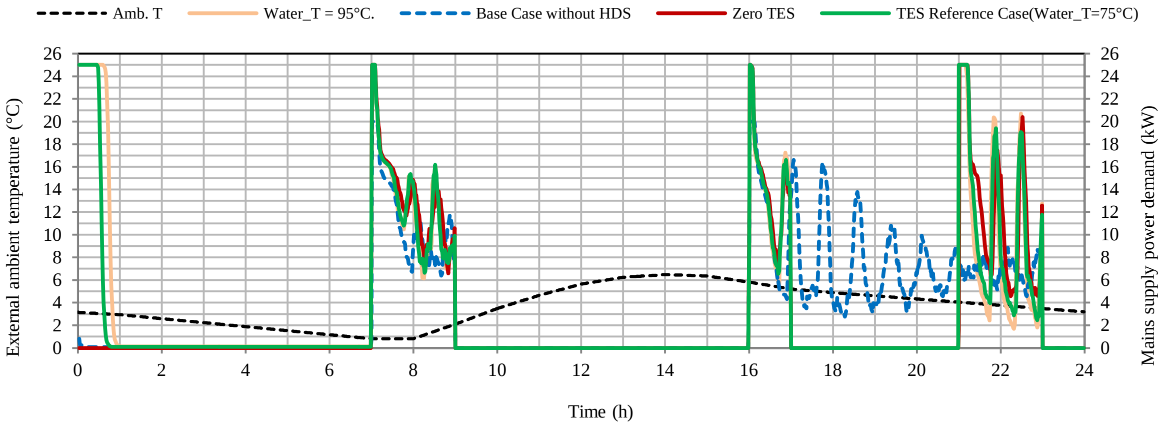


Figure 6-7. 60 day mean mains supply power demand impacts for TES hot water storage temperatures of 75°C and 95°C, simulating a 4 hour heat demand shift in a Det90 archetype.

The power demand predictions generated for the four building archetypes and the combination of TES capacity options are summarised in Table 6-2, showing the 60 day mean, maximum and minimum values. The table also shows the changes in the power demands caused by the TES size changing with respect to the corresponding TES Reference Case results as shown in the highlighted rows. As mentioned earlier, the DSP time power is provided by the TES tank, and is independent of the mains supply. The mean power demand values in the table are averages of the relevant time periods, and are not the instantaneous power demand, which could be as high as the power rating of the water heater as previously discussed.

Table 6-2. Summary of the 60 day mean mains supply power demand and three DSP period power demand impacts in the four building archetypes, due to varying TES tank sizes and hot water storage temperatures.

	Water Temperature	Building archetype	TES Size (m³)	Mains supply demand 00:00-24:00 Mean Metric 3 (kW)	Max. (kW)	Min (kW)	Heated hours 17:00-19:00 Mean Metric 4 (kW)	Max. (kW)	Min (kW)	Heated hours 17:00-20:00 Mean Metric 4 (kW)	Max. (kW)	Min (kW)	Heated hours 17:00-21:00 Mean Metric 4 (kW)	Max. (kW)	Min (kW)
TES Capacity impact	75°C	Det90	0.25	3.29	25.00	0.00	5.54	10.45	2.87	4.22	10.37	1.79	3.65	10.86	0.98
			0.50	3.44	25.00	0.00	6.75	10.65	4.42	5.96	10.56	3.67	5.27	10.75	2.64
			0.75	3.50	25.00	0.00	7.11	10.95	4.26	6.47	11.08	4.08	6.00	11.08	4.01
		Det150	0.25	4.59	30.00	0.00	6.80	15.73	2.78	5.21	15.75	1.45	4.20	15.35	0.85
			0.50	4.78	30.00	0.00	9.06	15.88	5.76	7.59	15.95	3.62	6.45	16.08	2.42
			0.75	4.90	30.00	0.00	9.91	15.99	6.31	8.82	16.07	5.86	7.84	15.77	4.20
		SDet90	0.25	3.08	25.00	0.00	5.21	9.29	2.90	4.22	9.44	1.63	3.51	9.50	0.99
			0.50	3.19	25.00	0.00	6.17	10.19	3.43	5.53	10.12	3.39	4.98	10.24	2.70
			0.75	3.23	25.00	0.00	6.32	9.89	3.68	5.85	10.01	3.57	5.56	10.25	3.62
		MTer90	0.25	2.81	25.00	0.00	4.92	8.61	3.00	4.04	8.70	1.79	3.39	8.71	1.05
			0.50	2.90	25.00	0.00	5.49	9.40	3.09	5.01	9.33	2.79	4.63	9.09	2.82
			0.75	2.93	25.00	0.00	5.64	9.63	3.01	5.27	9.53	3.00	4.75	8.37	3.06
		Flat90	0.25	2.58	25.00	0.00	4.52	8.68	1.88	3.86	8.90	1.93	3.29	8.86	1.11
			0.50	2.66	25.00	0.00	4.81	9.19	1.99	4.56	9.26	2.12	4.34	9.28	2.01
			0.75	2.69	25.00	0.00	4.87	9.03	2.03	4.65	9.21	1.86	4.57	8.97	2.05
	95°C	Det90	0.25	3.40	25.00	0.00	6.61	12.45	3.61	5.48	12.36	2.37	4.59	12.25	1.39
			0.50	3.53	25.00	0.00	7.20	12.55	3.07	6.64	12.75	3.10	6.14	12.74	3.45
			0.75	3.55	25.00	0.00	7.24	13.10	3.66	6.84	12.69	3.43	6.48	12.69	3.22
		Det150	0.25	4.70	30.00	0.00	8.44	17.82	4.02	6.57	17.70	1.93	5.30	17.83	1.08
			0.50	4.92	30.00	0.00	10.37	18.31	5.23	9.13	18.43	5.06	8.05	18.71	3.82
			0.75	5.01	30.00	0.00	10.52	18.49	5.27	9.85	18.51	4.95	9.19	18.62	4.98
		SDet90	0.25	3.16	25.00	0.00	6.11	10.18	3.41	5.17	10.21	2.56	4.40	10.68	1.46
			0.50	3.25	25.00	0.00	6.42	10.48	3.27	6.08	10.83	3.13	5.72	10.67	3.46
			0.75	3.28	25.00	0.00	6.44	11.31	3.00	6.14	11.27	3.01	5.94	11.30	2.98
		MTer90	0.25	2.87	25.00	0.00	5.52	11.25	2.92	4.78	11.09	2.34	4.15	11.18	1.72
			0.50	2.96	25.00	0.00	5.76	11.26	3.09	5.37	11.02	3.03	5.06	11.13	3.05
			0.75	2.99	25.00	0.00	5.75	11.45	3.07	5.46	11.39	3.08	5.18	11.34	3.09
		Flat90	0.25	2.64	25.00	0.00	4.88	9.37	2.02	4.43	9.60	1.93	3.99	9.70	1.92
			0.50	2.71	25.00	0.00	4.99	9.00	2.00	4.85	9.16	2.11	4.67	9.15	1.94
			0.75	2.73	25.00	0.00	5.01	9.04	2.08	4.89	9.34	2.00	4.74	9.16	2.07
Change from TES Reference Case	75°C	Det90	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	0.15	0.00	0.00	1.22	0.19	1.55	1.74	0.19	1.88	1.62	-0.10	1.66
			0.75	0.20	0.00	0.00	1.58	0.50	1.39	2.25	0.70	2.29	2.36	0.23	3.03
		Det150	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	0.19	0.00	0.00	2.26	0.15	2.97	2.37	0.21	2.18	2.25	0.73	1.57
			0.75	0.30	0.00	0.00	3.11	0.26	3.52	3.61	0.33	4.41	3.64	0.42	3.34
		SDet90	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	0.11	0.00	0.00	0.96	0.90	0.53	1.32	0.68	1.76	1.47	0.73	1.71
			0.75	0.15	0.00	0.00	1.11	0.60	0.77	1.63	0.58	1.94	2.05	0.75	2.62
		MTer90	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	0.09	0.00	0.00	0.57	0.80	0.09	0.96	0.62	1.00	1.24	0.39	1.77
			0.75	0.12	0.00	0.00	0.72	1.02	0.01	1.22	0.82	1.20	1.37	-0.33	2.00
		Flat90	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	0.08	0.00	0.00	0.29	0.51	0.11	0.69	0.36	0.20	1.05	0.41	0.89
			0.75	0.11	0.00	0.00	0.35	0.35	0.15	0.79	0.31	-0.07	1.28	0.10	0.94
	95°C	Det90	0.25	0.10	0.00	0.00	1.07	2.00	0.74	1.26	1.98	0.58	0.94	1.39	0.41
			0.50	0.23	0.00	0.00	1.66	2.10	0.20	2.42	2.38	1.31	2.50	1.89	2.47
			0.75	0.26	0.00	0.00	1.70	2.64	0.79	2.62	2.31	1.64	2.83	1.83	2.24
		Det150	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	0.22	0.00	0.00	1.93	0.49	1.22	2.56	0.73	3.13	2.75	0.88	2.74
			0.75	0.30	0.00	0.00	2.08	0.67	1.25	3.29	0.81	3.02	3.89	0.79	3.90
		SDet90	0.25	0.08	0.00	0.00	0.91	0.90	0.50	0.96	0.77	0.93	0.89	1.18	0.47
			0.50	0.17	0.00	0.00	1.21	1.19	0.37	1.87	1.40	1.50	2.21	1.17	2.47
			0.75	0.20	0.00	0.00	1.24	2.02	0.09	1.92	1.83	1.38	2.43	1.80	1.99
		MTer90	0.25	0.07	0.00	0.00	0.61	2.64	-0.08	0.73	2.38	0.55	0.76	2.47	0.66
			0.50	0.15	0.00	0.00	0.84	2.65	0.09	1.33	2.31	1.23	1.67	2.43	2.00
			0.75	0.18	0.00	0.00	0.84	2.84	0.07	1.42	2.69	1.29	1.79	2.64	2.03
		Flat90	0.25	0.07	0.00	0.00	0.36	0.69	0.14	0.57	0.70	0.00	0.70	0.83	0.81
			0.50	0.13	0.00	0.00	0.46	0.32	0.12	0.98	0.26	0.18	1.38	0.28	0.82
			0.75	0.15	0.00	0.00	0.48	0.36	0.20	1.03	0.44	0.07	1.45	0.29	0.95

Note

Metric 3: Whole building daily mean mains supply power demand (Daily_mean_MS_power_kW)

Metric 4(a,b,c): Space heating only mean power demand during the occupied hours from 17:00 to 19:00, 17:00 to 20:00 and 17:00 and 21:00.

6.3.3 Energy consumption

The effects of different TES tank sizes (0.25m³ and 0.75m³) and water storage temperature of 95°C on the 60 day mean mains supply energy draw profile for the Det90 archetype and a 4 hour heat demand shift is illustrated in Figure 6-8. The energy draw profile for the Base Case and the average external ambient temperature is shown for reference. As discussed earlier in Section 5.5.3, during the DSPs the energy draw profiles are flat or have zero gradients, indicating no loading of the mains supply. It can be seen that the draw profiles have positive gradient between 00:00 to about 01:30 indicating grid loading during this period and thus shifting of energy demand from period 17:00-21:00 to the period 00:00-01:30. It can be seen that the mains supply energy consumption is around 82.5kWh for the Base Case (see trace 'Base Case'). The energy consumption reduces when heat demand shift is implemented with a small TES. For example when a 0.25m³ TES is used the energy consumption reduces to around 76kWh (see trace TES0.25m³_WT95°C_4hDSP). The lower energy consumption is achieved at the expense of reduced space temperature during the DSP as discussed in Section 6.3.1. Large TES options, which maintain the space temperature at 18°C or higher, result in greater energy consumption in comparison to the Base Case. For example as shown in Figure 6-8, it increases by 2.5kWh to a value of 85.0kWh for a 0.75m³ TES (see trace TES0.75m³_WT95°C_4hDSP).

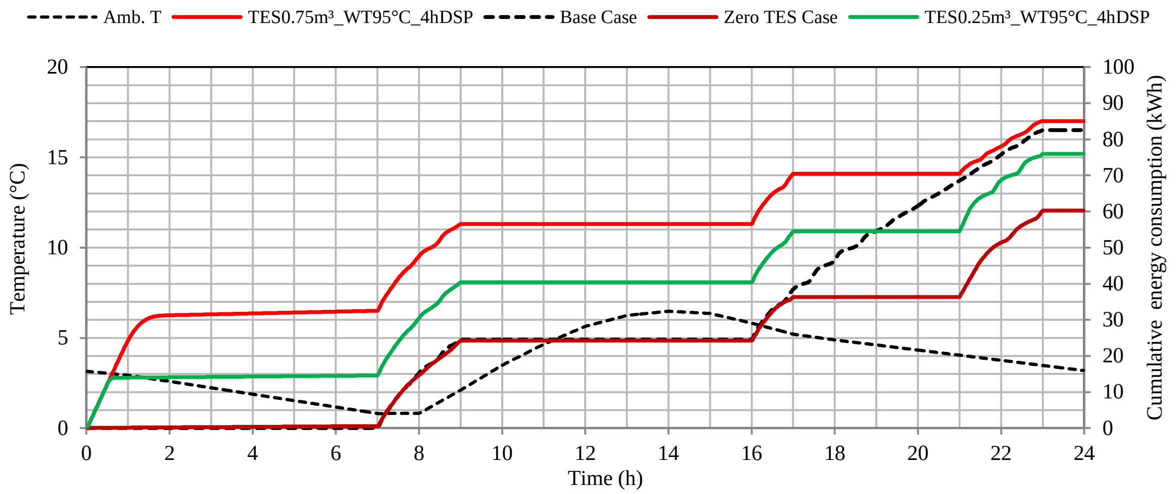


Figure 6-8. Mains supply energy draw profile for TES sizes of Zero (TES=Zero), 0.25m³ and 0.75m³ with 95°C water temperature, averaged over the 60 day simulation period, for the Det90 building archetype and a 4 hour heat demand shift simulation.

The energy consumption predictions for the five building archetypes considered in this analysis are summarised in Table 6-3. It shows: 1) the DSP hour space heating energy use; 2) mains supply energy use for the 3 DSPs; 3) the energy supplied from the TES tank for heat demand shifting or the energy shifted in time (Metric 9) for the 3 DSPs, and 4) the energy bill saving per day (Metric 10) for the 3 DSPs, based on the currently available discounted Economy 7 electricity price. The change in energy consumption, with respect to the TES Reference Case values, resulting from the adjustments in TES capacity options are also shown in Table 6-3. The results are arranged in order by water storage temperature, building archetype and TES size, and show the 60 day average values. For example, the daily mean mains supply energy consumption for the Det90, SDet90, Mter90 and the Flat90 building archetypes are 84.56kWh, 78.15kWh, 71.19kWh and 65.26kWh respectively, when a 4 hour HDS is implemented with a TES tank size of 0.5m^3 and a water storage temperature of 95°C. The corresponding amounts of heat shifted are 26.11kWh, 24.79kWh, 22.17kWh and 20.75kWh respectively. In contrast, the values for the TES Reference Case mains supply energy consumption are 76.59kWh, 71.67kWh, 65.87kWh and 60.46kWh, and the amounts of heat shifted are 13.68kWh, 13.46kWh, 13.11kWh and 12.86kWh. This shows that the amount of heat that can be shifted to off-peak times can be almost doubled, which could provide larger future energy bill savings for the households. Also, as discussed earlier, it provides higher room temperature during the DSP. These are likely to make heat demand shifting more acceptable to both supply and demand sides. However, they could also impose barriers to greater uptake, for example in terms of increased installation costs and taking up more space in the home, and therefore needs to be given the due consideration. This is beyond the scope of this work and not addressed in this thesis.

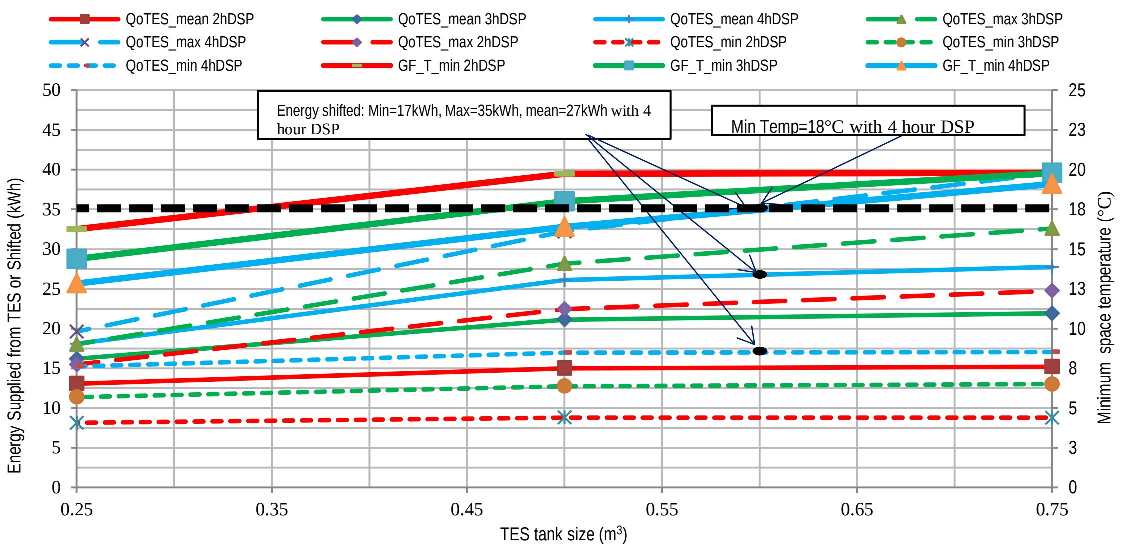
Table 6-3. Summary of the impact of TES capacity options on the 60 day mean: space heating only energy consumption during the DSP, daily mains supply energy consumption, heat energy shifted to off-peak time and the corresponding energy bill saving.

				Space heating energy only			Mains Supply energy			TES (shifted) energy			Energy Saving per day		
				Energy consumption during the DSP hours of:			Daily energy consumption with DSP hours of:			(Metric 9) With DSP hours of:			(Metric 10) With DSP hours of:		
	Water storage temperature	Archetyp	TES Size	17:00-19:00 (kWh)	17:00-20:00 (kWh)	17:00-21:00 (kWh)	17:00-19:00 (kWh)	17:00-20:00 (kWh)	17:00-21:00 (kWh)	17:00-19:00 (kWh)	17:00-20:00 (kWh)	17:00-21:00 (kWh)	17:00-19:00 (£)	17:00-20:00 (£)	17:00-21:00 (£)
TES impacts on Energy	75°C	Det90	0.25	11.22	13.09	14.77	82.13	75.13	76.59	10.17	12.06	13.68	1.00	1.18	1.34
			0.50	13.61	18.00	21.22	84.17	83.21	81.35	13.56	18.11	21.48	1.33	1.77	2.11
			0.75	14.32	19.53	24.15	84.79	84.25	83.61	14.58	20.04	25.16	1.43	1.96	2.47
		Det150	0.25	13.84	15.90	17.06	115.48	111.07	105.09	11.82	13.73	14.89	1.16	1.35	1.46
			0.50	18.32	22.99	26.05	117.94	115.63	111.88	17.45	22.10	25.20	1.71	2.17	2.47
			0.75	19.97	26.66	31.57	119.21	118.13	116.13	19.78	26.58	31.61	1.94	2.61	3.10
		SDet90	0.25	10.50	12.75	14.16	76.38	74.56	71.67	9.88	12.10	13.46	0.97	1.19	1.32
			0.50	12.37	16.66	20.00	77.68	77.13	75.62	12.79	17.28	20.79	1.25	1.69	2.04
			0.75	12.71	17.59	22.30	78.22	78.01	77.43	13.11	18.62	23.80	1.29	1.82	2.33
		MerT90	0.25	9.93	12.25	13.69	69.48	67.89	65.87	9.31	11.63	13.11	0.91	1.14	1.28
			0.50	11.02	15.10	18.61	70.62	69.81	69.14	11.38	15.73	19.51	1.12	1.54	1.91
			0.75	11.33	15.89	20.01	71.12	70.64	70.63	11.88	16.75	21.37	1.16	1.64	2.09
		Flat90	0.25	9.14	11.69	13.29	63.60	62.45	60.46	8.62	11.23	12.86	0.84	1.10	1.26
			0.50	9.68	13.74	17.45	64.64	64.25	63.40	10.01	14.48	18.48	0.98	1.42	1.81
			0.75	9.81	14.04	18.35	65.11	64.84	64.63	10.19	14.87	19.79	1.00	1.46	1.94
	95°C	Det90	0.25	13.33	16.58	18.52	83.58	82.40	79.57	13.06	16.19	18.09	1.28	1.59	1.77
			0.50	14.52	20.01	24.69	85.25	84.94	84.56	15.01	21.13	26.11	1.47	2.07	2.56
			0.75	14.58	20.61	26.03	86.01	85.44	85.05	15.20	21.92	27.76	1.49	2.15	2.72
		Det150	0.25	17.11	19.96	21.48	117.29	113.79	108.71	15.69	18.31	19.76	1.54	1.79	1.94
			0.50	20.93	27.59	32.44	119.69	118.78	116.82	20.86	27.57	32.50	2.04	2.70	3.19
			0.75	21.23	29.68	36.95	120.71	120.52	120.32	21.48	30.79	38.09	2.11	3.02	3.73
		SDet90	0.25	12.28	15.61	17.70	77.56	76.68	74.29	12.52	15.76	17.78	1.23	1.54	1.74
			0.50	12.87	18.29	22.93	78.40	78.30	78.15	13.96	19.88	24.79	1.37	1.95	2.43
			0.75	12.91	18.45	23.83	79.41	79.05	78.55	14.09	20.13	26.04	1.38	1.97	2.55
		MerT90	0.25	11.10	14.43	16.74	70.39	69.36	68.18	11.45	14.69	17.01	1.12	1.44	1.67
			0.50	11.58	16.19	20.33	71.55	71.30	71.19	12.54	17.63	22.17	1.23	1.73	2.17
			0.75	11.58	16.47	20.82	72.25	72.08	71.64	12.49	18.05	22.81	1.22	1.77	2.24
		Flat90	0.25	9.82	13.39	16.08	64.53	64.03	62.76	10.25	13.88	16.60	1.00	1.36	1.63
			0.50	10.05	14.61	18.76	65.36	65.25	65.26	10.98	16.20	20.75	1.08	1.59	2.03
			0.75	10.08	14.73	19.05	66.14	65.91	65.50	10.96	16.27	21.07	1.07	1.59	2.07
Change from TES Reference Case	75°C	Det90	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	2.39	4.91	6.45	2.05	8.08	4.76	3.39	6.04	7.80	0.33	0.59	0.76
			0.75	3.10	6.44	9.38	2.66	9.12	7.02	4.41	7.98	11.47	0.43	0.78	1.12
		Det150	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	4.48	7.09	8.99	2.46	4.56	6.79	5.62	8.37	10.31	0.55	0.82	1.01
			0.75	6.13	10.76	14.51	3.72	7.06	11.05	7.95	12.84	16.72	0.78	1.26	1.64
		SDet90	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	1.88	3.91	5.84	1.30	2.57	3.95	2.91	5.19	7.34	0.28	0.51	0.72
			0.75	2.21	4.84	8.13	1.83	3.45	5.76	3.23	6.52	10.34	0.32	0.64	1.01
		MerT90	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	1.09	2.85	4.92	1.14	1.92	3.27	2.07	4.09	6.40	0.20	0.40	0.63
			0.75	1.40	3.63	6.32	1.63	2.75	4.76	2.57	5.12	8.26	0.25	0.50	0.81
		Flat90	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.50	0.54	2.05	4.16	1.05	1.80	2.94	1.39	3.24	5.62	0.14	0.32	0.55
			0.75	0.67	2.35	5.06	1.51	2.39	4.17	1.57	3.64	6.93	0.15	0.36	0.68
	95°C	Det90	0.25	2.12	3.49	3.75	1.45	7.27	2.98	2.89	4.13	4.41	0.28	0.40	0.43
			0.50	3.30	6.92	9.92	3.12	9.81	7.97	4.84	9.07	12.43	0.47	0.89	1.22
			0.75	3.37	7.52	11.26	3.88	10.31	8.46	5.03	9.86	14.08	0.49	0.97	1.38
		Det150	0.25	3.26	4.06	4.43	1.80	2.72	3.62	3.86	4.58	4.87	0.38	0.45	0.48
			0.50	7.08	11.69	15.39	4.20	7.71	11.73	9.04	13.84	17.61	0.89	1.36	1.73
			0.75	7.38	13.78	19.89	5.23	9.45	15.24	9.65	17.06	23.20	0.95	1.67	2.27
		SDet90	0.25	1.78	2.86	3.54	1.18	2.12	2.62	2.64	3.66	4.32	0.26	0.36	0.42
			0.50	2.38	5.54	8.77	2.02	3.74	6.48	4.08	7.78	11.33	0.40	0.76	1.11
			0.75	2.41	5.70	9.67	3.02	4.49	6.88	4.21	8.03	12.58	0.41	0.79	1.23
		MerT90	0.25	1.17	2.18	3.05	0.90	1.47	2.31	2.13	3.06	3.90	0.21	0.30	0.38
			0.50	1.65	3.93	6.64	2.07	3.41	5.32	3.23	6.00	9.06	0.32	0.59	0.89
			0.75	1.65	4.21	7.13	2.77	4.18	5.77	3.17	6.41	9.70	0.31	0.63	0.95
		Flat90	0.25	0.68	1.69	2.79	0.93	1.58	2.30	1.63	2.64	3.74	0.16	0.26	0.37
			0.50	0.91	2.91	5.47	1.76	2.80	4.80	2.36	4.96	7.89	0.23	0.49	0.77
			0.75	0.95	3.04	5.76	2.54	3.46	5.04	2.34	5.04	8.21	0.23	0.49	0.80

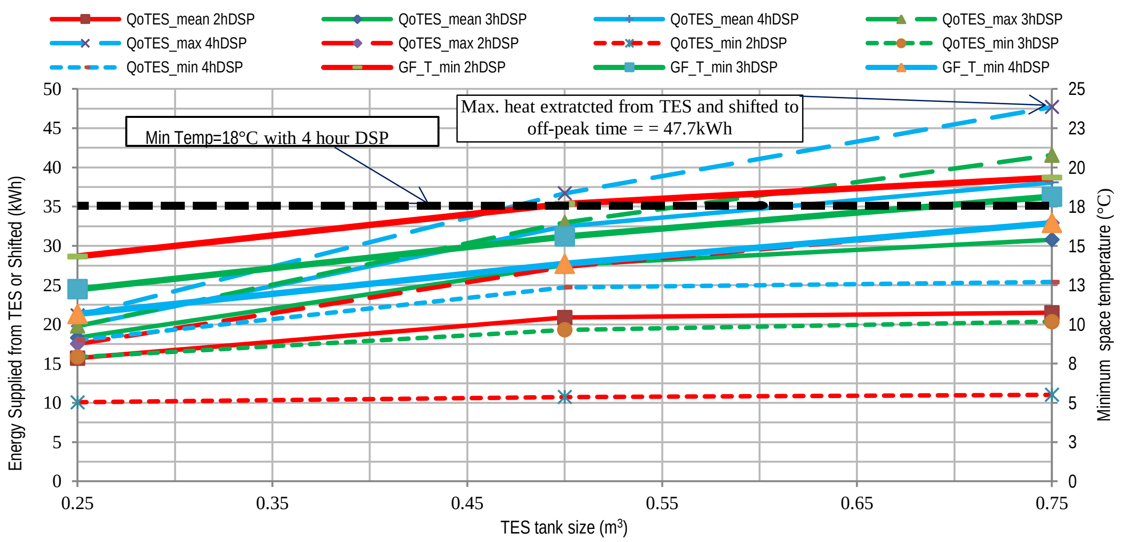
Note

Metric 9: TES_tank_energy_kWh (amount of heat provided by the TES store during the DSP or potentially shifted to off-peak time)

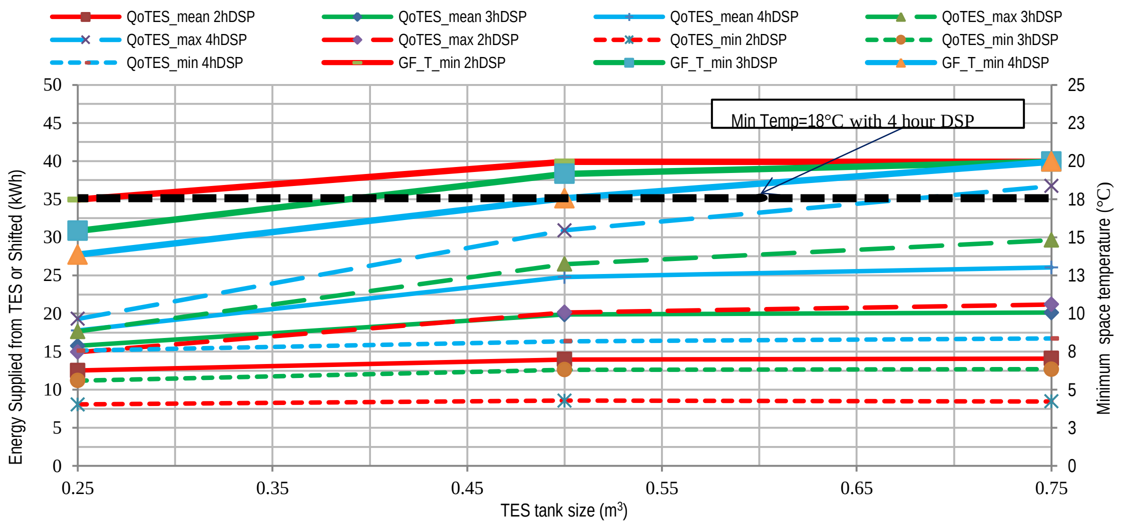
Metric 10: Energy_cost_saving/day (potential electricity bill saving based on current Economy7 price tariff and heat shifted to off peak time)



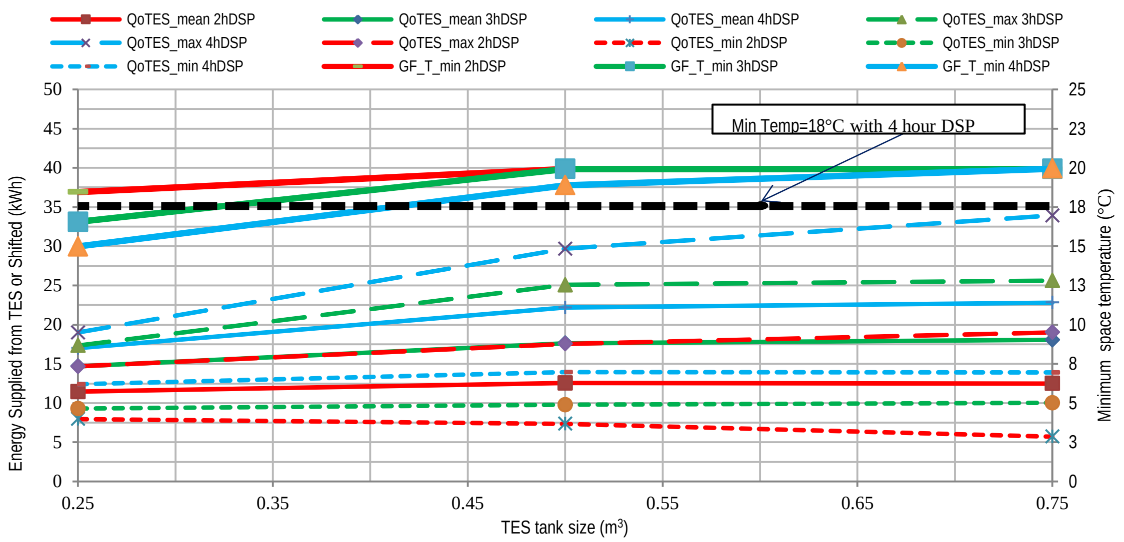
a) <u>Det90</u>



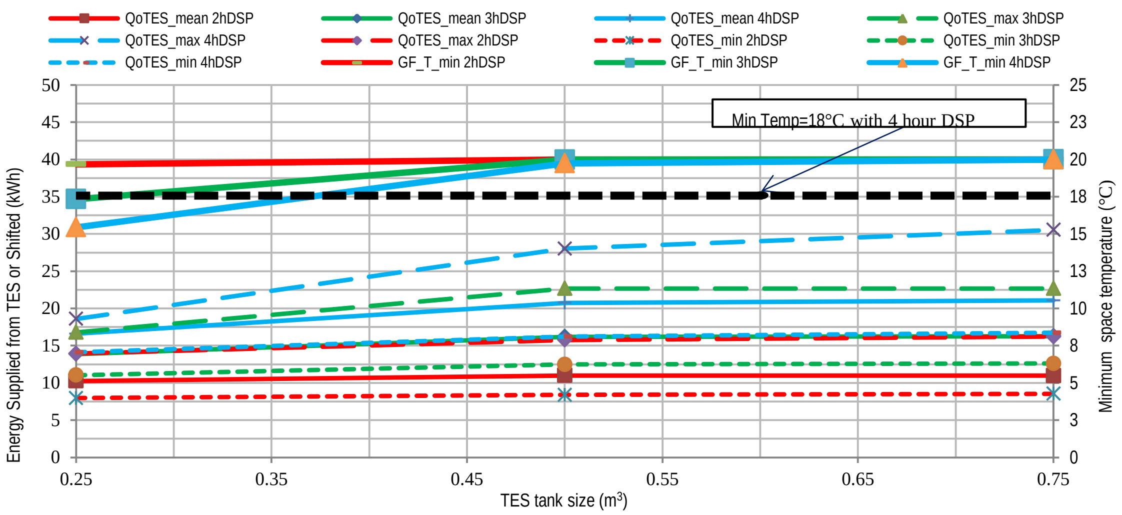
b) <u>Det150</u>



c) <u>SDet90</u>



d) MTer90



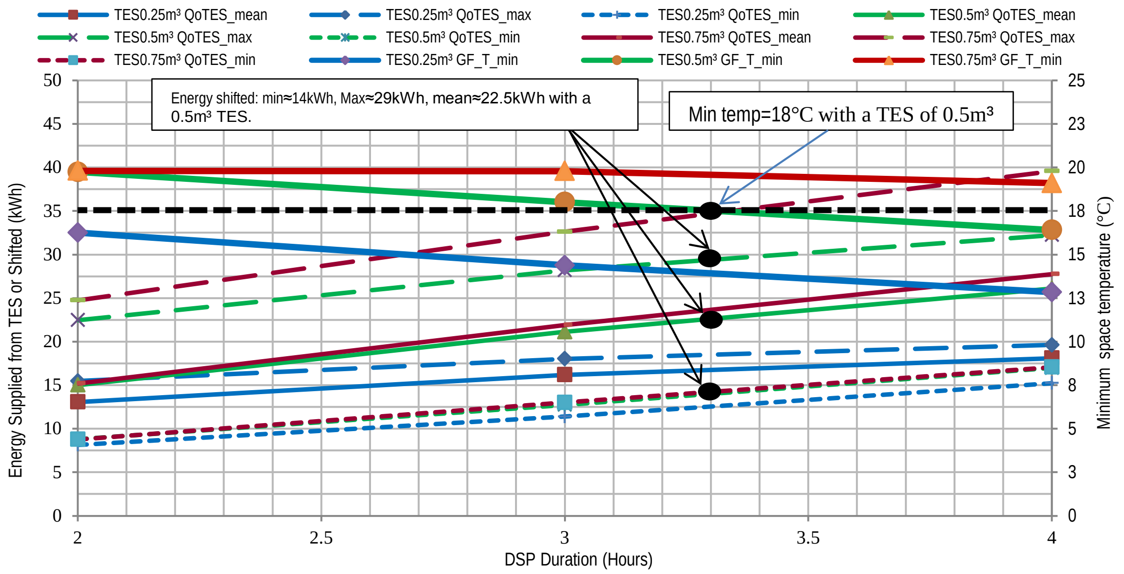
e) Flat90

Figure 6-9(a, b, c, d, e). Maximum, mean and minimum energy shifted (QoTES_max, QoTES_mean, QoTES_min) and minimum space temperature (GF_T_min) by TES size, for 2, 3 and 4 hour DSP (denoted by 2hDSP, 3hDSP and 4hDSP respectively) for: a) Det90, b) Det150, c) SDet90, d) MTer90 and e) Flat90. Water storage temperature of 95°C is used.

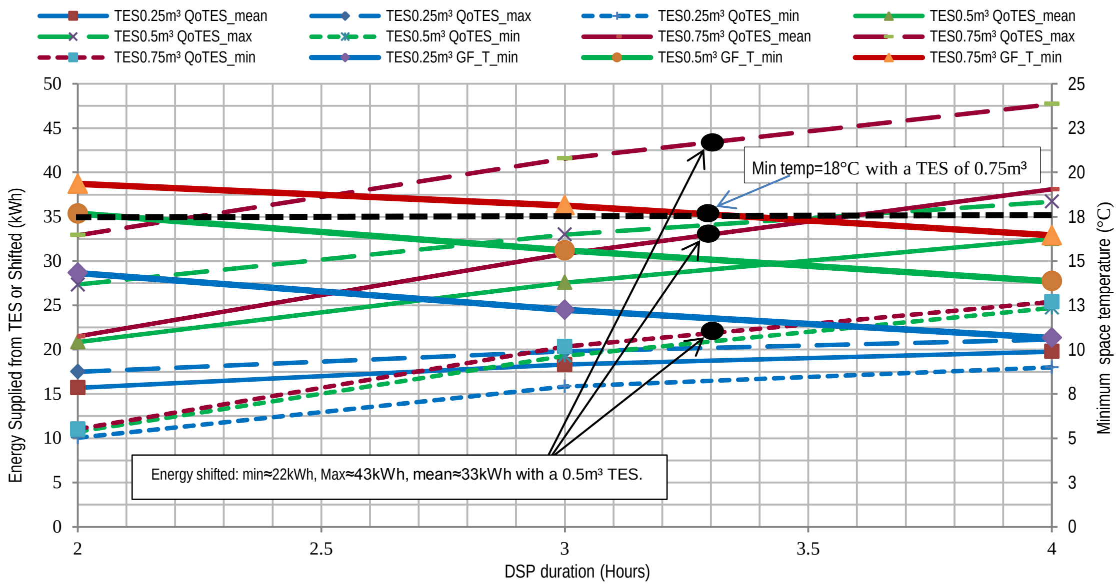
The data was used to generate the graphs in Figure 6-9(a, b, c, d, e) which illustrate the relationship between the 60 day mean, maximum and minimum heat output from the TES (or heat shifted) during 2, 3 and 4 hour DSPs (QoTES_mean_2hDS refers to the mean heat shifted during a 2 hour DSP) and the size of the TES. Only a water storage temperature of 95°C has been considered. The graphs also show how the minimum space temperature varies during the DSP with TES size. These graphs can be used to determine the TES size necessary to ensure a minimum space temperature during a particular DSP, and the range of heat energy values that are likely to be shifted per day. For example, as shown in Figure 6.9(a), a TES size of around 0.6m³ with a 95°C water temperature is required to achieve a 4 hour DSP in the Det90 building, where the minimum space temperature is maintained at or higher than 18°C thermal comfort threshold. It can be seen that with this DSP and TES setup, the minimum and maximum heat shifted will be around 17kWh, 27kWh and 35kWh respectively.

The maximum amount of heat which could be extracted from the TES tank and used for meeting the space heating and DHW service needs space was 47.7kWh (see Figure 6-9b) for Det150 and a 4 hour DSP. The least amount of heat that could be extracted and used was about 7.5kWh for Flat90 and a 2 hour DSP (see Figure 6-9e).

The graphs in Figure 6-10(a, b) show how the heat shifted varies with DSP duration for the different TES sizes and water storage temperature of 95°C, and the corresponding minimum space temperature during the DSP. The graphs in Figure 6-10(a, b) are for Det90 and Det150 dwellings, and the graphs relating to SDet90, MTer90 and Flat90 buildings are provided in Appendix D. For example, in the Det90 archetype a 0.5m³ TES with 95°C water temperature could shift heat demand by up to 3.3 hours with the minimum space temperature staying at about 18°C or higher. The corresponding amounts of heat shifted to off peak times could vary from a minimum of about 22.5kWh to a maximum of about 35kWh with a mean of about 29kWh. It can be seen that if the TES size is reduced to 0.25m³ then the worst case space temperature will reduce below 18°C for all DSP duration between 2 hours and 4 hours.



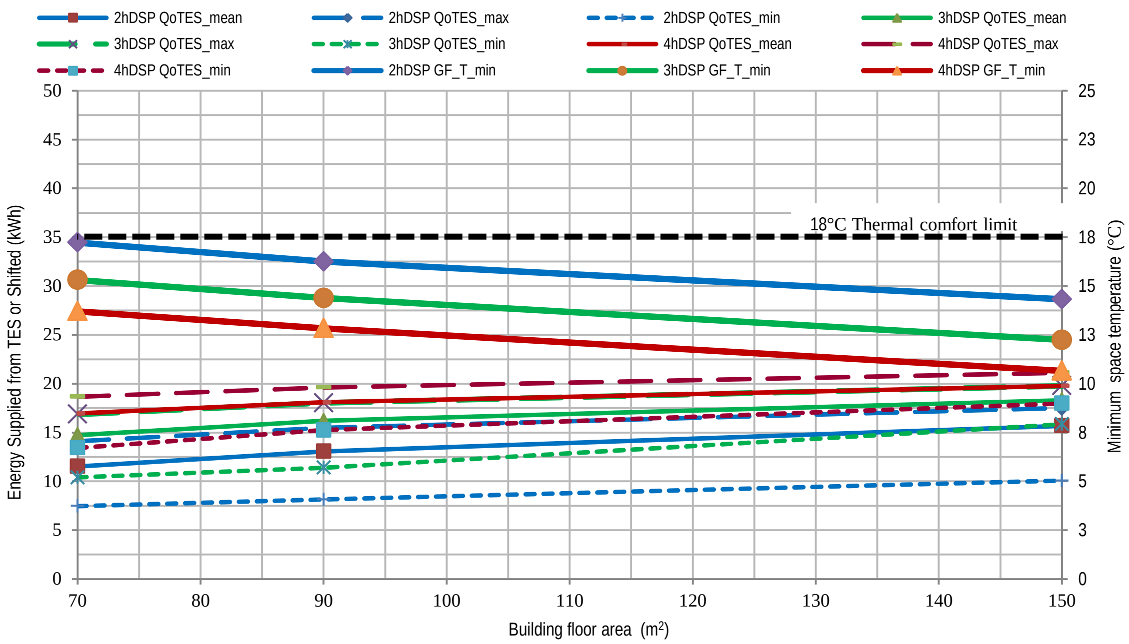
a) Det90



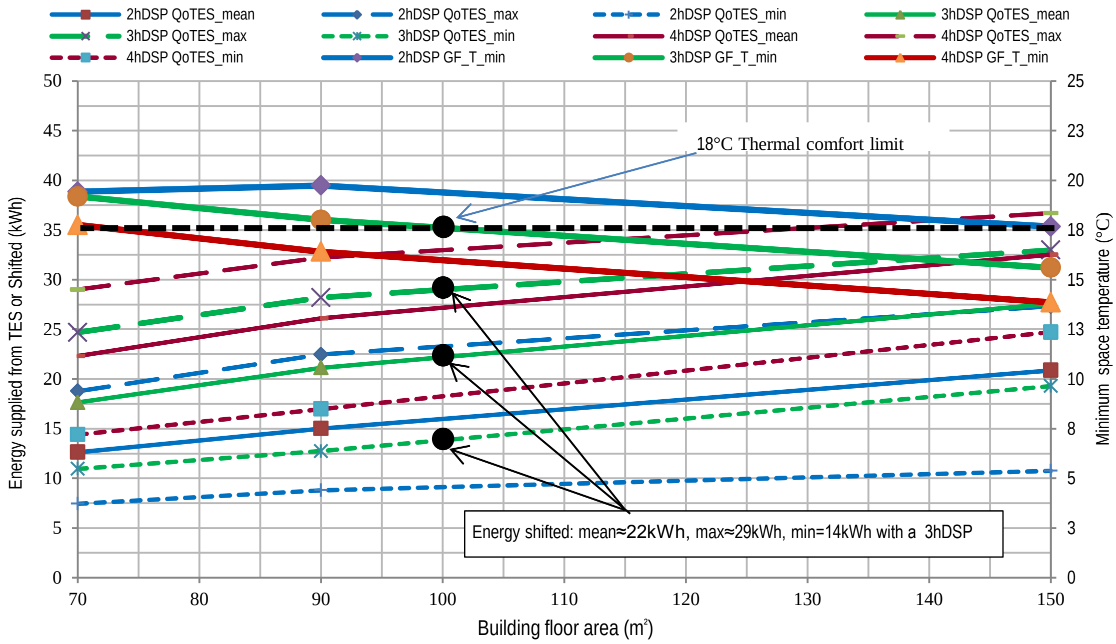
b) Det150

Figure 6-10(a, b). Maximum, mean and minimum energy shifted (QoTES_max, QoTES_mean, QoTES_min) and minimum space temperature (GF_T_min) by DSP duration, for 0.25m³, 0.50m³ and 0.75m³ and a water storage temperature of 95°C, and for: a) Det90, and Det150.

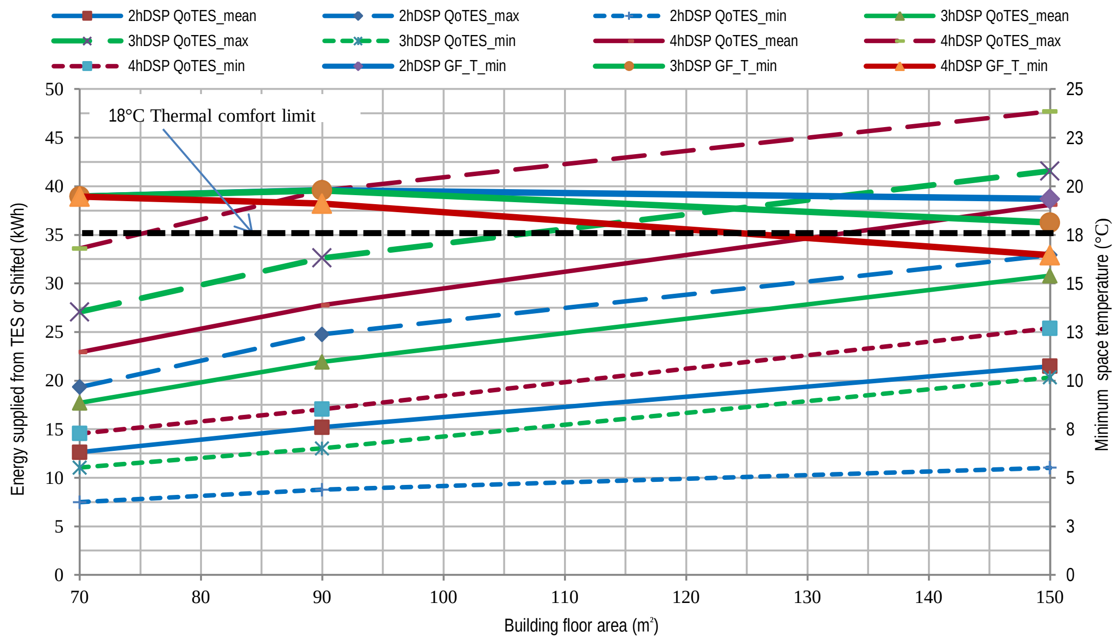
Establishing a link between the floor area and the heat shifted, for the different TES sizes and DSP durations, was considered to be potentially useful. The graphs in Figure 6-11(a, b & c) illustrates this link for detached dwellings of floor sizes from 70m² to 150m², and for TES sizes of 0.25m³, 0.5m³ and 0.75m³, each with a water storage temperature of 95°C. Only the detached built form, being the worst in terms of heat loss, has been considered in this analysis.



a) TES size 0.25m³



b) TES size 0.50m³



c) TES size 0.75m³

Figure 6-11(a, b, c). Maximum, mean and minimum energy shifted (QoTES_max, QoTES_mean, QoTES_min) and minimum space temperature (GF_T_min) by detached dwelling floor area for 2, 3 and 4 hour DSP and for: a) TES size 0.25m³, b) TES size 0.50m³ and c) TES size 0.75m³ each with a water storage temperature of 95°C.

These graphs could be used to determine the lowest space temperature likely in a detached dwelling of a certain size and DSP duration. For example, it can be seen in Figure 6-11(b) that a minimum space temperature greater than 18°C in a 3 hour DSP can be maintained with a 0.5m³ TES in detached dwellings (assuming 1990s building regulation level of thermal insulation) up to about 100m² floor area. For larger dwellings the space temperature would reduce below 18°C, and so they would require a larger TES or a reduced DSP to ensure that the temperature does not drop below the 18°C threshold.

The data presented in Table 6-1 and the graphs in Figure 6-9(a, b, c, d, e), Figure 6-10(a, b) and Figure 6-11(a, b & c) could be useful in developing TES systems for dwellings of different sizes, that take into account the DSP and the minimum space temperature requirement of the end users. They could also be used to develop TES systems to enable a certain amount of heat to be shifted given a dwelling size, a DSP requirement and a thermal comfort level acceptable to the occupiers.

The archetypes and TES options considered in these analyses resulted in 30 combination of building archetype, TES size and water temperature simulations to be performed as described earlier in Section 6.3, the data for which is presented in Table 6-1. The bar chart in Figure 6-12 has been created to identify the combinations that could provide a four hour heat demand shift, showing the corresponding minimum space temperature. The archetypes that need upgrading with larger TES to make them more suitable for a four hour heat demand shift can thus be identified. The bar chart illustrates the 60 day minimum space temperature, space heating only energy consumption and the amount of heat shifted, by a 4 hour heat demand shift in the 30 combinations. The combinations have been labelled 1 to 30, for example combination 1 (Flat90_TS0.25m3_WT75°C) refers to a simulation consisting of Flat90 archetype, TES tank size of 0.25m^3, water storage temperature of 75°C. The results are first arranged by the minimum space temperature during the DSP in an descending order left to right, followed by the mains supply energy consumption in an ascending order left to right, and then by the energy shifted in ascending order. The 60 day mean (of all 90m^2 archetypes and 150m^2 detached archetypes) mains supply energy consumption for the Base Case (See chapter 4, Section 4.4.1) and the TES Reference Case (See Chapter 5, Section 5.4.2) are illustrated. The minimum space temperature limit (18°C) for ensuring thermal comfort and TES Reference Case mean heat shifted to off peak times are also illustrated.

It can be seen in Figure 6-12 that a 4 hour heat demand shift could be achieved with the space temperature at 18°C or higher in combinations 1 to 8. Most of these include TES parameter values that provide higher thermal storage capacity, for example a larger size and higher water storage temperature. The amount of heat shifted by these combinations varies from 19.7kWh to 27.3kWh.

For combinations 9 to 30 the thermal comfort gradually reduces. The TES capacity options in these combinations include mostly 0.25m^3 TES tanks and 75°C water storage temperature, which provide lower TES capacity. This suggests that the building archetypes where the floor area is around 90m^2 or higher and a 4 hour DSP is required, a large TES tank sizes (greater than 0.25m^3) and high water temperatures has to be used in order to ensure that the space temperature does not degrade below 18℃.

An alternative to increasing the TES capacity to ensure thermal comfort is to reduce the duration of the DSP, so that the temperature drop does not continue for too long, and therefore stay above the thermal comfort limit. This is illustrated in Figure 6-13, which shows the space temperature, mains supply energy consumption and the heat shifted when a 2 hour heat demand shift is implemented. It can be seen that the space temperature in most of the 30 combinations (1 to 18) have remained at 18°C or above, indicating that a 2 hour heat demand shift is possible without degrading thermal comfort. The exceptions are combinations 19 to 30, which can be considered as the ones that require TES capacity or thermal insulation enhancing intervention in order to ensure that the space temperature does not degrade below the acceptable level. While reducing the DSP made it easier to ensure thermal comfort in more combinations, it also reduced the amount of heat shifted to off-peak times as shown.

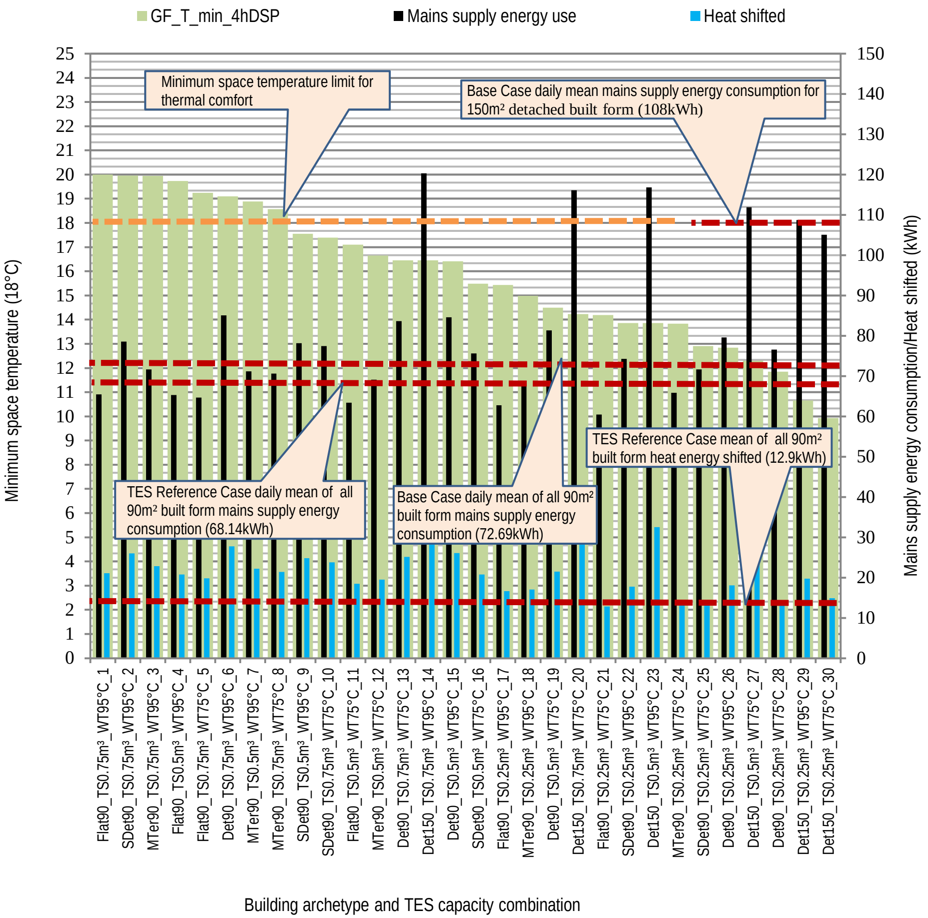


Figure 6-12. Minimum space temperature, overall heat energy consumption and energy shifted impacts in the four archetypes with varying TES capacity option combinations applied in simulating a 4 hour heat demand shift from 17:00 to 21:00, in descending space temperature order indicating the combination of archetype and TES capacity options best for maintaining indoor thermal comfort during the DSP.

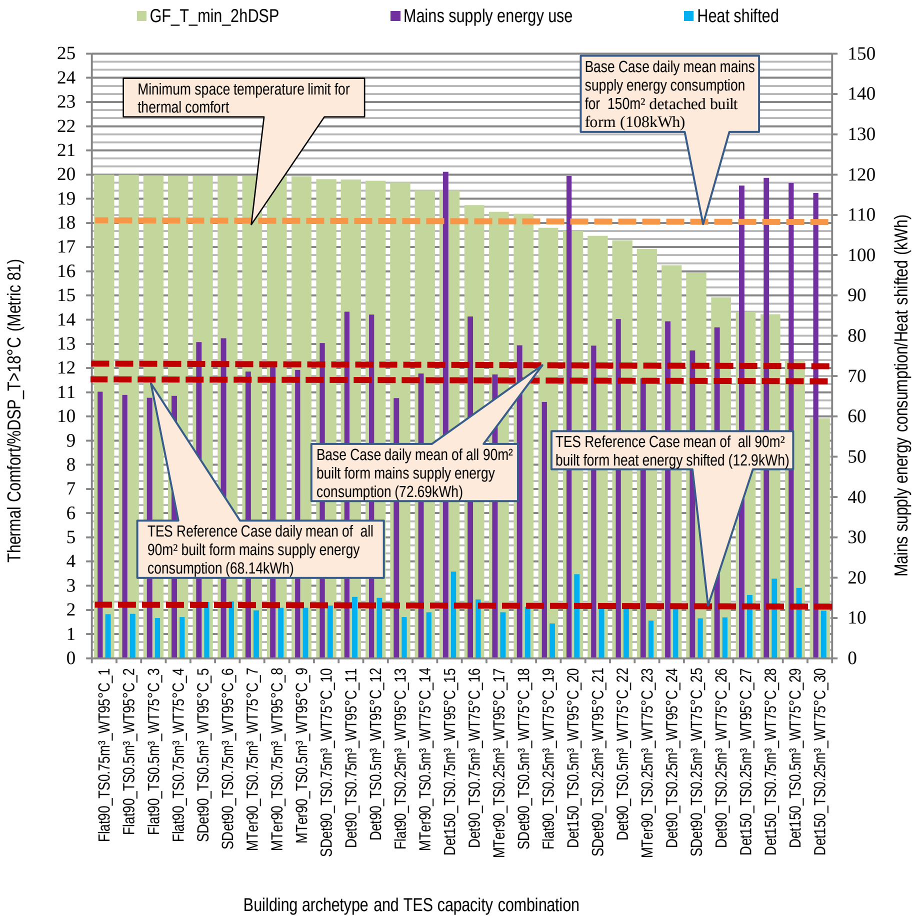


Figure 6-13. Minimum space temperature, overall heat energy consumption and energy shifted impacts in the four archetypes with varying TES capacity option combinations applied in simulating a 2 hour heat demand shift from 17:00 to 19:00, in descending space temperature order indicating the combination of archetype and TES capacity option best for maintaining indoor thermal comfort during the DSP.

Note: x-axis labels are made up of building archetype ID, TES tank size and water storage temperature option (e.g. Det90= Detached building with a 90m^2 floor size, TS0.75m^3=Tank Size of 0.75m^3 and WT95°C =Water storage Temperature of 95°C.

6.4 Impact of thermal insulation, thermostat setting, location, heating duration and occupancy variation

Overview

This section presents the predictions of the impact on temperature, power and energy consumption of five of the main building performance influencing parameter values (thermal insulation level, location, heating duration, thermostat set point and number of occupiers) when changed from the TES Reference Case values. Four building archetype models were used consisting of the four built forms each **with a UK housing stock mean floor area of 90m^2**. The thermal storage capacity used was as per the TES Reference Case comprising of tank size of 0.25m^3 and hot water storage temperature of 75℃. The DSP period considered is 4 hours from 17:00 to 21:00, this having the worst impact on the occupied space temperature as discussed in the previous sections. The results are compared with those obtained for the same building archetypes with the TES Reference Case parameter settings as described in Section 5.4.

6.4.1 Space temperature

The graphs in Figure 6-14 to Figure 6-15 show the mean ground floor occupied space thermal profile predictions for DET90 averaged over the 60 day simulation period, each corresponding to one of the five variables changed. These figures illustrate how the daily temperature profile varied as the respective parameter value changed in comparison with that of the TES Reference case.

As previously discussed in Chapter 4, thermal insulation of the building has a direct impact on the indoor space temperature and therefore thermal comfort. Therefore, thermal insulation enhancement is a solution for countering the thermal comfort impact of heat demand shifting using TES. The effect of enhanced thermal insulation level on the daily space temperature profile is shown by the graphs in Figure 6-14. The graphs show the 60 day mean daily room temperature profiles for thermal insulation levels corresponding to the recommendations of 1980s, 1990s, 2002s and 2010s building regulations, for the Det90 building. It can be seen that an insulation level corresponding to the 2010s level provides a comparatively higher space temperature during the unheated hours as well as the DSP. The temperature during the DSP remains above 18°C thermal comfort level. This indicates that a 4 hour HDS is achievable, whilst still maintaining thermal comfort, in a Det90 building with a TES Reference Case scale of thermal storage intervention, provided that the insulation level is updated to the 2010s' recommended level. As the insulation level is lowered, the minimum temperature during the DSP drops below 18°C, and reaches a value of around 14.5°C for the 1980s recommended level.

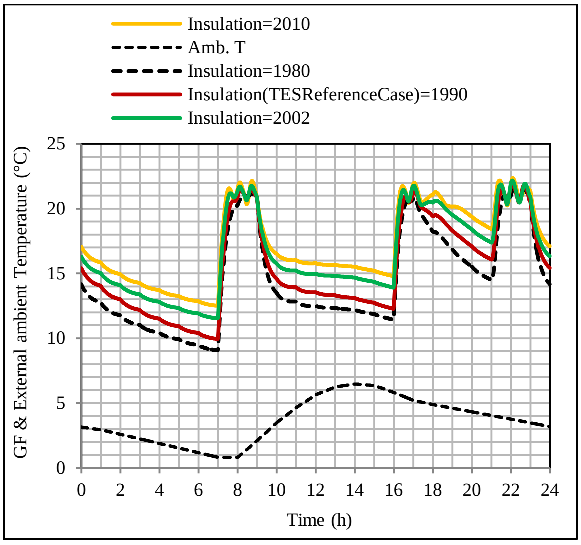


Figure 6-14. <u>Thermal Insulation Impact</u>: Effect of thermal insulation level on the indoor thermal condition for the Det90 archetype averaged over the 60 day simulation period.

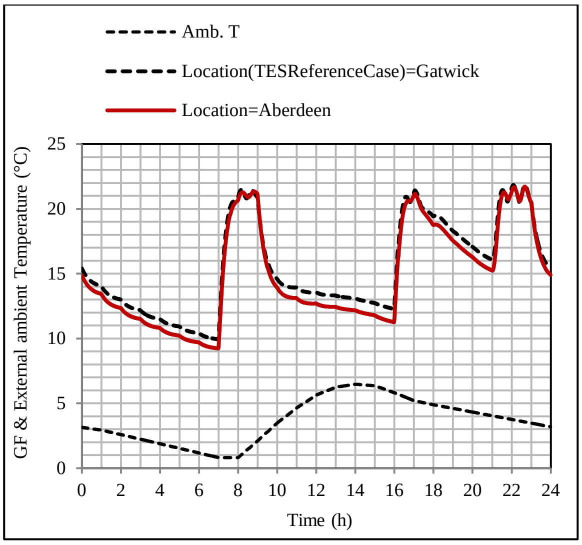


Figure 6-15. <u>Location Impact:</u> Effect of location on the indoor thermal condition for the Det90 archetype in comparison with the TES Reference Case, averaged over 60 day simulation period.

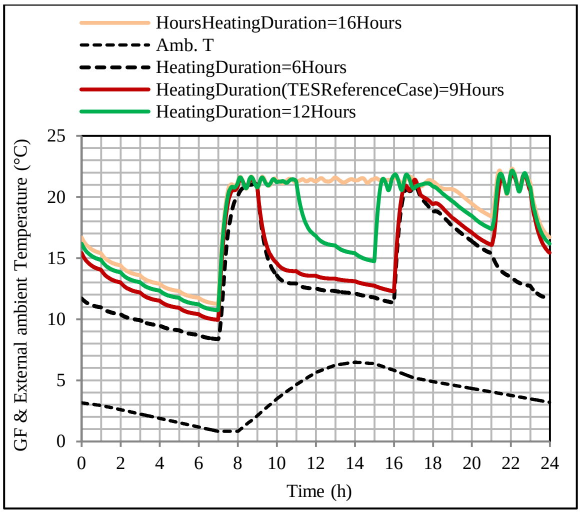


Figure 6-16. <u>Heating Duration Impact:</u> Effect of heating duration on the indoor thermal condition for the Det90 archetype in comparison with the TES Reference Case, averaged over 60 day simulation period.

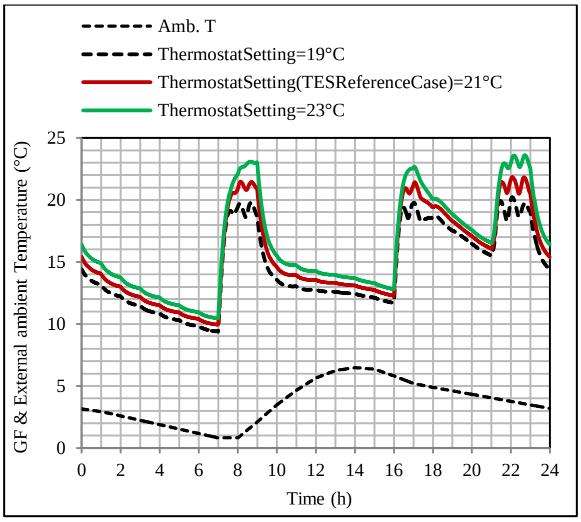


Figure 6-17. <u>Thermostat Setting Impact</u>: Effects of thermostat set point on the indoor space temperature for the Det90 archetype in comparison with the TES Reference Case, averaged over 60 day simulation period.

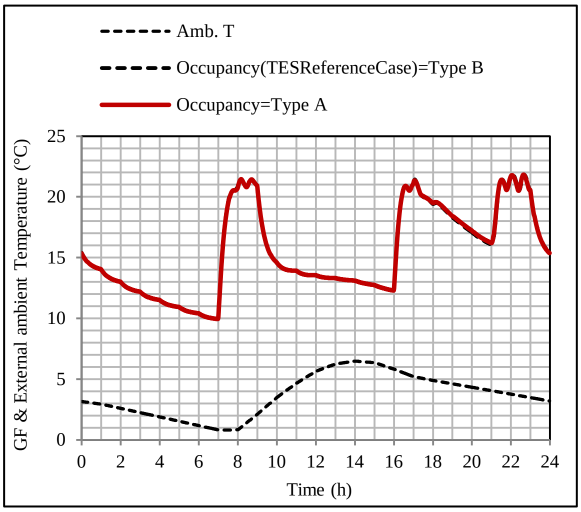


Figure 6-18. Occupancy Impact: Effect of occupancy on the indoor thermal condition for the Det90 archetype in comparison with the TES Reference Case averaged over 60 day simulation period.

Figure 6-15 shows how the space temperature profile changes with location. The difference in minimum temperature reached during the DSP is about 1℃ which is relatively small. However, thermal comfort level (Metric 8) during the DSP degrades from 54% to 41% indicating that buildings located in the north of the UK will require larger TES capacity to achieve the same level of heat demand shift as similar dwellings in the south as discussed later in this section.

Figure 6-16 shows how the temperature profile changes with the heating duration. As expected, shorter heating durations result in the largest temperature drop both in the unoccupied and the occupied DSP periods, for reasons as discussed previously in section 4.4.2. Heating duration of 16 hours can be seen to provide a 4 HDS without degrading the space temperature below the thermal comfort level of 18°C.

It can be argued that heating the buildings to a higher temperature prior to the DSP could ensure a more acceptable temperature during the DSP. This is explored by simulating the buildings with two thermostat set points (19°C and 23°C) in addition to the 21°C Base Case setting. Figure 6-17 shows how the daily space temperature profile changed. Higher thermostat setting results in a marginally higher unheated period temperatures and vice-versa. As can be seen, this affected the heat demand shifting ability, where the lowest room temperature and therefore the thermal comfort, remained more favourable for a thermostat setting of 23°C in comparison with a 19°C thermostat set point.

Figure 6-18 shows the average daily indoor space temperature profile and how it changes with the household size. It can be seen that the profiles virtually overlap each other both during the unheated periods and the DSP. This means number of occupier change considered here has negligible impact on thermal comfort.

The space temperature during the DSP period and how it is affected by changes in these five parameters is important. It could enable appropriate interventions to be applied to dwellings so that the negative effects of HDS are minimised. A better understanding of the thermal comfort impact during the DSP can be gained by examining the room temperatures reached during all of the 60 winter days considered in this research. This is done by determining the frequency distribution curves with 1°C class intervals, and using the minutely recorded DSP period temperature data for the five parameters, as shown in Figure 6-19 to Figure 6-23 for the Det90 sample building archetype. The temperature limit (18°C) for ensuring thermal comfort is shown in each of the frequency distribution graphs. The distributions have been plotted for a 2 hour and a 4 hour DSP, to show the effect of changing DSP duration.

As discussed earlier, thermal insulation can reduce the effectiveness of the TES in heat demand shifting. This is illustrated in Figure 6-19 which show the space temperature frequency distribution for the Det90 building archetype with thermal insulation according to the 1980s, 1990a, 2002 and 2010s recommended levels. It can be seen that for the 1980s insulation, a large proportion of the temperatures predicted are lower than 18°C for both 2 hour and 4 hour DSPs. The minimum temperature over the 60 days for a 4 hour DSP was in the 10°C to 11°C class interval for the 1980s insulation, and it moved to the 12°C to 13°C class interval for the 2010s insulation. But, for a 2 hour DSP, the minimum temperature rises above 13°C. With 2010s insulation level, the temperature remains above the 18°C thermal comfort limit for the entire 2 hour DSP. It gradually shifts downwards for the 2002s and 1990s insulation.

The effect of location on the room temperature over the 60 days is shown in Figure 6-20. A large proportion of the frequency distribution for both Gatwick and Aberdeen locations remains below 18°C, and is marginally worse for Aberdeen. The minimum temperature for a 4 hour DSP was between 10°C to 11°C for the location of Aberdeen and between 11°C to 12°C for Gatwick. But, for a 2 hour DSP these improve significantly, above 13°C and 15°C for Aberdeen and Gatwick respectively.

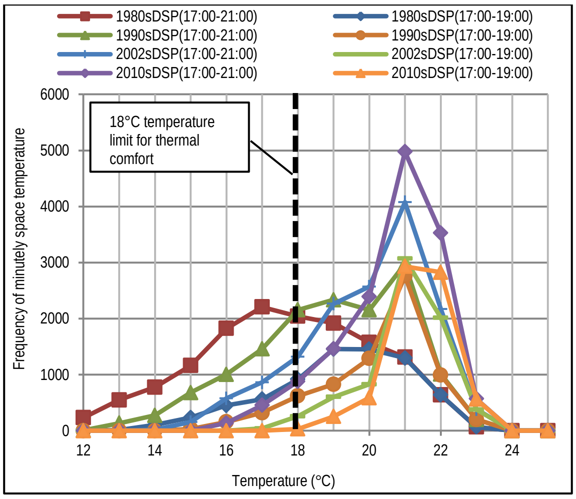


Figure 6-19. Frequency distribution of space temperature over a 2 hour and a 4 hour DSP for 60 days, for the Det90 archetype with thermal insulation of 1980s, 1990s, 2002s and 2010s recommended levels.

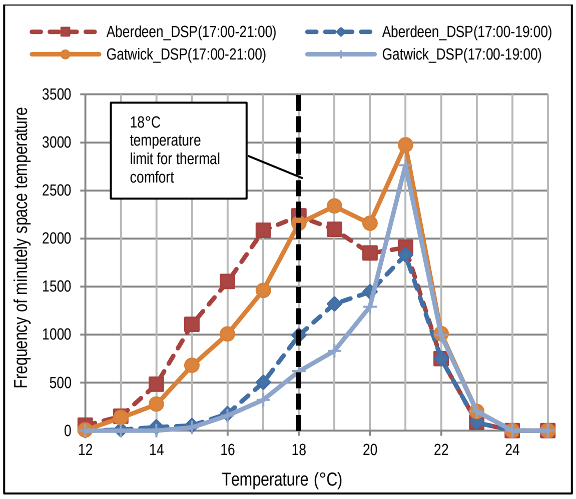


Figure 6-20. Frequency distribution of space temperature over a 2 hour and a 4 hour DSP for 60 days, for the Det90 archetype and locations of Gatwick and Aberdeen.

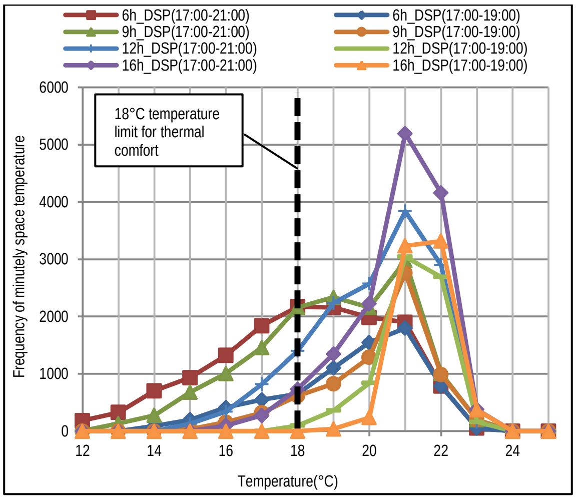


Figure 6-21. Frequency distribution of space temperature over a 2 hour and a 4 hour DSP, for the Det90 archetype and heating durations of 6, 9, 12 and 16 hours.

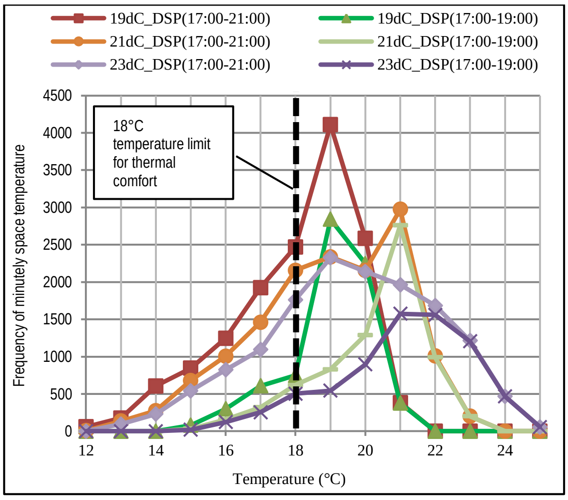


Figure 6-22. Frequency distribution of space temperature over a 2 hour and a 4 hour DSP for 60 days, for the Det90 archetype, and for thermostat set point of 19°C, 21°C and 23°C.

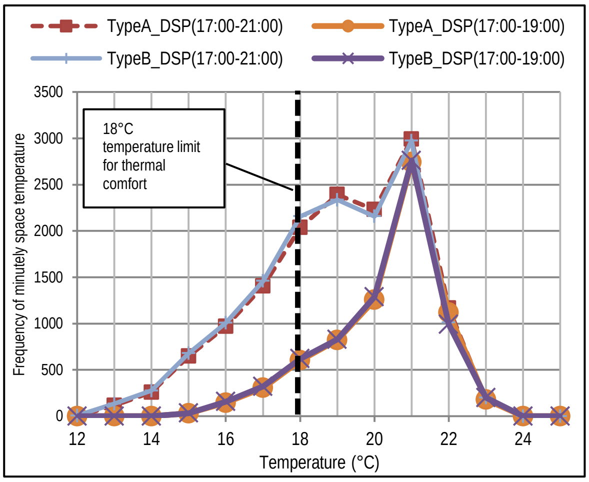


Figure 6-23. Frequency distribution of space temperature over a 2 hour and a 4 hour DSP for 60 days, for the Det90 archetype, and for occupancy type A and Type B.

Figure 6-21 shows the frequency distribution for heating durations of 6 hours, 9 hours, 12 hours and 16 hours. As the duration increases, the frequency of the temperature remaining above 18°C increases. The minimum temperature for a 6 hour heating duration and a 4 hour DSP was in 10°C to 11°C class interval. It increased to between 14°C to 15°C class interval for 2 hour DSP duration. Increasing the heating duration to 16 hours, results in space temperatures greater than 18°C for the entire 2 hour DSP.

The frequency distribution for the thermostat set points of 19°C, 21°C and 23°C is shown in Figure 6-22. As the thermostat set point increases, the frequency of the temperature remaining above 18°C also increases. The minimum temperature for a 19°C thermostat setting and a 4 hour DSP was between 12°C to 13°C class interval. It increased to 15°C to 16°C for the 2 hour DSP duration. Thermostat setting of 23°C results in the space temperature remaining above 18°C for the entire 2 hour DSP.

Changing the number of occupiers from 3 (Type B) to a single occupier (Type A) has a negligible effect on the space temperature as shown in Figure 6-23, for the reasons as previously discussed.

The space temperature predictions during the 4 hour DSP (17:00 to 21:00) for all four of the archetypes considered in this exercise are summarised in Table 6-4. The table shows the 60 day mean space temperature (Metric 2), 60 day average of the daily minimum temperature value and the 60 day mean thermal comfort (Metric 8) for all the different parameter changes considered. The table also shows the changes in the values from the TES Reference Case as discussed previously in Chapter 5 and also displayed in the highlighted columns. The overall average values for all four archetypes are also presented in Table 6-4 which provide a more general indication of the impacts of the five variables with respect to the TES Reference Case conditions.

As before, the detached dwelling had a marginally inferior space temperature during the DSP compared to the other built forms. For example, with a 1980s thermal insulation level, the minimum and the average temperatures were 17.04℃ and 14.49℃, and 19.31℃ and 16.85℃ for the detached and the flat dwellings respectively.

Table 6-4. Summary of the 60 day mean space temperature impacts compared to that of the TES Reference Case, due to changes in thermal insulation, location, heating duration, thermostat set point and occupancy type, for the four archetypes considered, and an average of the four archetypes.

			Thermal Insulation				Location		Heating Duration				Thermostat Setting			Occupancy	
			1980 (°C)	1990 (°C)	2002 (°C)	2010 (°C)	Gatwick (°C)	Aberdeen (%)	6 hours (°C)	9 hours (°C)	12 hours (%)	16 hours (°C)	19°C (°C)	21°C (%)	23°C (°C)	Type A (°C)	Type B (°C)
Room temperature with varying energy consumption influencing factors Heated hours 17:00-21:00	Mean (Metric 2)	Det90	17.04	18.36	19.42	20.10	18.36	17.69	17.75	18.36	19.53	20.23	17.47	18.36	19.02	18.46	18.36
		SDet90	17.75	18.90	20.03	20.41	18.90	18.26	18.32	18.90	20.35	21.18	17.87	18.90	19.68	19.01	18.90
		MTer90	18.63	19.58	20.29	20.73	19.58	18.99	19.11	19.58	20.35	21.22	18.36	19.58	20.52	19.68	19.58
		Flat90	19.31	19.86	20.31	20.50	19.86	19.44	19.23	19.86	20.50	21.27	18.59	19.86	20.95	20.06	19.86
	Minimum	Det90	14.49	16.07	17.38	18.39	16.07	15.24	15.36	16.07	17.38	18.39	15.50	16.07	16.54	16.19	16.07
		SDet90	15.16	16.68	18.23	18.82	16.68	15.87	15.93	16.68	18.74	19.91	16.01	16.68	17.22	16.82	16.68
		MTer90	16.26	17.59	18.68	19.32	17.59	16.82	16.95	17.59	18.74	19.99	16.79	17.59	18.21	17.74	17.59
		Flat90	16.85	17.63	18.41	18.75	17.63	16.96	16.64	17.63	18.77	20.00	16.88	17.63	18.31	17.97	17.63
	%DSP_T>18°C (Metric 8)	Det90	31%	54%	81%	100%	54%	41%	36%	54%	81%	100%	38%	54%	63%	56%	54%
		SDet90	42%	66%	100%	100%	66%	51%	44%	66%	100%	100%	48%	66%	77%	69%	66%
		MTer90	58%	87%	100%	100%	87%	69%	60%	87%	100%	100%	70%	87%	100%	92%	87%
		Flat90	73%	90%	100%	100%	90%	76%	58%	90%	100%	100%	73%	90%	100%	99%	90%
	Average of all four archetypes	Mean	18.18	19.17	20.01	20.43	19.17	18.60	18.60	19.17	20.18	20.97	18.07	19.17	20.04	19.30	19.17
		Minimum	15.69	16.99	18.18	18.82	16.99	16.22	16.22	16.99	18.41	19.57	16.29	16.99	17.57	17.18	16.99
		%DSP_T>18°C	51%	74%	95%	100%	74%	59%	49%	74%	95%	100%	57%	74%	85%	79%	74%
Change from TES Reference Case (17:00-21:00)	Mean	Det90	-1.32	0.00	1.05	1.74	0.00	-0.67	-0.61	0.00	1.17	1.86	-0.90	0.00	0.65	0.10	0.00
		SDet90	-1.15	0.00	1.13	1.51	0.00	-0.64	-0.58	0.00	1.45	2.28	-1.03	0.00	0.78	0.12	0.00
		MTer90	-0.95	0.00	0.71	1.15	0.00	-0.59	-0.47	0.00	0.77	1.64	-1.22	0.00	0.94	0.11	0.00
		Flat90	-0.55	0.00	0.45	0.64	0.00	-0.42	-0.63	0.00	0.64	1.41	-1.27	0.00	1.10	0.20	0.00
	Minimum	Det90	-1.58	0.00	1.31	2.32	0.00	-0.83	-0.71	0.00	1.31	2.32	-0.57	0.00	0.47	0.12	0.00
		SDet90	-1.52	0.00	1.55	2.14	0.00	-0.81	-0.75	0.00	2.07	3.23	-0.67	0.00	0.54	0.14	0.00
		MTer90	-1.33	0.00	1.09	1.73	0.00	-0.77	-0.64	0.00	1.15	2.40	-0.80	0.00	0.62	0.15	0.00
		Flat90	-0.79	0.00	0.78	1.11	0.00	-0.67	-1.00	0.00	1.13	2.37	-0.75	0.00	0.68	0.33	0.00
	%DSP_T>18°C	Det90	-23%	0.00	27%	46%	0.00	-13%	-18%	0%	27%	46%	-15%	0%	10%	3%	0%
		SDet90	-24%	0.00	34%	34%	0.00	-15%	-22%	0%	34%	34%	-18%	0%	11%	3%	0%
		MTer90	-29%	0.00	13%	13%	0.00	-17%	-27%	0%	13%	13%	-17%	0%	13%	5%	0%
		Flat90	-17%	0.00	10%	10%	0.00	-14%	-31%	0%	10%	10%	-16%	0%	10%	9%	0%
	Average of all four archetypes	Mean	-0.99	0.00	0.84	1.26	0.00	-0.58	-0.57	0.00	1.01	1.80	-1.10	0.00	0.87	0.13	0.00
		Minimum	-1.30	0.00	1.18	1.83	0.00	-0.77	-0.77	0.00	1.42	2.58	-0.70	0.00	0.58	0.19	0.00
		%DSP_T>18°C	-23%	0%	21%	26%	0%	-15%	-25%	0%	21%	26%	-17%	0%	11%	5%	0%

Note

Metric 2: DSP_hours_mean_GF_T (DSP mean temperature averaged over 60 days)

Metric 8: %DSP_T>18°C (% DSP temperature above thermal comfort level of 18°C averaged over 60 days)

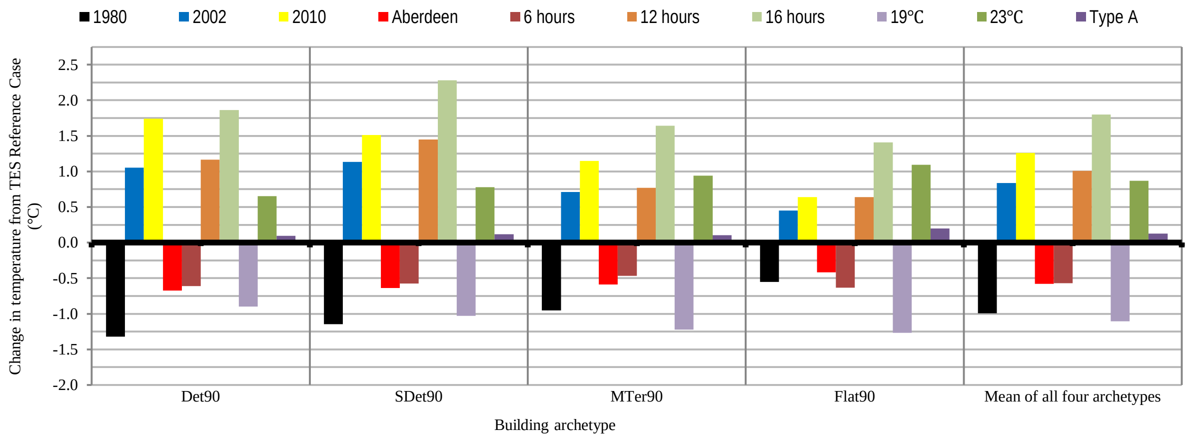


Figure 6-24. Illustration of the 60 day average DSP mean space temperature change from the TES Reference Case level, due changes in thermal insulation, location, heating duration, thermostat set point and occupancy type, for the four archetypes considered, and an average of the four archetypes.

The effects of the five parameter changes are highlighted by the bar chart in Figure 6-24. It shows the amount by which the 60 day mean room temperature rises or falls from the TES Reference Case levels, represented by the zero line or the X-axis, as the five parameter values vary. It can be seen that lower thermal insulation, lower thermostat setting, poorer weather condition (of Aberdeen) and shorter heating duration all have space temperature reducing impact, and in the same respective order. These parameters, therefore, can negatively affect the heat demand shifting ability in buildings, allowing smaller shift periods for a given TES capacity. Conversely, longer heating duration, better thermal insulation and higher thermostat setting have a greater impact in keeping the room temperature higher and in the same respective order, thus enabling heat demand shifting for longer durations with minimal thermal comfort degradation. As discussed before, the number of occupiers has a negligible effect regardless of the dwelling built form, as it is not related to the thermostat set point, heating duration or the heat loss in the dwellings.

Location can be seen to reduce the mean room temperature in the dwelling by around 0.5℃, and this leads to a less effective heat demand shifting ability in the sense that only smaller DSPs are possible without degrading thermal comfort. The shorter heating duration of 6 hours also had a space temperature reducing impact by around 0.5°C.

The physical and operational parameters in buildings which can alter and improve thermal comfort to counter the undesirable impacts of heat demand shifting are likely to be of interest to both the households and the supply side. Figure 6-25 shows the

60 day mean thermal comfort (Metric 8) during the 4 hour DSP (17:00 to 21:00) for the four building archetypes, and for the five parameters changed. It can be seen that the thermal comfort for the Flat90 and MTer90 built forms are relatively close to the target thermal comfort of 100% with the TES Reference Case level of thermal insulation, heating duration and thermostat set point. Further improving the insulation to the 2002 and 2010 level, prolonging the heating duration to 12 and 16 hours and raising the thermostat set point to 23°C increases the thermal comfort to 100%. These suggest that the Flat and Mid terrace built forms are more effective in terms of providing heat demand shifting with minimal thermal comfort impacts. Also, it could be concluded that the parameters of thermal insulation, heating duration and thermostat set points affect building thermal performance more. These parameters should be targeted first during efforts to improve building performance to make heat demand shifting more effective through, for example, retrofits. However, it must be noted that these parameters may not always be the best option in terms of energy consumption. For example, increasing heating duration may also increase the energy consumption and therefore heating bill, and make it less attractive to the households.

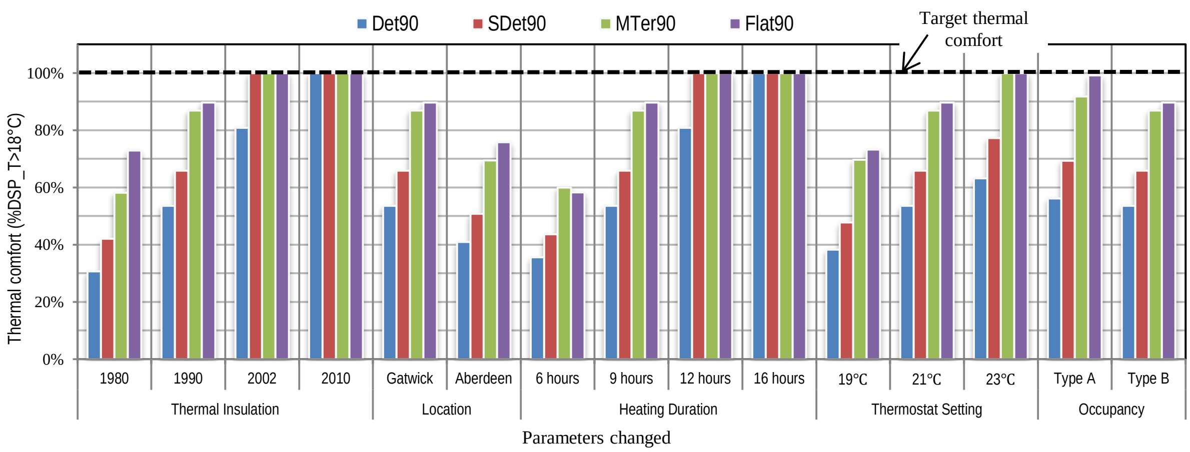


Figure 6-25. Illustration of the mean of 60 day mean thermal comfort (Metric 8) during the 4 hour DSP for all four building archetypes, and for the different thermal insulation, location, heating duration, thermostat set point and occupancy options.

6.4.2 Power demand

The graphs in Figure 5-12 illustrate the impact of varying the thermal insulation for the sample archetype of Det90. It shows the daily mean mains power demand profile averaged over the 60 days. As can be seen, no loading occurs from 17:00 to 21:00. There is a power demand from 00:00 to about 01:00 when the TES tank is charged up. The peak instantaneous power demand is 25kW as per the power rating of the water heater for the 90m^2 dwelling, and occurs during the TES charging and at the beginning of the heating periods when the demand for heat is at its maximum. The instantaneous power demand as water is re-heated during occupied hours varies in accordance with the heat needed to raise it to the required temperature, and is lowest for the building with the highest thermal insulation level of 2010. Similar power demand profiles were observed for the other three building archetypes considered during this exercise although the varying water re-heating power demand were lower in comparison.

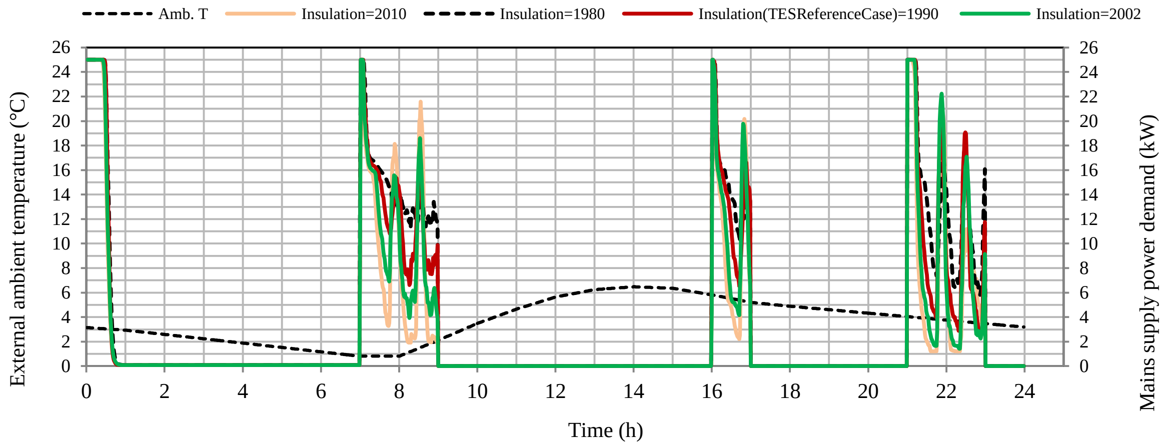


Figure 6-26. Illustration of the 60 day average mains supply power demand response for 4 hour DSP, and the Base case response, for the Det90 dwelling with a 0.25m^3 TES tank with 75°C water storage temperature.

Table 6-5 provides a summary of the 60 day average power demand for the four building archetypes considered. The table shows the mains supply daily (00:00 to 24:00) mean power demand, and the space heating only 4 hour DSP (17:00 to 21:00) mean and the maximum power demands. The daily mean mains supply power includes the power used during the occupied heated hours and also the power used during the TES charging period. The table also shows the changes in the power demands with respect to the corresponding TES Reference Case results (shown in the highlighted columns), caused by the changes in the five parameter values.

It should be noted that the power demand for space heating during the DSP is the power provided by the TES tank to the radiators, and is independent of the mains supply. As before, the mean power demand values in the table are averages of the relevant time periods and are not the instantaneous power demand.

It can be seen in Figure 4-27 that low thermal insulation, long heating duration and high thermostat setting are the mains parameters that increase the average power demands. Conversely, improved thermal insulation, shorter heating duration, and lower thermostat setting reduce the average power demand. It should be noted that the parameter changes that result in an increased power demand, for example high thermostat setting and long heating duration, may not necessarily be undesirable as they can improve the thermal comfort during the DSP. Some households that take up heat demand shifting may accept increased energy consumption in order to ensure better thermal comfort during the DSP. From the supply side point of view, it may be more useful to shift demand from the peak time to the off-peak time than to reduce energy consumption, for example to allow grid balancing.

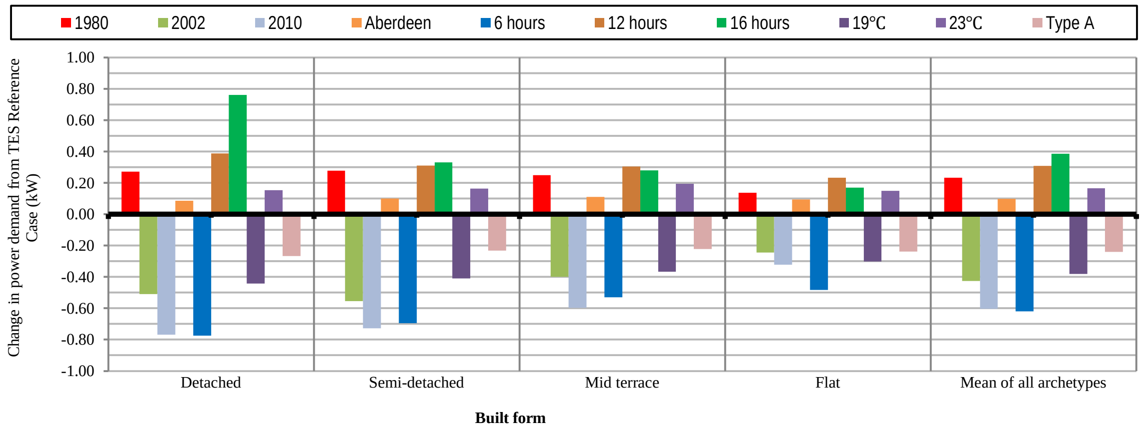


Figure 6-27. Illustration of the 60 day mean daily mains supply power demand change from the TES Reference Case, due to changes in thermal insulation(1980, 1990, 2002 & 2010), location, heating duration, thermostat set point and occupancy (Type A) type, by built form and average of all built forms.

Table 6-5. Summary of the 60 day mean daily mains supply and space heating power demand impacts compared to that of the TES Reference Case due to changes in thermal insulation, location, heating duration, thermostat set point and occupancy type, for the four archetypes considered.

		Building archetype ID	Thermal Insulation				Location		Heating Duration				Thermostat Setting			Occupancy	
			1980 (kW)	1990 (kW)	2002 (kW)	2010 (kW)	Gatwick (kW)	Aberdeen (kW)	6 hours (kW)	9 hours (kW)	12 hours (kW)	16 hours (kW)	19℃ (kW)	21℃ (kW)	23℃ (kW)	Type A (kW)	Type B (kW)
Power demand with varying energy consumption influencing factors	Mains Supply 00:00 - 24:00 (Metric 3)	Det90	3.55	3.28	2.77	2.51	3.28	3.36	2.50	3.28	3.67	4.04	2.84	3.28	3.43	3.01	3.28
		SDet90	3.33	3.05	2.50	2.33	3.05	3.15	2.36	3.05	3.37	3.39	2.65	3.05	3.22	2.82	3.05
		MTer90	3.05	2.80	2.40	2.20	2.80	2.91	2.27	2.80	3.10	3.08	2.43	2.80	2.99	2.57	2.80
		Flat90	2.70	2.56	2.32	2.24	2.56	2.65	2.08	2.56	2.79	2.73	2.26	2.56	2.71	2.32	2.56
	Mean Space heating only Heated hours 17:00-21:00 (Metric 4)	Det90	3.68	3.53	3.34	3.18	3.53	3.59	3.60	3.53	3.19	2.96	3.46	3.53	3.50	3.83	3.53
		SDet90	3.60	3.42	3.17	3.02	3.42	3.49	3.54	3.42	3.12	3.65	3.33	3.42	3.42	3.72	3.42
		MTer90	3.52	3.31	3.09	2.91	3.31	3.39	3.43	3.31	2.88	3.18	3.18	3.31	3.36	3.62	3.31
		Flat90	3.34	3.21	3.08	3.00	3.21	3.32	3.36	3.21	2.85	3.11	3.09	3.21	3.26	3.51	3.21
	Maximum Space heating only Heated hours 17:00-21:00	Det90	10.89	10.56	7.71	7.58	10.56	10.62	10.43	10.56	6.40	5.39	7.87	10.56	10.22	10.46	10.56
		SDet90	10.14	8.18	7.94	6.61	8.18	9.07	9.72	8.18	6.69	5.06	6.62	8.18	9.74	8.35	8.18
		MTer90	9.92	8.19	7.83	7.73	8.19	8.93	9.80	8.19	5.64	4.36	7.50	8.19	10.28	8.17	8.19
		Flat90	8.10	7.78	7.51	7.35	7.78	9.31	8.12	7.78	4.65	4.17	7.50	7.78	8.94	7.75	7.78
Change from TES Reference Case	Mains Supply 00:00 - 24:00	Det90	0.27	0.00	-0.51	-0.77	0.00	0.09	-0.77	0.00	0.39	0.76	-0.44	0.00	0.15	-0.27	0.00
		SDet90	0.28	0.00	-0.55	-0.73	0.00	0.10	-0.69	0.00	0.31	0.33	-0.41	0.00	0.16	-0.23	0.00
		MTer90	0.25	0.00	-0.40	-0.60	0.00	0.11	-0.53	0.00	0.30	0.28	-0.37	0.00	0.19	-0.22	0.00
		Flat90	0.14	0.00	-0.25	-0.32	0.00	0.09	-0.48	0.00	0.23	0.17	-0.30	0.00	0.15	-0.24	0.00
	Mean Space heating only Heated hours 17:00-21:00	Det90	0.15	0.00	-0.20	-0.35	0.00	0.06	0.07	0.00	-0.34	-0.57	-0.07	0.00	-0.03	0.30	0.00
		SDet90	0.18	0.00	-0.25	-0.40	0.00	0.07	0.12	0.00	-0.30	0.23	-0.09	0.00	0.01	0.31	0.00
		MTer90	0.20	0.00	-0.23	-0.40	0.00	0.07	0.11	0.00	-0.43	-0.13	-0.13	0.00	0.04	0.30	0.00
		Flat90	0.13	0.00	-0.13	-0.21	0.00	0.11	0.15	0.00	-0.36	-0.10	-0.12	0.00	0.05	0.30	0.00
	Maximum Space heating only Heated hours 17:00-21:00	Det90	0.33	0.00	-2.84	-2.97	0.00	0.06	-0.13	0.00	-4.15	-5.17	-2.69	0.00	-0.34	-0.10	0.00
		SDet90	1.95	0.00	-0.24	-1.58	0.00	0.89	1.54	0.00	-1.49	-3.12	-1.57	0.00	1.56	0.17	0.00
		MTer90	1.74	0.00	-0.36	-0.46	0.00	0.75	1.62	0.00	-2.55	-3.82	-0.69	0.00	2.10	-0.02	0.00
		Flat90	0.32	0.00	-0.27	-0.43	0.00	1.53	0.34	0.00	-3.13	-3.61	-0.28	0.00	1.17	-0.03	0.00

Note

Metric 3: Whole building daily mean mains supply power demand (Daily_mean_MS_power_kW)

Metric 4: Space heating only mean power demand during the occupied hours from 17:00 and 21:00.

6.4.3 Energy consumption

The graphs in Figure 6-28 to Figure 6-32 show the mean space heating only energy draw profile predictions from the mains supply, averaged over the 60 day simulation period, each corresponding to one of the five variables considered. These graphs illustrate how the daily temperature profile varies as the respective parameter value changes in comparison with that of the Det90 TES Reference Case scenario (see Table 3.14). As discussed previously, a flat response during the DSP (17:00 to 21:00) indicates that no loading of the mains supply occurs in this period, and instead energy is drawn during the off-peak period from 00:00 to around 01:00. A thermal insulation of 1980s level increases the overall energy consumption from the TES Reference Case value of about 76kWh to about 85kWh. Energy consumption impact of occupant number and location change considered is relatively small as can be seen in Figure 6-29 and Figure 6-32. The dominant parameters that impact energy consumption are thermal insulation, heating duration and thermostat set point as can be seen in Figure 6-28, Figure 6-30 and Figure 6-31. These can be adjusted through for example building fabric retrofits, to make heat demand shifting more effective, in terms of maintaining thermal comfort, prolonging the demand shift duration and the amount of energy shifted as discussed below.

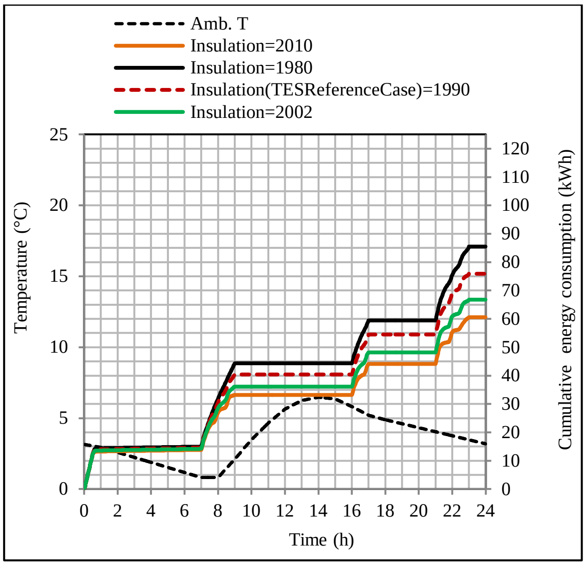


Figure 6-28. Thermal Insulation Impact: Effect of thermal insulation level on the energy draw profile for the Det90 archetype averaged over the 60 day simulation period.

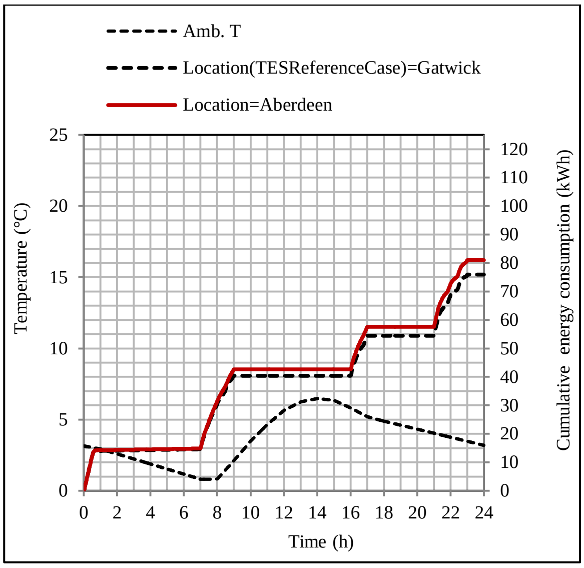


Figure 6-29. Location Impact: Effect of location on energy draw profile for the Det90 archetype in comparison with the TES Reference Case, averaged over 60 day simulation period.

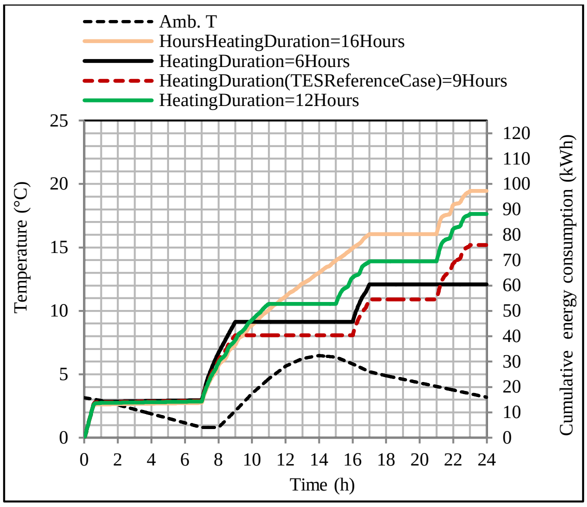


Figure 6-30. Heating Duration Impact: Effect of heating duration on the energy draw profile for the Det90 archetype in comparison with the TES Reference Case, averaged over 60 day simulation period.

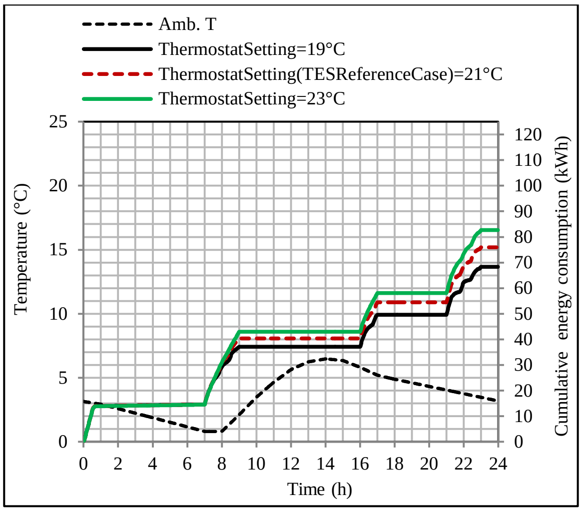


Figure 6-31. Thermostat Setting Impact: Effects of thermostat set point energy draw profile for the Det90 archetype in comparison with the TES Reference Case, averaged over 60 day simulation period.

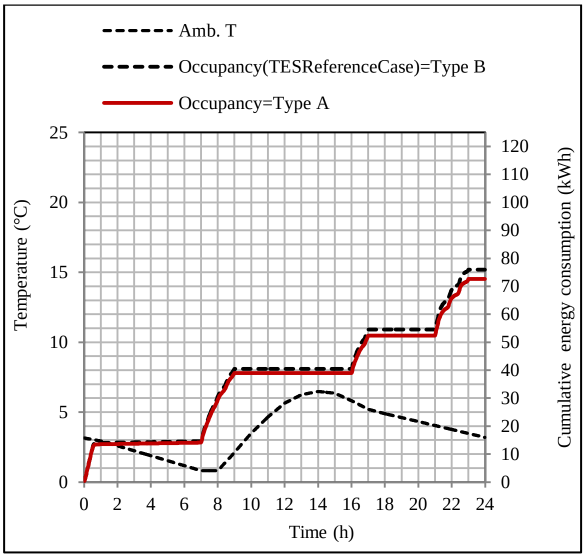


Figure 6-32. Occupancy Impact: Effect of occupancy on energy draw profile for the Det90 archetype in comparison with the TES Reference Case averaged over 60 day simulation period.

The energy demand impacts due to changes to the five parameters in the four building archetypes considered are summarised in Table 6-6. The table presents 60 day mean of the mains supply and space heating only energy consumption for all hours (00:00 to 24:00), the space heating only energy consumption for a four hour DSP (17:00 to 21:00) and the energy supplied by the TES tank during the four hour DSP. The energy supplied by the TES can be considered as the heat shifted to the off peak time. The highlighted values are for the TES Reference Case conditions. The table also indicates the quantity by which the energy consumption rise or fall from the TES Reference Case values as a result of the changes made to the five corresponding parameters. For example, the space heating only energy consumption for the Det90 TES Reference Case for all hours is 65.87kWh, and this value changes to 74.24kWh, 57.38kWh and 51.58kWh as the thermal insulation of the building changes to be in line with the 1980, 2002 and 2010 the building regulation respectively. These correspond to an energy consumption change of +8.90kWh, -9.82kWh and -16.02kWh compared to the TES reference Case respectively. Likewise, for the same building archetype, the space heating only energy consumption changed to 58.85kWh and 71.47kWh from the TES Reference Case value of 65.87kWh as the thermostat set point changed from the setting of 21°C to 19°C and 23°C respectively. The resulting change from the TES Reference Case this time is -8.21kWh and +6.04kWh respectively.

Table 6-6 also shows us how much energy was used during the critical DSP period (17:00 to 21:00) for the TES Reference Case, and how it changed as the five parameter values changed. Also, it shows how much of the energy used during the DSP came from the TES tank, which is the amount of heat demand shifted in time. For example, during the DSP hours of 17:00 to 21:00, the TES Reference Case heat use was 14.77kkWh of which 13.68kWh came from the TES tank, for the Det90 archetype. As the thermal insulation changed to the 1980s and 2010s level, the heat use changed to 14.91kWh (13.64kWh coming from the TES tank) and 12.84kWh (12.42kWh coming from the TES tank) respectively.

Table 6-6. Comparison of the DHW, space heating energy and mains supply energy consumption and predictions, and the daily average heating energy cost for the Base Case scenario and for simulations with varying building regulation, built form, floor size, location, heating duration, thermostat setting and occupancy.

				Thermal Insulation				Location		Heating Duration				Thermostat Setting			Occupancy	
Prediction	Period	variable	Built form	1980 (kWh)	1990 (kWh)	2002 (kWh)	2010 (kWh)	Gatwick (kWh)	Aberdeen (kWh)	6 hours (kWh)	9 hours (kWh)	12 hours (kWh)	16 hours (kWh)	19°C (kWh)	21°C (kWh)	23°C (kWh)	Type A (kWh)	Type B (kWh)
Energy demand with varying energy consumption influencing factors	All hours 00:00-24:00	Mains	Det90	85.49	76.59	66.78	60.57	76.59	81.04	60.41	76.59	88.26	97.23	68.38	76.59	82.63	72.61	76.59
			SDet90	80.28	71.67	60.36	56.20	71.67	76.01	56.99	71.67	81.07	81.57	63.83	71.67	77.56	68.07	71.67
			MTer90	73.40	65.87	57.89	53.13	65.87	70.12	54.78	65.87	74.74	74.15	58.66	65.87	72.09	62.12	65.87
			Flat90	65.08	60.46	55.91	54.06	60.46	64.02	50.22	60.46	67.38	65.85	54.54	60.46	65.38	56.08	60.46
		Space heating	Det90	74.24	65.87	57.38	51.58	65.87	69.84	51.55	65.87	79.01	87.65	58.85	65.87	71.47	67.43	65.87
			SDet90	68.69	60.56	51.54	46.82	60.56	64.42	48.38	60.56	71.72	79.98	53.66	60.56	66.27	62.21	60.56
			MTer90	63.37	56.42	48.99	44.18	56.42	60.11	46.29	56.42	65.78	71.87	49.81	56.42	62.16	58.17	56.42
			Flat90	55.16	51.02	46.91	45.04	51.02	54.00	42.43	51.02	58.45	63.58	45.42	51.02	56.11	52.26	51.02
	Heated hours 17:00-21:00	Space heating	Det90	14.91	14.77	13.47	12.84	14.77	14.55	14.59	14.77	12.83	11.91	13.97	14.77	14.18	15.50	14.77
			SDet90	14.56	14.16	12.80	12.16	14.16	14.10	14.31	14.16	12.60	14.62	13.43	14.16	13.86	15.03	14.16
			MTer90	14.23	13.69	12.47	11.77	13.69	13.69	13.87	13.69	11.56	12.75	12.84	13.69	13.61	14.60	13.69
			Flat90	13.51	13.29	12.42	12.10	13.29	13.43	13.57	13.29	11.44	12.44	12.50	13.29	13.20	14.17	13.29
		TES energy supplied	Det90	13.64	13.68	12.81	12.42	13.68	13.48	13.44	13.68	12.92	12.32	13.22	13.68	13.15	12.71	13.68
			SDet90	13.39	13.46	12.39	12.09	13.46	13.29	13.22	13.46	12.59	8.18	12.98	13.46	12.97	12.48	13.46
			MTer90	13.17	13.11	12.19	11.65	13.11	13.02	12.94	13.11	12.19	7.33	12.51	13.11	12.73	12.17	13.11
			Flat90	12.82	12.86	12.13	11.94	12.86	12.76	12.85	12.86	12.01	7.32	12.27	12.86	12.51	11.87	12.86
Change from TES Reference Case	All hours	Mains	Det90	8.90	0.00	-9.82	-16.02	0.00	4.45	-16.18	0.00	11.67	20.64	-8.21	0.00	6.04	-3.98	0.00
			SDet90	8.62	0.00	-11.30	-15.47	0.00	4.34	-14.68	0.00	9.40	9.90	-7.84	0.00	5.90	-3.60	0.00
			MTer90	7.53	0.00	-7.98	-12.74	0.00	4.25	-11.09	0.00	8.87	8.28	-7.21	0.00	6.22	-3.75	0.00
			Flat90	4.62	0.00	-4.55	-6.40	0.00	3.56	-10.24	0.00	6.92	5.39	-5.92	0.00	4.92	-4.39	0.00
		Space heating	Det90	8.37	0.00	-8.49	-14.28	0.00	3.98	-14.32	0.00	13.14	21.79	-7.02	0.00	5.60	1.56	0.00
			SDet90	8.13	0.00	-9.02	-13.74	0.00	3.86	-12.18	0.00	11.16	19.42	-6.90	0.00	5.71	1.65	0.00
			MTer90	6.94	0.00	-7.43	-12.24	0.00	3.69	-10.14	0.00	9.36	15.44	-6.62	0.00	5.74	1.75	0.00
			Flat90	4.13	0.00	-4.11	-5.98	0.00	2.98	-8.59	0.00	7.42	12.55	-5.61	0.00	5.09	1.23	0.00
	Heated hours 17:00-21:00	Space heating	Det90	0.14	0.00	-1.30	-1.93	0.00	-0.22	-0.18	0.00	-1.94	-2.86	-0.80	0.00	-0.59	0.73	0.00
			SDet90	0.40	0.00	-1.36	-2.00	0.00	-0.06	0.15	0.00	-1.56	0.46	-0.73	0.00	-0.30	0.87	0.00
			MTer90	0.54	0.00	-1.22	-1.91	0.00	0.00	0.18	0.00	-2.12	-0.94	-0.85	0.00	-0.08	0.91	0.00
			Flat90	0.22	0.00	-0.86	-1.18	0.00	0.14	0.28	0.00	-1.85	-0.85	-0.79	0.00	-0.09	0.88	0.00
		TES energy supplied	Det90	-0.05	0.00	-0.87	-1.26	0.00	-0.20	-0.24	0.00	-0.76	-1.37	-0.46	0.00	-0.54	-0.97	0.00
			SDet90	-0.07	0.00	-1.07	-1.37	0.00	-0.17	-0.24	0.00	-0.87	-5.28	-0.48	0.00	-0.49	-0.98	0.00
			MTer90	0.06	0.00	-0.91	-1.46	0.00	-0.08	-0.17	0.00	-0.92	-5.78	-0.60	0.00	-0.38	-0.94	0.00
			Flat90	-0.05	0.00	-0.73	-0.93	0.00	-0.10	-0.01	0.00	-0.85	-5.54	-0.60	0.00	-0.36	-0.99	0.00

The bar chart in Figure 4-26 illustrates energy consumption impact of the five variables on buildings categorised by built form. It shows the mean percentage change in space heating energy consumption from the TES Reference Case levels. The TES Reference Case level is represented by the zero line or the X-axis. Longer heating duration, low thermal insulation (1980s level), higher thermostat setting and cold location (Aberdeen) all have energy consumption increasing impact, and in the same respective order. It varies from about 6% to 34%, in relation to the TES Reference Case values, with longer heating duration being the most dominating factor. Impact of occupancy change is negligible at around 3%. Improved thermal insulation to 2010 level, lower heating duration of 6 hours and a thermostat set point of 19°C reduce the energy consumption by around 8% to 22% compared to the TES reference Case, with the thermal insulation having the greatest impact.

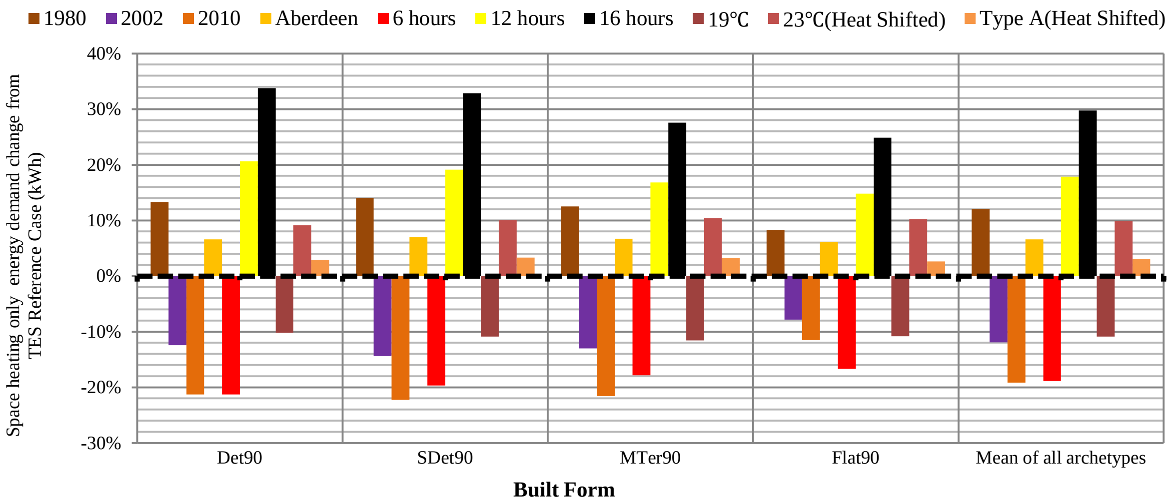


Figure 6-33. 60 day average space heating only energy consumption change compared to the TES Reference Case, due to changes in thermal insulation (1980, 1990, 2002 & 2010), location, heating duration, thermostat set point and occupancy type, by built form.

The parameter changes that have a dominant effect in reducing the heating energy consumption are: 1) improved thermal insulation, 2) lower heating duration, and 3) lower thermostat set point. These could be targeted during any building energy and thermal performance enhancing interventions, for example retrofits.

The analyses below focus on identifying the combination of archetype and the three dominant parameters that affect thermal comfort (Metric 8), heating energy consumption (Metric 5) and the amount of heat shifted (Metric 9), from the more expensive grid-peak time to a less expensive grid off-peak time.

The graphs in Figure 6-34, Figure 6-35 and Figure 6-36 illustrate the 60 day mean thermal comfort and heat demand shifted during a 4 hour DSP in the four building archetypes considered. The simulation variable settings were as per TES Reference Case together with different values for the three dominant parameters mentioned above. Archetypes that have low thermal comfort for a given set of parameter values can be taken as the ones that require interventions to make them more suitable for heat demand shifting. It can be seen in Figure 6-34 that the 2002s and 2010s insulation level in the Flat90, MTer90 and the SDet90 archetypes maintain a 100% thermal comfort whilst allowing around 11.5kWh to 12.5kWh of heat demand shifting. The Det90 can only provide a 100% thermal comfort with a 2010s insulation level. A 100% thermal comfort is achieved in all four archetypes when the heating duration is increased to 16 hours as shown in Figure 6-35. A heating duration of 12 hours also provides 100% thermal comfort in all archetypes except det90. Increasing the thermostat set point to 23°C provides 100% thermal comfort only in the Flat90 and MTer90 archetypes as can be seen in Figure 6-36. It can be realised from these that a 4 hour heat demand shift with a 100% thermal comfort could be achieved in most building archetypes by changing the thermal insulation to 2010s and 2002s level, or by increasing the heating duration to 16 and 12 hours or by raising the thermostat set point to 23°C. This implies that building archetypes with these parameter values could be and should be targeted for heat demand shifting with the TES Reference Case value of TES capacity, where a 4 hour shift could be achieved. The thermal comfort drops in archetypes with other parameter values, and therefore, a shorter demand shifts period might be more appropriate so that there is less time for the temperature to drop, thus maintaining thermal comfort.

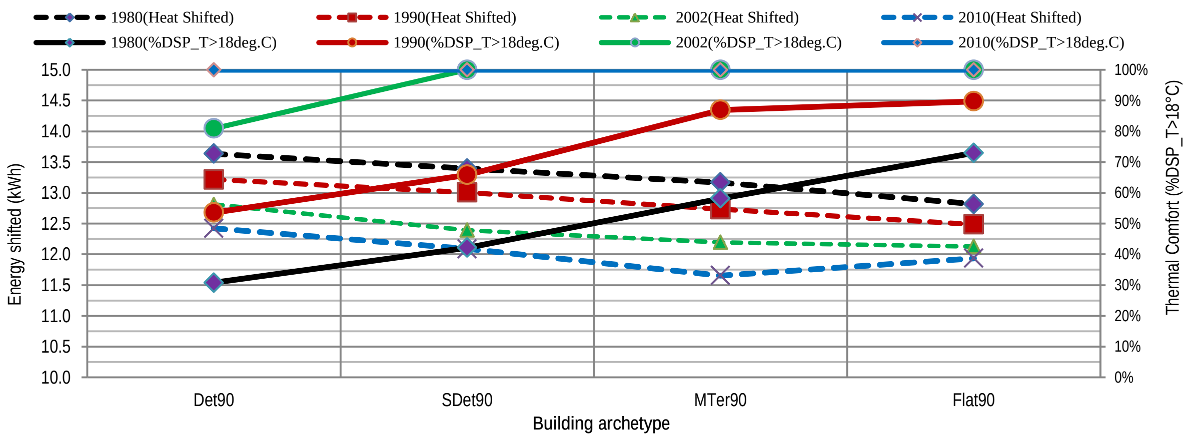


Figure 6-34. Illustration of the 60 day average heat shifted and thermal comfort - Metric 8(%DSP_T>18°C) during a four hour DSP from 17:00 to 21:00, for the four building archetypes, with varying thermal insulation values.

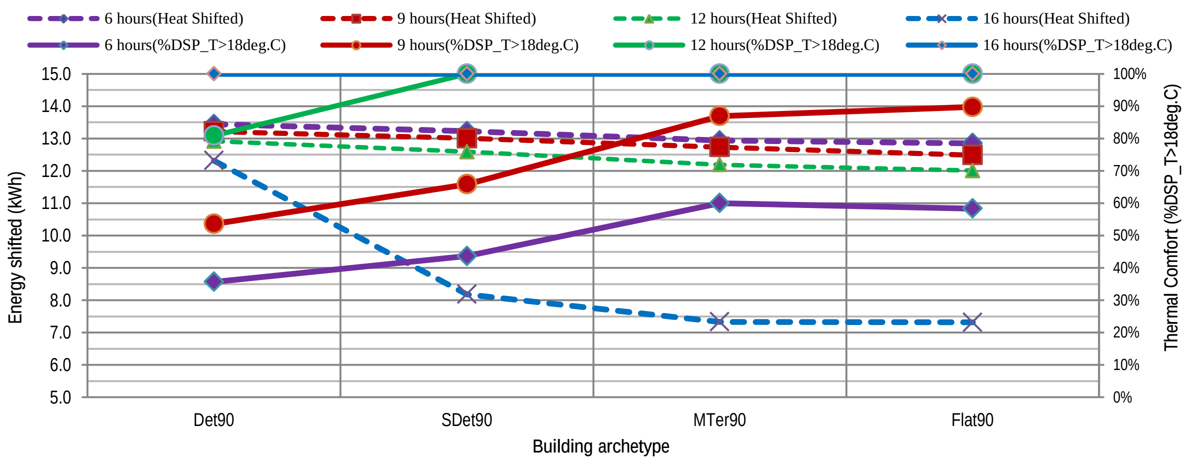


Figure 6-35. Illustration of the 60 day average Heat Shifted and thermal comfort - Metric 8(%DSP_T>18°C) during a four hour DSP from 17:00 to 21:00, for the four building archetypes, with varying heating duration values.

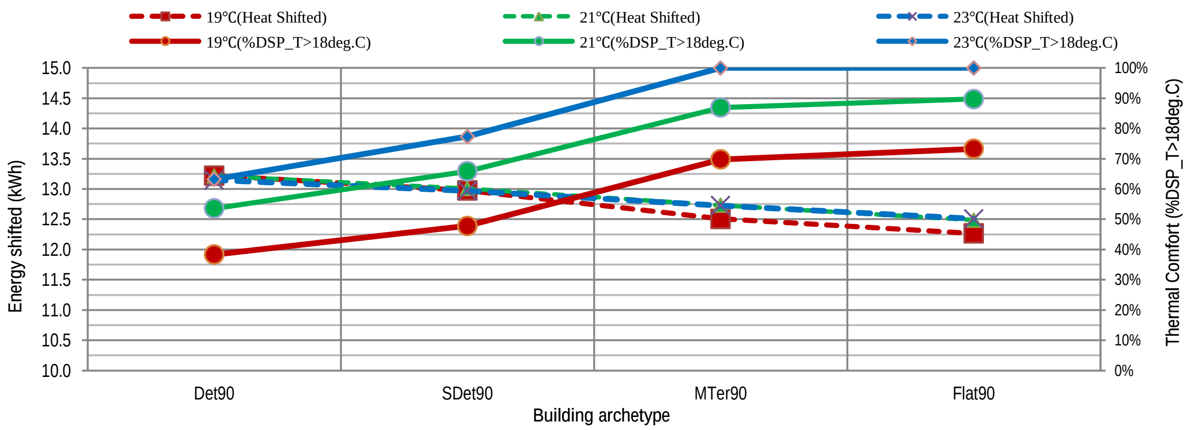


Figure 6-36. Illustration of the 60 day average heat shifted and thermal comfort - Metric 8(%DSP_T>18°C) during a four hour DSP from 17:00 to 21:00, for the four building archetypes, with varying thermostat set point values.

The four building archetypes together with the three dominant energy and thermal comfort influencing parameters as discussed earlier formed 44 combinations. These were analysed to determine how they performed in heat demand shifting using TES Reference Case level of thermal storage. Results are presented as bar charts in Figure 6-37 and Figure 6-38. These can be used to identify archetypes that could provide a four and a two hour heat demand shift with the respective parameter value changes. The archetypes that need upgrading with relevant parameter value changes to make them more suitable for a these DSP can also be identified.

The bar chart in Figure 6-37 illustrates the 60 day mean thermal comfort (Metric 8), space heating only energy consumption and the amount of energy shifted in the 44 combinations when a 4 hour heat demand shift is implemented. The combinations are labelled 1 to 44, and arranged by thermal comfort in a descending order left to right, followed by the energy consumption in ascending order left to right. The thermal comfort and the heating energy consumption levels predicted for the corresponding Base Case (See chapter 4, Section 4.4.1) and TES Reference Case (See Chapter 5, Section 5.4.2) mean values are illustrated.

It can be determined from the bar chart that a 4 hour heat demand shift could be achieved with 100% thermal comfort in combinations 1 to 16. The energy shifted in each combination is also shown and is around 12-13kWh. The combinations on the left hand side of the chart have less energy consumption. This is because the buildings in these combinations are mainly those that have better thermal performance, such as the flat, mid-terrace and semi-detached built form as discussed previously in Chapter 4. It can be seen that in the 16 combinations, thermal insulation upgrades to 2002s and 2010s level is the main intervention that provides 100% thermal comfort, low energy consumption. All archetypes with heating durations of 12 and 16 hours also provide 100% thermal comfort but at the expense of higher energy consumption. In some cases the amount of heat shifted reduces significantly which may make this intervention less attractive both in terms of the potential heating bill savings achievable for the households, and in providing effective grid load balancing capability for the supply side. Using thermostat set point of 23℃ provides 100% thermal comfort in the Flat90 and MTer90 archetypes without increasing energy consumption, and therefore may be an acceptable option for application in the buildings represented by these archetypes.

The thermal comfort for combinations 17 to 44 reduce gradually as can be seen. Building archetypes in these combinations, especially those towards the right, with the given parameter value settings provide worst thermal comfort during the DSP. Shifting heat demand by 4 hours in buildings represented by these archetypes and the parameters values are unlikely to be acceptable to the occupiers. Such buildings therefore could require interventions found in the first 16 combinations, to enable them to provide improved thermal comfort.

The bar chart in Figure 6-38 can be used to identify combinations of building archetypes and the three parameter values that could allow a 2 hour heat demand shift with a best possible thermal comfort and quantity of heat shifted, such that they are effective and acceptable to both the supply and the demand sides. As mentioned before, reducing the duration of the heat demand shift can ensure higher thermal comfort in the occupied space during the DSP. For example, a 4 hour demand shift in the Det90 archetype with a 1990s thermal insulation (see combination 36 in

Figure 6-37) has a thermal comfort value of about 58%. However, it increases to 100% when a 2 hour heat demand shift is implemented in the same archetype with the same thermal insulation as shown by combination 7 in Figure 6-38. The drawback is that the amount of heat shifted reduces when a shorter DSP is used, from 13.22kWh to 9.26kWh in the example given above.

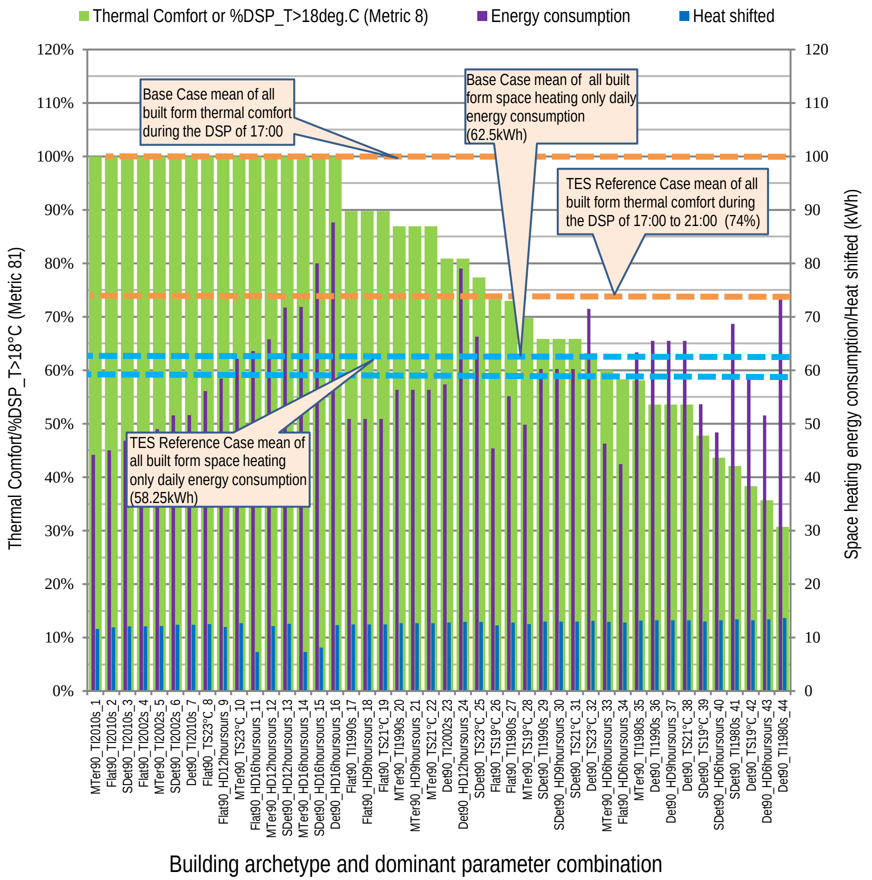


Figure 6-37. Thermal comfort and heating energy consumption impact in the four archetypes with three of the dominant parameter value changes applied in simulating a 4 hour heat demand shift from 17:00 to 21:00, in descending thermal comfort order and ascending space heating energy consumption order.

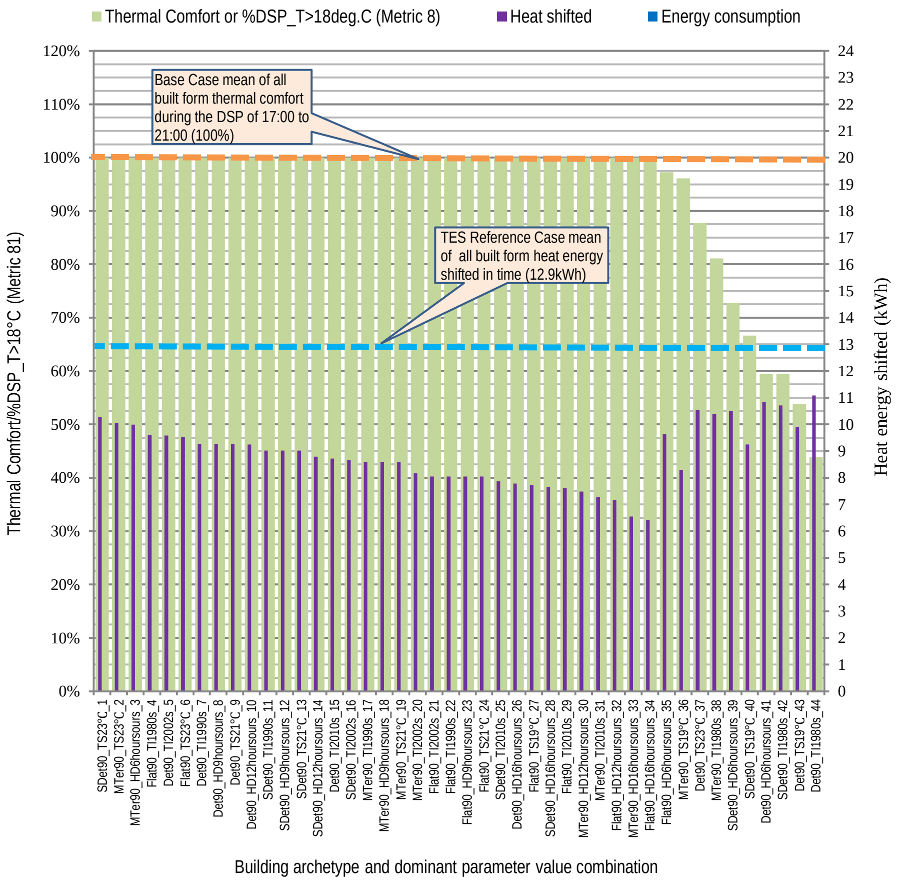


Figure 6-38. Thermal comfort and heating energy consumption impact in the four archetypes with three of the dominant parameter value changes applied in simulating a 2 hour heat demand shift from 17:00 to 19:00, in descending thermal comfort order and ascending space heating energy consumption order.

Note: X-axis labels are made up of building archetype ID and one of the five parameter value change (e.g. MTer90=Mid terrace with a 90m^2 floor size, TI2010s=thermal insulation corresponding to 2010 building regulation recommendation, TS23°C=thermostat setting of 23°C and HD12hours=daily heating duration of 12 hours.

6.5 Summary

This chapter presented the results of the parametric analyses carried out to explore and understand the impacts of varying the TES capacity (by using three tanks volumes and two water storage temperatures) in heat demand shifting in four building archetypes, and the effects of changing five of the key energy consumption influencing parameters (thermal insulation, geographical location, heating duration, thermostat set point and number of occupiers). The archetypes used represented detached, semi-detached, mid-terrace and flat built forms, each with a UK housing stock average floor area of 90m^2. In addition, 70m^2 and 150m^2 detached dwelling archetypes were simulated to explore the effects of varying TES capacity over a range of dwelling floor sizes. The outputs observed include the impacts on the temperature of the occupied space, power and energy consumption, and the amount of energy shifted when the heat energy demand within three fixed future DSPs, from the grid peak period of 17:00 to 21:00 hours, is implemented.

The results shows that all building archetypes (with Base Case level of thermal insulation) considered in this exercise can provide a 2 hour heat demand shift with virtually no thermal comfort degradation[20] with a 0.5m^3 TES and water storage temperature of 95°C. But the amount of heat shifted is relatively small and varies from around 6kWh to 14kWh depending on the combination of the building archetype and operational condition. A 0.75m^3 TES with 95°C water storage temperature can provide 4 hours' worth of heat demand shift in all archetypes except Det150, and the amount of heat shifted varies from about 6kWh to about 40kWh over the 60 days.

Changing the number of occupants to one adult had virtually no impact on the thermal condition whilst a location change to Aberdeen marginally worsened the thermal comfort. Thermostat set point also had a relatively large impact, for example lowering it to 19°C reduced the thermal comfort to 38% whereas raising it to 23°C increased thermal comfort to 63% compared to a TES Reference case value of 54% for the DET90 building. Overall, the Flat and Mid Terrace built forms have been shown to provide better thermal comfort for the heat demand shift considered, and should be targeted first in any heat demand shifting interventions.

[20] It is assumed that a space temperature of 18°C or above is sufficient for ensuring thermal comfort

7 CHAPTER SEVEN: DISCUSSION

7.1 Introduction

This chapter discusses the results presented in chapters 4 to 6 and a possible strategy for rolling out TES in buildings. The chapter is arranged as follows:

Section 7.2: Energy and thermal performance of UK domestic buildings: Discusses the thermal performance and energy consumption of the 12 building archetypes simulated. The impacts of the building size and built-form used to differentiate between the Base Case archetypes are discussed followed by the impacts of varying the thermal insulation, location, heating duration, thermostat set-point and occupancy.

Section 7.3: Heat demand analysis in buildings with Zero TES: Discusses the implication of deliberately not heating the buildings during the DSP hours (Zero TES Case)

Section 7.4: HDS with TES Reference Case: Discusses the implications of applying a sensible TES (TES Reference Case) to shift the heat demand from three DSPs during the evening peak hours from 5pm to an off peak period from 12am.

Section 7.5: Impacts of TES capacity variation: Discusses the effects of varying the physical size of the TES tank and water storage temperature to increase the heat storage capacity

Section 7.6: Impacts of varying thermal insulation, location, heating duration, thermostat set-point and occupancy: Discusses the implications of varying the thermal insulation, location, heating duration, thermostat set point and occupancy, when a 4 hour HDS is simulated with TES Reference Case level of thermal storage.

Section 7.7: Possible TES strategy for UK domestic buildings: explores one possible strategy that could be followed in rolling out HDS in UK domestic buildings using sensible TES, and presents some sample pathways that could be used in selecting a TES size for a given building size, thermal insulation and DSP requirement.

Section 7.8: Provides a summary of this chapter.

7.2 Energy and thermal performance of UK domestic buildings

Base Case Results

Results of the twelve Base Case buildings has confirmed and quantified the generally accepted perception of the changes in space temperature and energy consumption that occur in buildings due to built-form differences. For example, the detached built forms, due to larger exposed external walls, have on average consumed 7% more energy for space heating compared to a semi-detached built-form, assuming identical thermal insulation, occupancy and operational conditions. The flat built form is better at maintaining the indoor temperature. Dwellings with larger floor area are slightly worse at retaining heat compared to the smaller dwellings, and had the lowest minimum temperature, reaching 8.96°C. This pattern followed for all thermostat settings and heating durations considered, and also for the occupancy and location options used. Similarly, the energy demand during the grid peak hours (future DSP) varied with built-form and floor area in a similar manner (see Section 4.4.3.)

As described earlier in Section 3.5.7, resistance element water heater with power ratings of 20kW, 25kW and 30kW, to cover the power demand of the worst case buildings, were used in this work. It has been stated before that a combination of resistance element heating and heat pumps, with peak power demand 2 to 3 times smaller, are likely to support the electrification of domestic heating in the future (Wilson et al., 2013). Therefore the power demand results generated in this work cannot be generalised for buildings across the existing housing stock. However, the results can be useful in two ways: 1) it shows that the peak power demand in some buildings with low thermal insulation, large size and resistance element heating could be considerably high; and 2) it indicates the variables that can be targeted to minimise the peak power demand. For example, given the energy inefficient UK housing stock and that 16.6% of the English housing comprising of detached dwellings (nearly 3.8 million) with an average of 153m^2 floor area, even a small percentage of these, for instance 1%, with 1980 building regulation level of thermal insulation and electrical resistance heating could introduce a worst case additional 1.1GW of load to the grid. Other implications could include local electricity distribution issues such as electrical wiring and single phase to 3-phase upgrades. These need to be taken into account in developing any heat demand management strategies through demand shifting.

The results showed that dwelling size and built-form have a significant energy consumption impact. The daily mean mains supply (which includes space heating and DHW) energy consumption averaged over the 60 winter days varied from 52.6kWh (Flat70) to 117.8kWh (Det150). This changes, when the worst case effects of weather variation over the 60 days is considered, to 36.8kWh (Flat70) to 159.66kWh (Det150). On average, the semi-detached, mid terrace and the flats consumed 7.0%, 13.8% and 22.7% less energy per day for space heating compared to the detached built-form respectively. This indicates that energy consumption during the winter days can vary considerably even in buildings with similar thermal insulation. The variation would amplify further when other key energy consumption influencing factors, such as thermal insulation, thermostat setting and heating duration, are taken into account as discussed below. The corresponding heat energy cost, based on current standard electricity price tariff of British Gas Ltd., also varied accordingly, from an absolute minimum value of £5.55/day (Flat70) to a maximum of £24.09/day (Det150) over the 60 day winter period, with an overall average of all building sizes and built-forms of £12.09/day. These are significantly high, by a factor of 3.2, compared to the current natural gas based equivalent cost, which are £1.73/day and £7.50/day respectively, with the average cost of all archetypes being £3.77/day. It must be noted that the high cost for electrical heating is based on the worst case assumption that electrical resistance heating is used with a COP of 1. But, as discussed by Wilson et al., (2013), HPs with COP between 2 and 3 are likely to dominate the electrification of domestic heating. As discussed before, if the heat consumption predictions mentioned above were to be satisfied by HPs with a COP of 3, then the associated costs would drop significantly, to just 7% above the gas equivalent, and would reach parity with gas if the COP was 3.2. This could be considered particularly encouraging given that the COP for HP systems can vary from about 0.2 to 6, although it is, at present, mostly between 2 and 3 (Hepbasli et al., 2009). As technology advances, it may be possible to produce HPs with COP of 3.2 or higher, making electrical heating more affordable and at parity with gas.

Exploring the energy consumption predictions during critical grid peak hours (or future DSP hours) was important as it indicated the amount of heat needed to be stored and supplied into the building to ensure thermal comfort. The variation of energy consumption during the DSP hours was large. For example the maximum and minimum values over the 60 days were 4.19kWh and 33.4kWh; 5.39kWh and 46.0kWh; and 7.8kWh and 58.7kWh for the 2, 3 and 4 hour DSP respectively. These worsen when other main energy consumption influencing factors are taken into account as discussed below. The 60 day average energy needed to ensure a space temperature at or above the thermostat set point during the DSP is shown in Figures 4.17 for the 12 Base Case archetypes. Obviously, the DSP duration affects the amount of heat needed to maintain the space temperature at the thermostat set point. The relationship between the two is shown in Figure 4.18 (showing the mean of 60 days for the 12 Base Case archetypes) and Figure 4.19 (showing the absolute minimum, maximum and mean over the 60 days). Building size is one major factor that impacts the heat needed during the DSP, the relationship of which is illustrated in Figure 4.20 (showing the absolute minimum, maximum and the mean over the 60 days). These graphs are useful in that they indicate the different range of energy storage required, and can be used to determine the TES system requirements based on the building archetype and the design DSP.

Performance impacts of thermal insulation, thermostat setting, location, heating duration and occupancy

The results generated during this exercise provided an insight into how and to what extent the thermal condition of the occupied space and the heating energy consumption are likely to change, in relation to the Base Case values, given the variations in five key energy consumption influencing parameters. Figures 4.21 to 4.26, illustrate how the indoor thermal profile reacts with changes in these variables. In terms of thermal comfort, it is preferable to ensure that the space temperature remains as close to the thermostat set point as possible during all times, including the unoccupied hours, so that it can be easily raised and maintained at the thermostat set point. The parameter that is most effective in achieving this is the thermal insulation and a value corresponding to the 2010 building regulation. Longer heating duration and higher heating duration also has similar effect though not as pronounced. The main and important difference is that with improved thermal insulation, the effect is realised without increasing the energy consumption as opposed to longer heating duration and higher thermostat setting.

Out of the five key heat energy consumption variables investigated, short heating duration, low thermal insulation and low thermostat set points reduce the unheated period space temperature as shown in Figure 4.26. These variables are likely to increase the heat requirement during the heated period, and also during the DSP period, to raise the space temperature to the required level. This means larger TES capacity would be required to achieve a given head demand shift.

Larger heating duration, better thermal insulation and higher thermostat set points make the unheated space temperature rise closer towards the thermostat set point. These are the potential variables that could be utilised to reduce the TES size requirement.

The most influential parameters (see Figure 4.2.8) in terms of reducing the average power demand below the Base Case level is longer heating duration. However, this leads to greater energy consumption. Nevertheless, it is an option that could be used to reduce electrical heating related grid peaks. Reducing the thermostat set-point also provides some scope for power demand reduction but this is achieved at the expense of reduced thermal comfort which may not be acceptable to all occupiers. Increasing the thermal insulation to 2002 and 2010 building regulation level reduce power demand and without affecting thermal comfort or increasing the energy consumption. Therefore this can be considered as the best option for reducing the power demand during critical grid peak times.

From the five main energy consumption influencing parameters investigated, thermal insulation had the greatest overall heat demand reducing impacts (see Figure 4.29). For example, updating the thermal insulation in the Det90 building from the 1980s recommended level to the 1990s, 2002s and 2010s recommended levels could reduce the mains supply energy consumption by 15.0% (to 82.5kWh), 26.8% (to 71.1kWh) and 35.0% (to 63.2kW) respectively compared to that of the 1980s value (97kWh). The average power demand and the thermal comfort also improved with enhanced thermal insulation.

Longer heating duration and higher thermostat setting both increase the overall energy consumption significantly, from around 11% to 24% depending on the size and built-form. Reducing these below the required level would cease to satisfy the heating service needs. Therefore they can only be considered as valid options for reducing energy consumption, up to a point where it begins to reduce the temperature below the minimum acceptable level, which in this work has been assumed to be 18℃.

The mean energy use during the critical grid peak period (17:00 to 21:00) increased for 1980s thermal insulation by 21% compared to the Base Case (see figure 4.30), indicating that larger TES would be required for heat demand shifting. Conversely, 2010s thermal insulation level reduces energy consumption by 25% compared to the Base Case.

Thermostat set point and heating duration can increase or decrease the energy consumption during the critical period, but these can be controlled by the user and are not imposed. They provide some scope for reducing the energy requirement during the DSP period, and could be used to make HDS using TES more effective in terms of thermal comfort and shift duration achievable.

It can be concluded from the above that the thermal insulation enhancing interventions is the best tool that could be used to: 1) reduce the overall and grid peak time energy consumption, 2) reduce the power demand, and 3) ensure thermal comfort, all of which combined could make future heat demand shift in building using TES more effective.

7.3 Heat demand analysis in buildings with Zero TES

As discussed previously, it may become necessary to introduce variable time-of-use electricity price tariffs in the future to encourage demand shifting to off-peak times, and therefore make peak time grid balancing easier. Electricity price tariffs with high peak time charges may encourage and/or force people, especially households in fuel poverty, to avoid heating during the peak hours. It is therefore important to appreciate the thermal comfort impacts this could cause. This exercise highlighted the potential impacts and benefits of avoiding heating the buildings during the grid peak time.

The results indicated that the 60 day minimum space temperature during the occupied hours is worse for the Det150 and best for the Flat90 archetypes, reducing by over 8.2℃ and over 4.7℃ below the thermal comfort threshold of 18℃ respectively. The worst case average thermal comfort was 12% for Det150 with a 4 hour DSP which meant that the temperature remained below the thermal comfort limit for up to 88% of the heating inhibited period. The best case thermal comfort was 50% for Flat90 with a 2 hour DSP, which meant that the space temperature remained below the thermal comfort limit for half of the DSP. For all other archetypes, the values were in between these extremes depending on the DSP duration and the archetype.

In most cases, the thermal comfort degradations are unlikely to be acceptable and could be harmful for the residents. Whilst it is not suggested that households will or should avoid heating their homes to reduce energy bill, it may be forced upon them for reasons as discussed above. The consequences of this are highlighted in this work for the different buildings represented by the 12 Base Case building archetypes.

The mains supply energy consumption reduces when the heating system is inhibited during the heating periods. The results showed that the energy consumption avoided could vary from 1.87kWh for the Det70 to 40.23kWh for Det150 respectively. Obviously, the more energy consuming buildings will result in greater energy use avoidance. This could potentially benefit the supply side due to a reduction in power demand during the peak time, decreasing the need for investment in extra generation capacity. The benefit for the households would be a reduction in heating bill, which could range from £0.63/day to £8.85/day based on the current standard electricity price and electrical resistance heating. The benefit comes at a significant cost in terms of reduced thermal comfort as mentioned above.

7.4 HDS with TES Reference Case

For TES to be successfully adapted by the end users, the occupied space temperature, which could degrade due to a lack of heat supplied during the peak hours, has to be maintained at or above an acceptable limit to ensure thermal comfort. This limit has been assumed to be 18℃ in this work.

The results showed that with a TES Reference Case level of TES, a 2 hour heat demand shift can be achieved in all of the 70m^2 and 90m^2 floor area archetypes with a 60 day mean thermal comfort of 100%. The minimum temperature however falls below 18℃ occasionally during the coldest days (see Figure 5.15). This is assuming that their thermal insulation, occupancy and operational conditions are as per the Base Case (see Table 3.10). Given the large quantity (63.8%) of the English housing stock having floor area up to 90m^2 (See Chapter 3, Section 2.3) with just over 80% having double glazing, around 69% of building with cavity walls having cavity insulation, and over 60% having 100mm or less loft insulation (DCLG, 2013), a significant number could meet the Base Case assumptions making them suitable for a 2 hour heat demand shift. In these buildings a mean thermal comfort of 100% could be maintained using the TES Reference Case level of thermal storage. For example assuming 5% (725,852) of the dwelling with floor area below 90m^2 resort to electrical resistance heating and that they adopt a 2 hour heat demand shift, each shifting an average of 8.3kWh/day (see table 5.9), could shift a total of around 6.0GWh of heat to off peak times per day. This is equivalent to moving around 3.0GW of potential peak time grid load, assuming that heat is used evenly over the two hour DSP. This is significant given the current winter time peak grid load is around 55GW as discussed previously in section 2.2.3.

A three hour heat demand shift with average thermal comfort of 100% was predicted to be possible in five out of the twelve Base Case archetypes: SDet70, MTer70, Flat70, MTer90 and Flat90. A four hour heat demand shift without thermal comfort compromise was predicted to be possible only in the two out of the twelve Base Case archetypes: MTer70 and Flat70 (see Figure 5.15). This implies that heat demand shift higher than 2 hours could not be achieved in large dwellings, although they have greater energy use and likely to make larger impact in terms of adding to the peak time grid load. Larger TES size with increased storage capacity is therefore required in these dwellings to ensure an acceptable thermal comfort during the DSP. The benefit of utilising larger TES size is also to shift more heat to off peak times making them more effective as discussed below.

The benefits for the households could come in the form of reduced energy cost by shifting the energy use time to coincide with low energy price times, such as 00:00 to 07:00 in the Economy7 variable electricity price tariff. This work showed that by applying HDS with a TES Reference Case level of heat storage, energy shifts from 4.27kWh to 15.53kWh with a mean value of 10.94kWh could be achieved. This is 7.3% to 26.4%, with mean value of 14.5% as percentage of the Base Case mains supply energy use. The corresponding potential energy bill savings range from £0.42/day to £1.52/day with a mean of £1.07/day. This is assuming that electrical resistance heating with Economy7 level of off-peak electricity price is used. The level of saving depends on the duration of the heat demand shift period, and the building floor size and built form. The graphs in figures 5.19 and 5.20 show the mean (over 60 days and of all four built forms) energy shifted, the corresponding thermal comfort and the corresponding potential electricity bill saving, by floor area of the building, for a 2, 3 and a 4 hour DSP. It can be deduced from the graphs that the most amount of heat demand shifted (~16.2kWh/day) and bill saving (~£1.4/day) achieved is in the 150m^2 buildings with 4 hour DSP, but for a thermal comfort of around 44%. The least amount of heat shifted (~8kWh/day) and bill saving (£0.77/day) could be achieved in the 70m^2 buildings with a 2 hour DSP, but this time the thermal comfort is maintained at 100%. Using these graphs it is possible to work out the mean heat demand shift with a 2, 3 or 4 hour DSP, for a given building size and a thermal comfort acceptable to the occupiers, and also determine the mean bill saving possible, provided the Base Case and TES Reference Case assumptions are satisfied.

7.5 Impacts of TES capacity variation

TES systems with larger capacity allow greater amounts of heat to be shifted to off-peak times, and enable larger DSP to be achieved with less impact on thermal comfort. To explore the effects of TES capacity in detail, heat demand shift simulations were performed with TES tank sizes of 0.5m^3 and 0.75m^3 and a water storage temperatures of 95°C in addition to the tank size of 0.25m^3 and water temperature of 75°C used during the TES Reference Case simulations. These allowed the stored heat to vary from 24kWh (for a size 0.25m^3 and water storage temperature of 75°C) to about 71kWh (for a size of 0.75m^3 and water storage temperature of 95°C), based on water being heated from an average mains water supply temperature of 9°C provided by the weather data. The maximum amount of heat extracted and supplied from the 0.75m^3 TES was into Det150, during the coldest of the 60 days and for a 4 hour DSP, and was 47.7kWh, which is about 67% of the maximum stored heat. The corresponding values for the 0.5m^3 and 0.25m^3 TES tanks are 36.7kWh (76.9%) and 21.0kWh (87.5%) respectively. The extracted heat from smaller TES tanks reach close to 90% of the stored heat because the water gets recirculated around the heating loop more often, losing the heat and lowering the temperature. This continues until the end of the DSP by when most of the heat is extracted, thus reaching a figure close to the maximum stored value.

Increasing the TES capacity significantly improves the thermal comfort during the DSP. For example, a 0.75m^3 TES tank size with a hot water storage temperature of 95°C could be used to achieve a 4 hour heat demand shift with 100% mean thermal comfort in all the archetypes considered (Det90, Det150, SDet90, MTer90, Flat90), and with the minimum space temperature during the DSP staying above the thermal comfort limit (18°C) in all except Det150, for which it drops to about 16.5°C. In comparison, a 0.5m^3 TES tank with 95°C water storage temperature could be used to achieve 4 hour heat demand shift with 100% mean thermal comfort in the same archetypes, but the minimum space temperature during the DSP would drop below the thermal comfort limit for all except MTer90 and Flat90. However, if the DSP is reduced to 2 hours then the 0.5m^3 TES tank could ensure thermal comfort of 100% in all archetypes and with the minimum temperature falling marginally below the thermal comfort limit to 17.7°C only for Det150. These examples and the results presented in section 6.3 show the TES sizes appropriate for dwellings with a Base Case level of thermal insulation, occupancy and operational conditions, and for the variables relating to built-form, size and DSP duration. The set of graphs provided in figures 6.3, 6.4 and 6.5 can be used to determine the correct TES size depending on the variables mentioned. Selecting the right TES tank could play a large part in future uptake by preventing unnecessary costs in terms of using up more space and higher capital expenses.

Increasing the TES capacity means large loads, equivalent to the power rating of the water heater, will be applied to the mains supply from the beginning of the off-peak period, in charging up the TES. These will remain for a longer duration compared to the TES Reference Case (see Figure 6-6). Large scale adaptation of this in the UK housing stock could create a new peak at the national grid. However, the current mains grid loading is relatively low in this period (See Section 2.2.3) and in reality most of the heat is likely to be provided by HP with COP between 2 and 3, which could cut the load by a factor equal to the COP as discussed earlier. Also, control strategies can be relatively easily applied to the water heater in the TES storage system so that the tank is changed up over a longer period, for example over the entire off-peak period from 00:00 to 07:00, thereby spreading the power demand and preventing the load peaking.

The energy draw profile resulting from the HDS process is likely to be important to both to the supply side and the demand side stakeholders. This is because a heat draw profile that spreads over the grid off peak time and avoids the peak times could be beneficial for the supply side in terms of easing short term grid balancing problems, and provide heating cost reducing benefits for the households. Increasing the TES size allowed the energy drawn to be concentrated in the off-peak time period as shown in Figure 6.8.

Increasing the TES capacity had the effects of: 1) increasing the heat shifted to off-peak time, 2) enabling larger DSP to be achieved, and 3) increasing the potential bill saving for the households. The smallest change in heat shifted was from 8.6kWh for Flat90 archetype with a 2 hour DSP to 10.25kWh, which is an increase of about 16.2%. The largest change in heat shifted was from 14.9kWh for Det150 archetype with a 4 hour DSP to 38.1kWh, which is an increase of 155.8%. Clearly, greater amounts of heat can be shifted with bigger TES in large buildings and with longer DSP. However, as illustrated in Figures 6.9, 6.10 and 6.11 large energy shifts are also associated with reduced thermal comfort in the respective buildings, and installing large TES tanks might not be appropriate in certain buildings, which have to be taken into account.

The TES size appropriate for a given building will depend on many factors including: building size and type, heat consumption, thermal comfort requirement of the occupiers and the costs in terms of the space used for housing the TES and capital expenses. The data presented in Table 6-1 and the graphs in Figure 6-9, Figure 6-10 and Figure 6-11 take many of these factors into account and form a set of tools which could be used to determine the TES system required for a given building archetype, occupancy and operational scenario.

7.6 Impacts of varying thermal insulation, location, heating duration, thermostat set-point and occupancy

Out of the five parameter changes implemented, thermal insulation and heating duration had the greatest impact on the thermal condition of the occupied spaces during the DSP. For example, the mean thermal comfort (Metric 8) changed from 74% with 1990s (TES Reference Case) thermal insulation to: 1) only 51% with a 1980s thermal insulation, and 2) 100% with a 2010s thermal insulation. Enhancing this parameter also means extending the DSP duration achievable for a given TES. Similarly, changing the heating duration from 9 hours to 6, 12 and 16 hours changed the thermal comfort from 74% to 49%, 95% and 100% respectively.

Changing the number of occupants to one adult had minimal impact on the thermal condition, where it increased by a mean of 5%. The reason as mentioned previously, is that the occupants are independent of the heating system setting. They also did not play a part in the dwelling heat loss. The small effect occupants had was an increase in the internal heat gain and DHW consumption which added to the space temperature and used up heat from the TES respectively. Location change to Aberdeen reduced the mean space temperature by about 0.6°C, reducing the mean thermal comfort by 15% compared to the Base Case. Thermostat set point also had a relatively large impact, for example lowering it to 19°C reduced the mean thermal comfort by 17% from the Base Case value of 74% whereas raising it to 23°C increased thermal comfort by 11%.

The overall power demand impact of the five parameters indicate the expected trend, where dwellings with low thermal insulation level, larger heating duration and higher thermostat set point have relatively high daily mean power demand.

The way energy consumption is affected by the five parameters could be of great interest to the demand side, supply side and the policy implementing authorities alike. For example, retrofit interventions can be targeted to dwellings and households with high energy use, to ensure that they have the right conditions that will make heat demand shifting more cost effective. This will lead to a reduction in the overall energy consumption which could benefit: 1) the households in terms of reduced energy costs, 2) the supply side in terms of reducing generation capacity, and 3) the environment in terms of reduced CO_2 emission.

This work showed that the parameter changes that have a dominant effect in changing the overall heating energy consumption are: 1) improved thermal insulation, 2) heating duration, and 3) thermostat set point. These parameters could be targeted during any building energy and thermal performance enhancing interventions, for example building retrofits. Such interventions might be necessary in some buildings before installing TES and heat demand shifting systems. This is so that the heat requirement during the DSP, for ensuring a space temperature higher than 18°C, is reduced as discussed previously in Section 4.4.2 of Chapter 4. Thus, it may become easier to carry out heat demand shifts of worthwhile quantities and durations, with smaller TES systems sizes and with minimum degradation to the thermal comfort. This is demonstrated by the results presented in Section 6.4. Enhancing the thermal insulation from the Base Case level to 2002 and 2010 building regulation level showed a mean (of the four built forms considered) overall energy consumption reduced by 8.4kWh and 12.7kWh respectively, and increased the corresponding thermal comfort by 21% and 36% respectively, compared to the TES Reference Case values.

It may also be possible to carryout heat demand shifting more effectively in buildings where energy consumption reduction interventions cannot be implemented. For example, the amount of heat stored passively in the building due to its thermal mass could be increased before the DSP and outside of the grid peak period, so that the rate of heat loss during the DSP does not result in the space temperature dropping below 18°C. This was done by setting the thermostat to a higher value and by increasing the heating duration. Although these options facilitated heat demand shifting with slightly better thermal comfort, they increased the overall energy consumption, by 26% for heating duration increase from 9 hours to 16 hour, and by 11% for thermostat set point increase from 21°C to 23°C. However, there may be occasions where higher electricity use at the demand side is more acceptable if it allows peak demands to be shifted to off-peak times. An example of such an occasion is where the supply surpasses the demand due to excessive off-peak time production by intermittent distributed generators. Instead of wasting the excess electricity it could be used to re-charge the TES and heat the buildings to higher temperatures where possible, and use the stored heat during the peak time to achieve heat demand shift in time, thereby facilitate grid balancing. With the forthcoming smart grids, it is highly likely that interconnection of the grid and TES integrated heating system can be relatively easy achieved, and the heat demand shifting can be automated to make the above possible. As discussed previously, there is a large potential for energy storage in the UK housing stock using TES, and could provide a substantial grid balancing opportunities in the future. Therefore, it may be in the interest of the supply side to provide financial incentives to the households to install and integrate TES into heating systems, and increase future uptake.

It can be realised that three of the five parameters (heating duration, thermostat set-point and occupant numbers) are independent of the physical building structure and can be controlled and varied by different occupiers and over different times, both to increase or decrease energy use. Therefore, although they provide short term options for achieving certain heat demand shift for some thermal comfort need, it may not be appropriate to use them to determine the TES requirements for the long term. However, it was right to investigate and understand the potential impact of these parameters as they could easily change the effects of HDS on thermal comfort, heat shifted and the benefits provided for both the supply and demand sides as discussed. With this in mind, it can be concluded that the parameter that has a dominant overall effect on energy consumption and thermal comfort, and should be considered in selecting TES sizes, is thermal insulation.

7.7 A potential TES strategy for UK domestic buildings

The results presented in this thesis showed that there is potential for carrying out HDS in residential buildings using sensible TES. One of the main factors on which its uptake is likely to be dependent upon is demonstrating that the thermal comfort will not be degraded. As discussed previously, thermal comfort depends on three key parameters: 1) thermal insulation level of the buildings, 2) the DSP duration, and 3) the amount of heat to be shifted. In addition to showing that thermal comfort does not degrade below an acceptable level, the potential financial benefits in terms of electricity bill reduction, and cost of deployment in terms of space usage for housing the TES and capital expenses also have to be shown to be viable. Exploring the space usage and the initial installation costs of such systems was not an objective of this work and has not been given much consideration. However, in developing any future TES strategies for the UK, it is important to take both of these into account which could impact acceptability and uptake. For example, a TES system that is too costly may not be attractive enough for occupiers to invest in, and ones that take too much space or is too heavy could also prove unacceptable and/or unsuitable regardless of the heat they shift or bill reducing benefits they provide. It is reasonable to suggest that if such systems can be proven to be useful in future grid balancing challenges then the initial installation cost could be subsidised or even absorbed by the supply side stakeholders, thereby making the initial installation costs less relevant.

This work showed that relatively simple sensible heat storage could achieve heat demand shifts up to 4 hours in most buildings with the indoor space temperature remaining within an acceptable limit that ensures thermal comfort. Longer DSP duration could be more easily achieved with better thermal insulation. Where thermal comfort dropped, the DSP duration could be reduced to maintain thermal comfort within the acceptable limit. By controlling the DSP duration, occupants could decide how much heat they shift and the benefits they gain in terms of energy bill saving. Depending on the installed TES capacity, occupants can decide, on a day to day basis, how much energy demand they want to shift based on the thermal condition they can tolerate and benefit accordingly. This could be seen as a potential selling point for TES based domestic heat energy management system.

The following two tasks could be integrated into a TES rolling out strategy:

1) Identifying buildings which are suitable for TES.
2) Determine a suitable TES system specification and operational parameters.

The results showed that low thermal insulation increases the energy consumption making TES less effective in terms of the DSP achievable without degrading thermal comfort. Insulation in buildings according to 1980 building regulation level (see Table 3.3) could increase energy consumption by around 17.5% compared to the 1990 level, and also reduce thermal comfort for a given DSP and storage capacity (see Figure 6.37 & 6.38). The negative impact it has in both energy consumption and thermal comfort areas could make the TES, if installed in such buildings, unusable or/and unacceptable to the occupants. Taking these into account, it is suggested that the thermal insulation of buildings is raised to at least 1990 or later level prior to installing TES. Alternatively, those buildings with at least 1990s level of thermal insulation could be selected as potential candidates for TES interventions. Other checks that could be performed includes ensuring that buildings already have or have the potential to be fitted with gas based wet central heating systems with hot water storage tanks, as they are required in TES based heat demand management system simulated in this work.

It was seen in Section 6.3 that greater amounts of heat can be shifted with bigger TES size, in larger buildings and with longer DSPs. But as illustrated in Figures 6.9, 6.10 and 6.11, buildings in which large energy shifts are possible also provide low thermal comfort. Installing large TES tanks might not be feasible or appropriate in some buildings. Therefore, a balanced and more appropriate option might be to consider the thermal comfort as the primary requirement based on the minimum temperature acceptable to the occupants, and then to select the TES size based on the DSP duration and/or heat shift they would prefer to achieve. The results presented in this thesis could be used to do this. The flow chart in Figure 7-1 shows some potential pathways that could be followed in selecting a TES size for a certain building insulation level, occupied floor area, built form and a DSP, such that a heat demand shift is achieved while ensuring thermal comfort. For example, as shown by the blue pathway, a building that meets the selection criteria as discussed above, that has a 1990 building regulation level of thermal insulation, floor area of 70m^2, of detached built-form and in which a TES size of 0.5m^3 is installed could provide a DSP of 4 hours. The red, purple, yellow, black dashed, pink, brown and green lines show the pathways possible for other respective building insulation, size, built-form and target DSPs shown. The chart in Figure 7-1 only illustrates the exact value of TES that could be used for the specific floor size and DSP values shown. Also, it assumes that the building occupancy and operational conditions are as per the assumptions made during this research. Many other pathways are also possible and can be determined from the results presented in this thesis.

The findings presented in this thesis could be used by policy makers to target groups and quantity of buildings for installing TES to achieve a certain combined grid peak load shifting capacity. For example, if a 10GW of peak load was to be shifted to off-peak times, the pathway shown by the black dashed lines (Figure 7.1) could be followed to determine that 150m^2 detached buildings with 1990 thermal insulation, and 0.5m^3 TES tank could achieve a 2 hour demand shift, with an average heat demand shift of 20.86kWh (from Table 6.3 or Figure 6.9b). This implies an energy demand shifting of 10.43kWh per dwelling in one hour which means curtailing 10.43kW of electricity load. Therefore to achieve 10GW housing stock combined peak load displacement, approximately 958,773 homes of the same type and operational conditions could to be fitted with the same level of TES. With this level of TES these dwellings could provide a combined mean heat demand shifting capacity of approximately 20GWh per day without degrading thermal comfort.

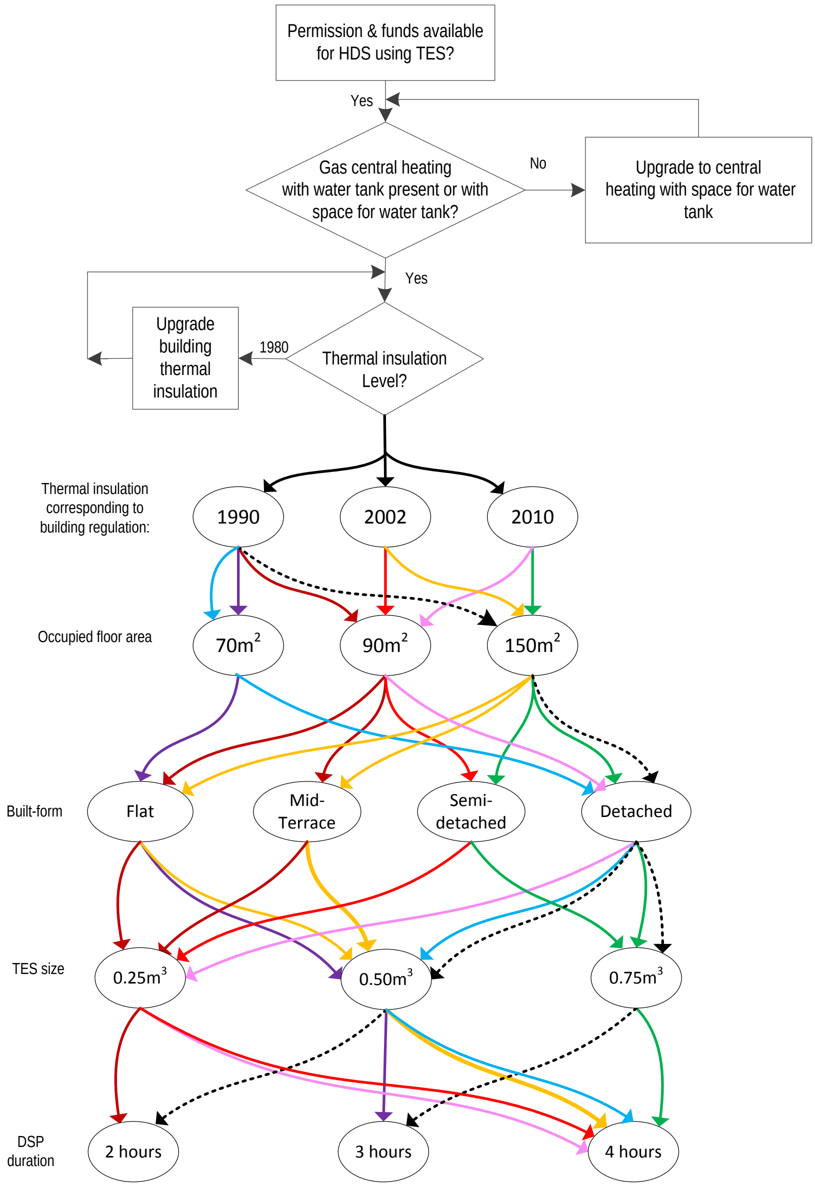


Figure 7-1. Flow chart illustrating some possible pathways which could be followed in selecting a TES size (assuming a water storage temperature of 95°C) for a given building thermal insulation, size and DSP, that could allow the desired HDS to be achieved without degrading thermal comfort.

7.8 Summary

This chapter contained discussions of the results presented in the Chapters 4 to 6. The results of the simulations performed to explore the thermal and energy consumption characteristics of common UK residential buildings, represented by the 12 Base Case models, were first discussed. The effects of varying thermal insulation, heating duration, thermostat set-point, location and number of occupiers, found in the UK housing were discussed.

The implications of not heating the homes, during the grid peak period, in terms of thermal comfort and energy use, were discussed followed by the results generated when HDS over three fixed DSP were simulated with a TES Reference Case level of thermal storage. The implication of varying TES capacity and key energy influencing parameters on thermal comfort, power and energy consumption were discussed. Based on the results, one possible strategy that could be followed in rolling out HDS in residential buildings using sensible rechargeable TES was presented.

8 CHAPTER EIGHT: CONCLUSIONS AND FURTHER RESEARCH

8.1 Introduction

This chapter presents a summary of the work carried out to address the original research objectives, the main conclusions drawn from the research and its contribution, limitations of the findings and recommendations for further work. The chapter is arranged as follows:

Section 8.2: Addressing the original objective: Summarises the work undertaken and how the original objectives of the research were addressed.

Section 8.3: Main conclusions: Provides details of the main conclusions drawn from the research.

Section 8.4: Contribution to knowledge: Discusses the contribution to knowledge arising from the research.

Section 8.5: Limitations of this work and recommendations for further research: highlights the main assumptions made during this research and the limitations which might apply to the findings, and proposes further studies that could be carried out to minimise and/or eliminate the limitations, and further advance the knowledge and understanding of the relevant subject areas.

8.2 Addressing the original objectives

Six objectives were devised to enable the aim of the research to be achieved (See Chapter 1). These objectives were addressed and attained as discussed below:

Addressing Research Objective 1:

(To review the potential role of domestic scale thermal energy storage in the UK energy system, and its relevance to the national energy policy.)

This objective was addressed through conducting a literature review which established that energy storage is an important and an integral part of the UK energy and greenhouse gas emission mitigation policy. The 2050 energy and climate change targets assume large scale electrification of domestic heating and transport (e.g. electric vehicles), and greater uptake of intermittent distributed generation. There is evidence showing that the UK policy and drive towards achieving the 2050 targets are weakening although the targets themselves remain relatively unchanged. Energy storage could be used to mitigate these challenges by providing backup capacity and by enabling intermittent generators to be integrated into the electricity network. The current state of electricity supply and demand was examined and established that residential building scale TES could have a significant impact in the minutes, hours and days challenge categories, in a daily demand levelling role, to decouple the heating energy demand and supply timings. TES could enable heating energy demand management, through demand shifting, and allow more effective use of the locally generated renewable energy, minimising the variation between peak and off-peak electricity demand.

Addressing Research Objective 2:

(To review the academic and non-academic literature relating to: the thermal performance and energy use characteristics of residential buildings in the UK; the TES technologies which are suitable for domestic heat demand management application; and the modelling and simulation of TES for heat demand management in domestic buildings.)

To address this objective, academic and non-academic literature was reviewed which showed that rechargeable TES could be an effective tool in decoupling the heating energy demand and supply. It highlighted that sensible, latent and thermochemical heat storage methods have the potential to be used in residential buildings although sensible TES using water is more widely used and well proven, cheap, but has relatively low storage capacity per unit volume.

Literature highlighted that domestic heating load profiles are mainly dependent on the occupancy characteristics of the households and the thermal performance of the buildings. Both of these parameters determine the indoor temperature profile and DHW consumption, which should be represented in a domestic heating and thermal storage model. It was suggested that a thermal store capable of storing 100kWh is considered sufficient to heat a domestic building for one day, and that it is feasible to achieve a 3 hour heat demand shift with a thermal storage capacity of 21kWh, in a 1990’s dwelling of 100m^2 floor space, and with an outside ambient temperature of -3℃. A research gap, in the area of holistic study of TES in domestic settings with the interaction of the occupants, was seen to exist. In particular, it highlighted a lack of in-depth and higher time resolution modelling of small scale TES, within the domestic built environment and the operational surroundings. Literature indicated that a wide scale adaptation of domestic TES could provide considerable benefit for the electricity supply side stakeholder community, by deferring construction and upgrades of generation, transmission and distribution facilities (Nair et al., 2010).

Addressing Research Objective 3:

(To develop dynamic building, heating and TES system models to simulate the thermal and energy performance of residential buildings and the effects of heat demand shifting using TES in UK homes.)

This objective was addressed by developing 12 building archetype models in TRNSYS. The models consisted of detached, semi-detached, mid-terrace and purpose built flat built-forms, and occupied floor sizes of $70m^2$, $90m^2$ and $150m^2$. The building archetypes were arranged to represent thermal insulation level corresponding to the 1990 building regulations recommendations. A wet central heating system with electricity being the energy source was integrated into the building models. A set of occupancy and operational conditions typically found in the UK were developed and applied to form 12 Base Case simulation scenarios. The models were set to output predictions of the occupied space temperature, power and heat energy demands.

Upgraded versions of the models were created to enable the impacts of five main energy consumption influencing parameters to be explored. These five parameters were: thermal insulation equivalent to 1980, 1990 (Base Case), 2002 and 2010 building regulation; locations of Gatwick (Base Case) and Aberdeen in the UK; heating duration of 6, 9 (Base Case), 12 and 16 hours per day; thermostat settings of 19°C, 21°C (Base Case) and 23°C, and number of occupiers of 1 person and 3 persons (Base Case) per household. The models were upgraded further to include cylindrical sensible TES tanks. The size of the TES tanks were $0.25m^3$, $0.5m^3$ and $0.75m^3$, and hot water storage temperatures used were 75℃ and 95℃. These were arranged such that the stored heat could be pumped into the buildings during three fixed DSPs (2, 3 and 4 hours from mains grid peak period of 17:00 to 21:00) to enable the peak time heat demand to be shifted to an off-peak period (00:00 to 07:00).

Addressing Research Objective 4:

(To simulate the winter time heat demand and thermal performance characteristics of common UK home types and how they are affected by varying building fabric thermal insulation, occupancy and operational conditions.)

This objective was addressed by simulating common domestic buildings with typical occupancy and operational conditions, represented by 12 Base Case scenarios. Predictions of heat and power demand and daily occupied space temperature profiles were generated for 60 winter days from 2nd of January in 1 minute intervals. The data was analysed in Microsoft Excel to extract information corresponding to six metrics relating to the indoor space temperature, power and energy demands. Predictions of how the space temperature, power and energy consumption are affected by changes in the thermal insulation, physical size, location, occupancy and operational conditions were produced. Heating energy cost predictions were generated based on the energy consumption figures and the currently available electricity price tariffs.

Addressing Research Objective 5:

(To simulate heat demand management capabilities in domestic buildings using TES, to shift heat demand from the grid peak times to the grid off-peak times. To assess the benefits and trade-offs and how these change with varying TES sizes, building archetypes, operational conditions and occupancy scenarios.)

This objective was addressed by investigating the occupied space temperature, heating load and energy consumption impacts generated when: a) heating was prevented during three fixed DSPs during the evening occupied hours, without the use of any TES back-ups (Zero TES Case); and b) the heat demand from the same fixed DSPs was shifted to off-peak times using thermal storage referred to as 'TES Reference Case', consisting of a 0.25m^3 TES tank and a water storage temperature of 75°C. The 12 Base Case building scenario options were used in both cases. Potential heating energy cost impacts were explored based on the currently available Time-of-Use Economy 7 electricity price tariff. The results allowed comparison of the impacts and benefits to be made, for example in terms of thermal comfort degradation and energy cost savings.

Parametric analysis was carried out to explore and understand the impacts of varying the TES capacity (by using three tank volumes and two water storage temperatures) and five key energy consumption influencing parameter values (thermal insulation, geographical location, heating duration, thermostat set point and number of occupiers). The findings helped identify the levels of thermal comfort degradation likely in the occupied spaces, given the variations in thermal insulation, occupancy, operational scenarios found in UK homes, and for varying TES capacity.

Achieving Research Objective 6:

(To identify and recommend further research, and recommend domestic thermal energy storage strategy to aid policy development to enhance the security and resilience of the UK energy system.)

This objective was addressed by analysing the results to gain a better understanding of the way temperature, power and energy consumptions behave during the winter days due to the variations inherent in the UK residential housing system. These included built form, size, thermal insulation, occupancy, operational circumstances and external weather conditions. Results were analysed to highlight and quantify the potential impacts of the key energy consumption influencing parameters in 12 Base Case building archetypes, so that interventions could be applied in a targeted and measured manner to minimise energy consumption. The variations in daily power and energy demand profiles resulting from the building system components changing were explored. The extent of their influence in the different building archetypes were identified, so that measures can be put in place before TES systems are installed to improve their effectiveness in terms of, for example, ensuring larger DSPs without degrading thermal comfort. Based on the results a potential strategy that could be followed in selecting buildings for HDS intervention using sensible TES systems, and some sample pathways which could be followed in selecting a suitable TES size, was presented. The limitations of this study have been discussed and recommendations and suggestions for further research are presented in Section 8.5.

8.3 Main conclusions

This thesis presented predictions of heating energy and power demands, and occupied space temperature characteristics, determined through dynamic simulation in TRNSYS, of 12 Base Case building models. It also presented the results of HDS simulations performed to transfer the heat demand in three fixed DSPs, from the grid peak time to a grid off peak time, with sensible TES system. The simulations were performed with a set of typical occupancy and operational conditions for 60 winter days from 2nd January, and in one minute intervals. The thesis also presented the findings of parametric analyses performed to determine the impacts and benefits of varying TES system capacity, and five key energy consumption influencing parameters changing in line with values found in the housing stock. The main conclusions drawn are:

- The energy consumption for space and water heating in buildings, due to changes in built-form, size and weather conditions, vary significantly. The overall daily (00:00-24:00) and grid peak time (17:00-21:00) energy consumption predictions range from 36.8kWh to 159.7kWh and 7.8kWh to 58.8kWh respectively. This indicates the potential challenges, in terms of additional demand on the grid, and the opportunities that could exist, in terms of shifting the extra demand to off peak times to minimise grid peak, in the future with electrified residential heating.

- Built form has a significant impact on energy consumption. Semi-detached, mid-terrace and flat built-forms consumed 7%, 13.8% and 22.7% less energy respectively compared to the detached built-form, with an identical thermal insulation, operational and occupancy conditions. The energy used during the grid peak hours vary for different built-forms in a similar manner.
- Thermal insulation has a considerable impact in energy consumption. Improving it from the 1980 building regulation level to 1990, 2002 and 2010 level predicted a reduction in energy consumption of 15.0%, 26.8% and 35.0% respectively in an average sized detached building with typical (Base Case) occupancy and operational condition. Thermal insulation improvement to the later building regulation standards by itself could reduce the peak time energy demand and thus the peak time grid load. Therefore, interventions for improving the thermal insulation level in the housing stock are recommended.
- Avoiding heating during the grid peak hours without TES significantly degrades the space temperature to levels which could be unacceptable and harmful to the occupants. A two hour heating avoidance from 17:00 to 19:00 has been predicted to reduce the mean (of all built-forms and occupied floor sizes) space temperature in that period to around 11.9°C assuming that the dwellings are insulated to the 1990 building regulation level. Future electricity supply structures with variable ‘time-of-use’ price tariffs and high peak time prices, which could encourage vulnerable occupants such as the elderly and those in fuel poverty to avoid heating their homes during the peak hours, could present health risks.
- Heat demand shift in buildings with 1980 building regulation level of thermal insulation causes the space temperature to degrade too quickly due to the greater heat loss, and makes the TES less effective by reducing the demand shift period achievable per unit TES size. Therefore, it is recommended that thermal insulation upgrades to the latest, or at least to the 1990 (Base Case level) building regulation level is achieved prior to carrying out TES deployment activities and heat demand shift interventions.

- A 0.25m^3 TES system and a water storage temperature of 75°C could be used to achieve a two hour DSP with a 60 day mean thermal comfort value of 100%, in all built-forms up to a floor size of 90m^2, assuming the Base Case thermal insulation and occupancy and operational conditions apply. The minimum space temperature over the 60 days however could drop below 18°C thermal comfort limit for all built forms, to a lowest predicted value of 14.8°C for the detached built-form. Using a water storage temperature of 95°C could raise the 60 day minimum space temperature by around 1.5°C for all built forms.
- A 0.75m^3 TES system and a water storage temperature of 95°C could achieve a three hour DSP while ensuring that the temperature during the DSP remain higher than 18°C thermal comfort limit, in all built-forms and floor sizes considered. This is assuming the Base Case thermal insulation and occupancy and operational conditions apply. The same TES size and water storage temperature could provide a 4 hour DSP in all built-forms and floor sizes with 100% mean thermal comfort, but the 60 day minimum space temperature could fall below 18°C thermal comfort limit, to a predicted worst case value of about 16.5°C in the 150m^2 detached dwelling.
- Thermal insulation has been found to be the most dominant factor that could affect the effectiveness of the TES and allow larger DSP to be achieved per unit volume of the TES. A 4 hour HDS with 100% thermal comfort could be obtained in all buildings with 90m^2 floor area with a 0.25m^3 tank and a water storage temperature of 75°C (TES Reference Case Case) provided that the thermal insulation is as per 2010 building regulation.

8.4 Contribution to knowledge

The aims and objectives of this study have been largely met as described above. Achieving the objectives required carrying out tasks pertinent to the range of inquiries prescribed by the research questions set out in Section 1.5. and Section 3.2. The findings, which provided answers to the research questions, culminated into knowledge that advances our understanding of the subject area and fills in knowledge gaps identified during the literature review. The knowledge gained could be beneficial to the supply and demand side stakeholders, the relevant policy development and implementation authorities, and other researchers looking to further advance the understanding of the subject area through, for example, carrying out work as discussed in the recommendations for further research, section 8.5. The knowledge gained includes:

1) Recognising how daily and grid peak time energy consumption vary for different building types, thermal insulation levels, sizes and operational conditions and occupancy scenarios found in the UK housing system, over the coldest period in the winter when heat energy consumption is at its greatest. This knowledge could be used by relevant authorities to target energy efficiency improvement measures to improve energy efficiency and reduce CO_2 emission from the residential heating, and maximise 'return on investment' in terms of the energy use reduction achieved against cost.

2) Demonstrating the potential heat demand shifting ability in buildings of numerous physical, thermal, occupancy and operational conditions. This is the first study of its kind that places particular emphasis on the impacts and benefits for the end users. It is the end users of the buildings whom, through their acceptance or rejection of HDS using TES as presented in this thesis, could ultimately decide the scale of its uptake in the housing stock, and the overall impact it has in being able to use it to addressing the future short terms peak time electricity demand and supply matching challenges, through demand shifting in residential buildings.

3) The ability to determine the range of DSPs and amounts of heat which could be shifted to off-peak times, while ensuring thermal comfort, given the range of variables in the housing stock as mentioned above.

4) The ability to determine the TES size necessary to achieve a certain HDS or a DSP, in the presence of the variables mentioned above, and a thermal comfort level which is acceptable to the occupants.

8.5 Limitations of this work and recommendations for further research

The limitations which apply to this work have arisen due to the modelling nature of the research which required certain assumptions to be made to ensure focus. The assumptions can be categorised as: 1) General assumptions, 2) model development assumptions and 3) occupancy and operational assumptions. These are discussed below together with recommendations for further research that could be carried out to minimise or eliminate the limitations, and to further advance the understanding of the relevant and/or related issues.

General assumptions

This study assumed that future decarbonisation of domestic building sector will include electrification of residential heating, which could be achieved through the use of HPs and resistance element electrical heating. To explore the worst case scenarios, only resistance element water heaters with power ratings of 20kW, 25kW and 30kW were used, resulting in large peaks in the load power during the occupied hours. As previously discussed, future heating electrification is likely to be achieved through the use of a combination of HPs (with COP mostly between 2 to 3, and possibly higher with advancement in HP technology) and resistance heating, thus reducing overall effective load (Wilson et al., 2013; Hepbasli et al., 2009). Therefore the power demand predictions presented in this thesis cannot be considered representative of all dwellings with electrical heating. Producing more generalised power demand predictions is an important and a recommended area of further research. These could be done by integrated HPs into the building models as the heat source. Simulations could be performed with varying COP values. The results could then be combined with those presented in this thesis, to explore how electric heating penetration levels in the housing stock with resistance heating, HPs with varying COP values and HDS with rechargeable TES, could affect the grid loads and potentially create electricity supply and demand matching, and distribution challenges. For example, given the relatively large winter demand for heat in the UK compared to electricity (Wilson et al. 2013), the current off-peak period (12am to 7am) may become the new peak period if the heat demand of the DSP is moved to the off-peak period throughout most of the UK building stock, especially if low COP heating systems are used. Where resistance element heating is used, the water heater control strategy could be changed to proportional control instead of on-off control, which could prevent the electricity load peaking to the power rating of the water heater.

In addition to the evening heating period (17:00 to 21:00) on which this work is focused, the grid load during the morning heating period (for example 07:00 to 09:00) could also peak and create supply and demand balancing challenges. Exploring and understanding the potential consequences, of a large scale shift to electric heating, in this occupied period is equally important and should be studied further. A solution to minimising the load peaks during both the morning and evening occupied hours might be to store heat in the TES during all times of low electricity demand at the grid. The release of stored heat into the space could be combined with heating from the grid, spreading the stored heat use over both the morning and the evening heating periods, and replenishing the store as and when the grid load becomes low. This could mean shifting bulk of the heat demand to off-peak times and spreading the remaining demand over an extended demand shift period, resulting in a more uniform heating load curve. Intelligent control of the TES charging and discharging, where the parameters such as real-time grid load, external and internal temperatures and building heating patterns are taken into account, could make this possible. Individual household heating load curve could be manipulated so that when combined with the existing electricity load profile, resulting from the use of other electrical equipment such as appliances as explore by Yohanis et al., (2008), a levelling effect of the overall load applied to the grid is realised. The models developed during this research, with further enhancement, could enable exploration and understanding of these issues and scenarios, which is essential for formulating a viable future domestic heat demand management strategy.

This work does not take into account installation cost and space requirement for housing the TES system. It will be often impractical, in terms of the physical size, and/or costly to install TES tank in some dwellings. Some occupants may prefer to use the space, required for housing the TES, as part of the living space. Demonstrating an economic benefit, or a lack of it, for the household, may be a way of enabling informed decision making in terms of uptake at the demand side. These are practicality and preference issues which are important, and it is suggested that research is focused in this area.

This study only considered sensible heat storage using water, which although is comparatively simple and low cost, is bulky and does not always provide the best storage capacity per unit volume (Hadorn, J. 2007; Pinel et al., 2011; Dincer, 2002).

Latent heat storage based TES using Phase Change Materials (PCM), can store 5 to 14 times more heat per unit volume compared to that of sensible heat storage (Sharma et al., 2009; Hadorn, J. 2007). This technology could be used to increase the heat capacity and reduce the physical size of the TES systems. However, lower thermal conductivity of PCM makes them less suitable for applications where rapid heat transfer rate is needed (Huang et al., 2011). Complicated heat exchange and heat transport mechanisms are often required which could add to the cost. Nevertheless, PCM based TES provides a real possibility of enhancing the energy storage capacity per unit volume, which could make heat demand shifting more effective, and needs to be investigated with a UK domestic building heat demand shifting context.

Model development assumptions

Some limitations in this work have resulted from the assumptions carried out during the modelling and simulation processes. Some of these assumptions relate to the representation of the housing stock in the modelling environment. Twelve building archetypes consisting of: detached, semi-detached, mid-terrace and flat built forms and floor sizes of $70m^2$, $90m^2$ and $150m^2$ were used in this study. Four thermal insulation levels corresponding to the 1980, 1990, 2002 and 2010 building regulation recommendations were also used to make up a total of 48 different building models. Simplified building representations were created by excluding features such as kitchens extensions, conservatories and bay windows which are often found in UK. Heat loss mechanisms such as, thermal bridging, imperfect construction practices resulting in higher U-values and forced ventilation via opening windows were not taken into account. Also, the adjacent properties, in the case of the semi-detached, mid-terrace and flats, were assumed to be identically heated, which will not always be the case is reality. These could add to the overall heat loss of the buildings (Lomas K. J., 2010; Lomas K. J., 2009; Beizaee, A., 2015; Lowe, et al., 2007), and reduce thermal comfort during the DSP. However, the simplifications mentioned above are not expected to affect the results presented in this thesis significantly. As demonstrated by Taylor et al., (2013) and Korolija et al., (2013), simplified models can produce similar results (within 10%) compared to those that have more detailed features, but at a much reduced model development and simulation time. To create a better representation of the housing stock, future work should include creating greater number of building models with more detailed building features, and take into account heat loss mechanisms mentioned above.

The TES tanks were modelled to have only six fully mixed stratified zones. Modelling the TES tanks with a larger number of fully mixed thermal zones is recommended in the future which could mean a better representation of the real world system. The impact of this on the results presented in this thesis however is likely to be insignificant. For example, there is virtually no difference (+0.004%) in the maximum amount energy stored in a 0.75m^2 TES tank with a 95°C water storage temperature when modelled with 18 thermal zones as opposed to 6 thermal zones.

Occupancy and operational assumptions

This work assumed household sizes of three persons (in line with mean household size) and one person for all sizes of buildings. In reality larger dwellings, especially the 150m^2 ones are likely to be occupied by more than three people. Although, household size change from one to three persons showed relatively small thermal comfort and energy consumption impact (as discussed in Sections 4.5 and 6.4) it may change with, for example, 5 or 6 persons. As DHW and space heating both utilise heat from the TES system during the demand shift period, larger number of occupiers could mean less heat for space heating. However, this is unlikely to affect the results presented in this thesis significantly for the reason that energy use per person for DHW is considerably small compared to space heating.

The DHW draw rate was assumed to be identical at 5.9lt/person/hour throughout the occupied hours for reasons as discussed in Section 3.5.7. In reality this will not always be the case. It could be argued that the DHW draw rate can be considerably higher during some demand shift periods when, for example, occupants are having a shower or a bath. It could also be argued that occupants may decide not to carry out high energy use activities during the demand shift periods when HDS using TES is active, knowing that it could affect their thermal comfort level, or increase their electricity bill should they decide to override HDS and use the grid to meet their heat demand. In such a scenario the DHW draw rate may be less than that considered in this work. It is reasonable to assume that both scenarios will exist in reality. Therefore it is suggested that simulations are performed with the DHW rate set to both extremes during the demand shift period, and generate predictions of its impacts and benefits.

Both the ground floor and the first floor thermal zones in the dwellings were heated simultaneously and without individual temperature controls. This meant heating the first floor zone during the grid peak hours even though it is not normally occupied during that period, which lead to using up the stored heat quickly and reducing the demand shift period achievable. One possible way the demand shift period could be extended is by applying zonal temperature control, where only the rooms that are occupied at a certain time period are heated. One option could be not to heat the first floor zone at all or to a lower temperature during the grid peak period. This could allow more heat to be used in the ground floor zone to ensure a better thermal comfort, or a longer demand shift period. Beizaee (2015) demonstrated that zonal temperature control can be implemented through the use of electrically controlled TRVs and zone specific thermostats. He showed that an annual heat energy saving of around 12% is possible. Given the heat energy saving and demand shift period increasing possibilities, zonal temperature control and HDS using sensible rechargeable TES could be a great combination, in which further research should be focused. They could enable more effective heat demand management in residential buildings that provide options for addressing short term electricity supply and demand matching challenges, which could be present in the future where electric heating is wide spread.

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Appendices

Appendix A: Dwelling thermal zone and heat capacity details

Table A1. Thermal zone sizes and heat capacity values used in the models.

		Ground floor zone				First floor zone				Roof zone				
Built form	Archetype ID	Floor area (m²)	Height (m)	Volume (m³)	Air furniture thermal capacity (kJ/K)	Floor Area (m²)	Height (m)	Volume (m³)	Air furniture thermal capacity (kJ/K)	Floor Area (m²)	Max Height (m)	Volume (m³)	Air/furniture thermal capacity (kJ/K)	Orientation
Detached	Det70	35	2.60	91.00	601	35	2.60	91.00	601	35	3.85	49.00	65	North facing
	Det90	45	2.60	117.00	773	45	2.60	117.00	773	45	3.85	64.00	85	North facing
	Det150	75	2.60	195.00	1288	75	2.60	195.00	1288	75	3.85	107.00	141	North facing
Semi detached	SDet70	35	2.45	85.75	566	35	2.45	85.75	566	35	3.85	5.80	8	North facing
	SDet90	45	2.45	110.25	728	45	2.45	110.25	728	45	3.85	9.80	13	North facing
	SDet150	75	2.45	183.75	1214	75	2.45	183.75	1214	75	3.85	22.50	30	North facing
Mid terrace	MTer70	35	2.45	85.75	566	35	2.45	85.75	566	35	3.85	43.75	58	North facing
	MTer90	45	2.45	110.25	728	45	2.45	110.25	728	45	3.85	55.00	73	North facing
	MTer150	75	2.45	183.75	1214	75	2.45	183.75	1214	75	3.85	93.60	124	North facing
Flat	Flat70	70	2.55	178.50	1179									North facing
	Flat90	90	2.55	229.50	1516									North facing
	Flat150	150	2.55	382.50	2526									North facing

Appendix B: Water heater power rating and its effects

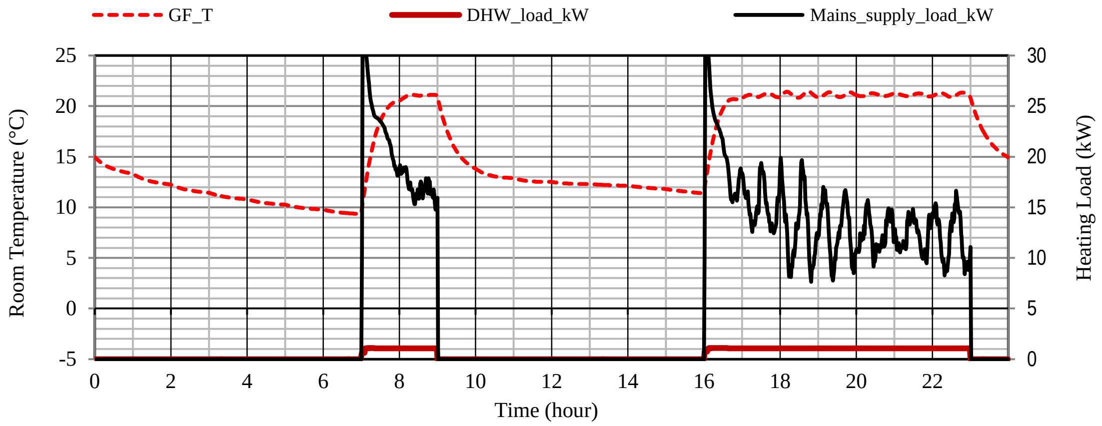

Figure B1. 60 day average indoor temperature profile for Det150 building archetype with a 1980s thermal insulation, with a 30kW water heater

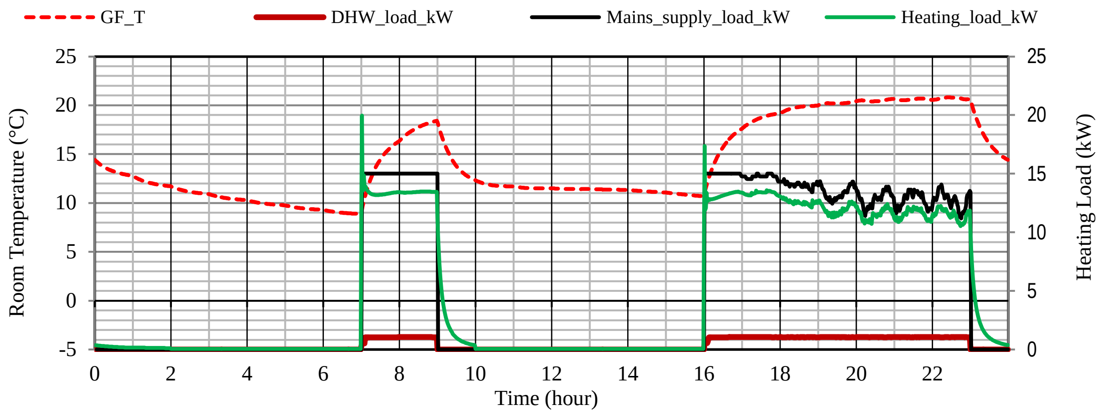

Figure B2. 60 day average indoor temperature profile for Det150 building archetype with a 1980s thermal insulation, with a 15kW water heater

Appendix C: Impact of thermal insulation on space heating only energy consumption by floor size

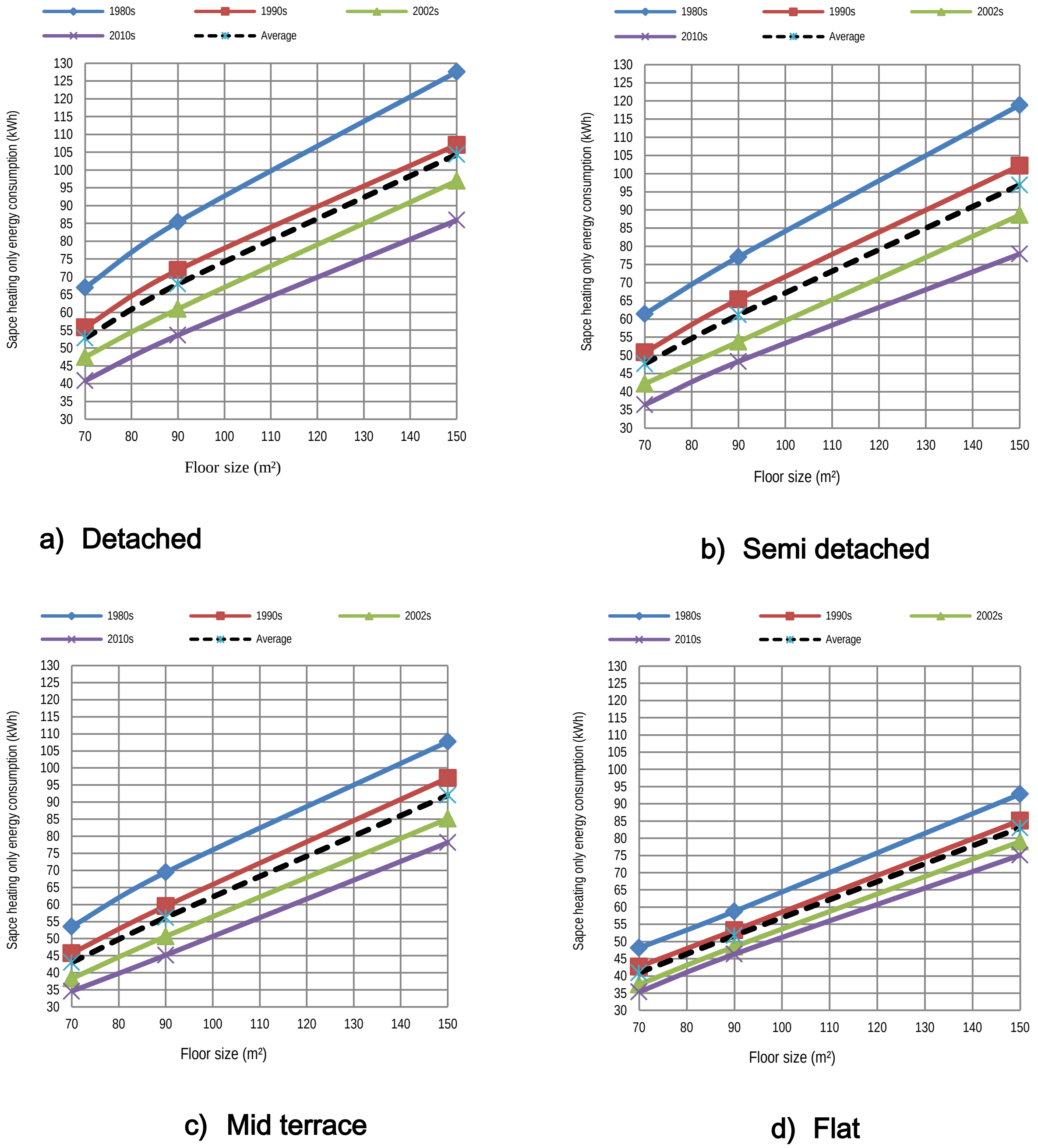

Figure C1. Graphs illustrating the relationship between energy consumption (for space heating only) and floor size, and how it is affected by thermal insulation level corresponding to 1980, 1990, 2002 and 2010 building regulation, for the built-forms: a) Detached, b) Semi-detached, c) Mid terrace and d) Flat. The mean of all four thermal insulation levels is also shown.

Appendix D: Impact of DSP duration on energy shifted and space temperature

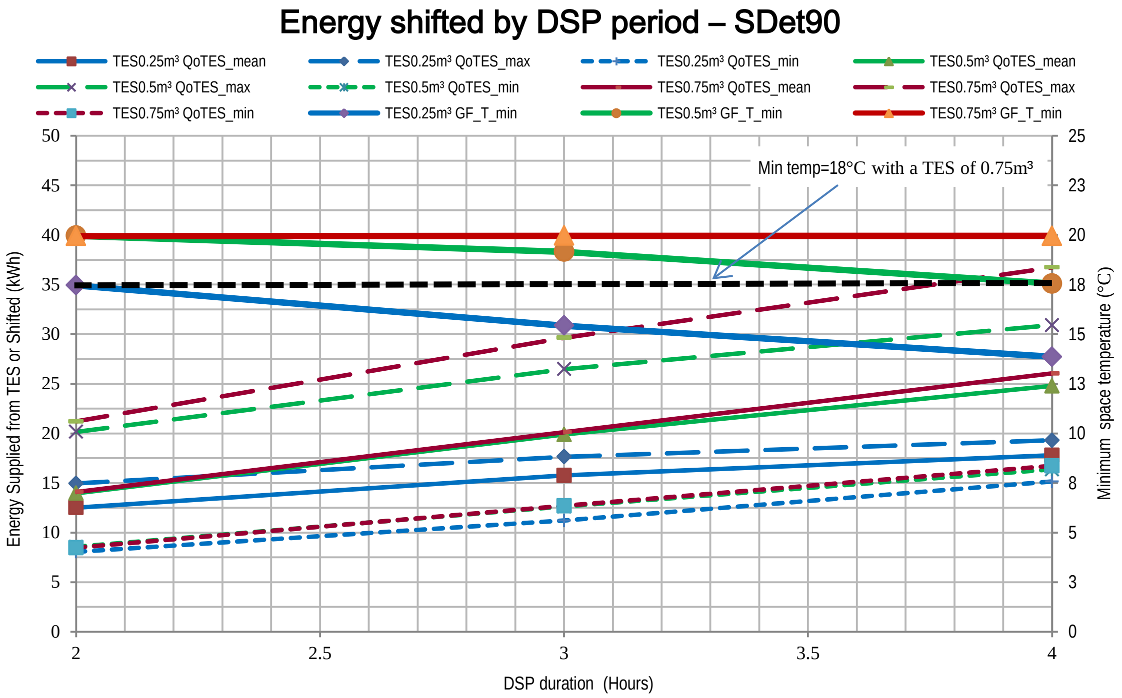

Figure D1. 60 day Mean, minimum and maximum Energy shifted in SDet90 by DSP duration with 0.25m³, 0.5m³ and 0.75m³ TES size and a 95°C water storage temperature.

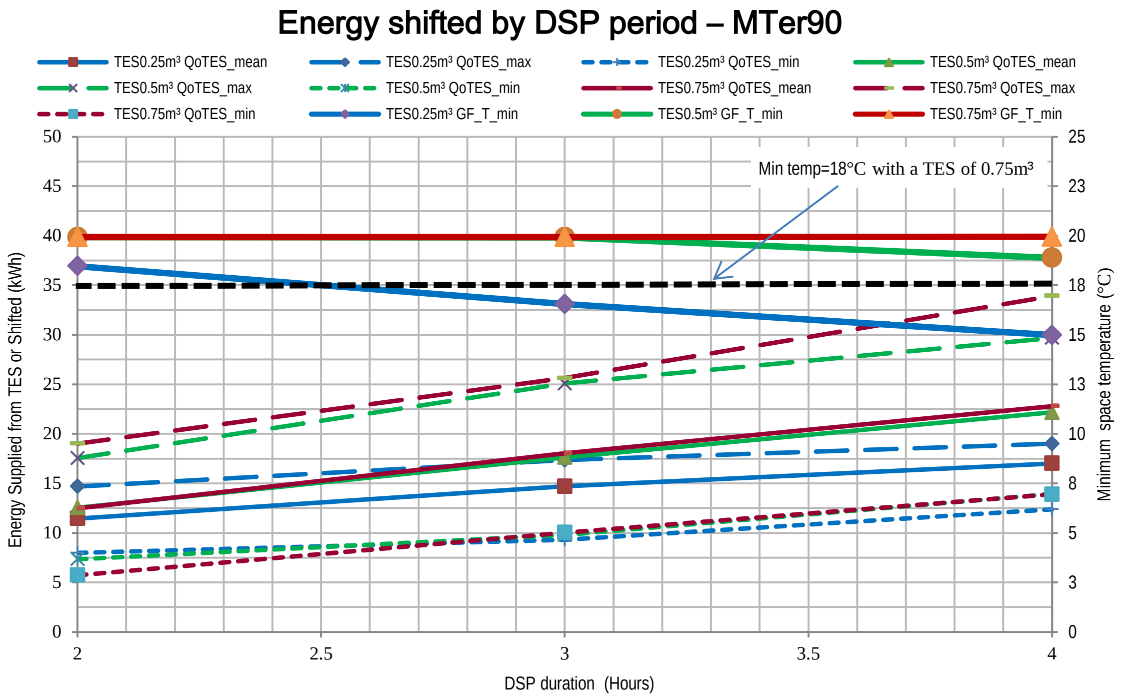

Figure D2. 60 day Mean, minimum and maximum Energy shifted in MTer90 by DSP duration with 0.25m³, 0.5m³ and 0.75m³ TES size and a 95°C water storage temperature.

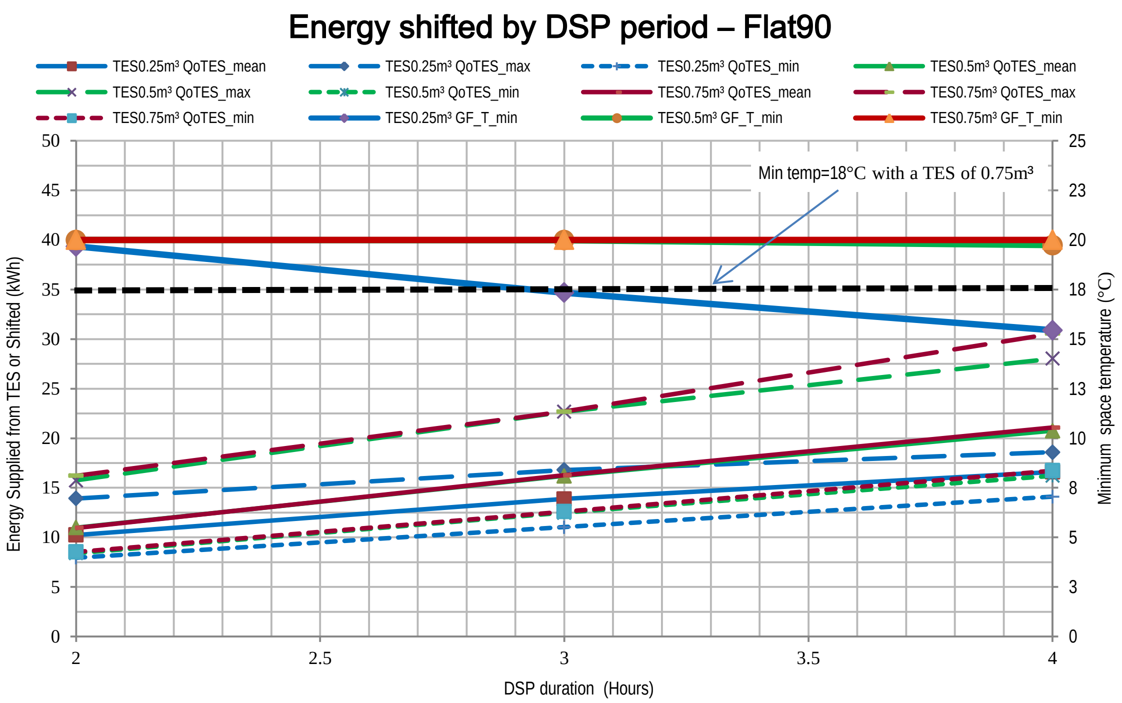

Figure D3. 60 day Mean, minimum and maximum Energy shifted in Flat90 by DSP duration with 0.25m³, 0.5m³ and 0.75m³ TES size and a 95°C water storage temperature.