# The heating performance of air-to-water-heat-pumps in the retrofit of domestic building stock

by

Paraskevi Vatougiou

**Doctoral Thesis**

Submitted in Partial Fulfilment of the Requirements for the Award of Doctor of Philosophy of Loughborough University

November 2020

# Abstract

Mitigating climate change necessitates the adoption of a clear decarbonisation pathway, with the residential building sector being a priority for the UK Government. To date, the high heating demand of existing domestic buildings constitutes a significant barrier to the smooth transition to a decarbonized future. The deployment of low-carbon heating technologies as well as the upgrade of building fabric is considered to be imperative in order for the UK to achieve the target of net-zero greenhouse gas emissions by 2050. In this direction, the UK Government has recognised the high potential of targeting towards the large-scale electrification of domestic heating, which will come in parallel with the increasing share of renewables in electricity generation. In this context, electrically driven Air-to-Water-Heat-Pumps (AWHPs) are considered to be a very promising alternative to fossil-fuel based heating systems. Although the current uptake of heat-pumps is low in the UK compared to other European countries, the UK heat-pump market is expected to grow within the next few decades. Following the suggestions of the Committee on Climate Change (CCC), the connection of new-built UK houses with the gas grid will be banned by 2025, with this being a significant step to phase-out the installation of gas boilers. Nevertheless, apart from new-built houses, CCC mentions that retrofitting the existing building stock is a major UK infrastructure priority in order to tackle climate change.

The thesis describes the development of a methodology to assess heating system retrofit linked with fabric retrofit targets for dwellings using building performance simulations at the stock level. The developed methodology is generic and directly applicable to any housing stock within the UK context. For the case of this thesis, the effectiveness of AWHPs to be used as a retrofit heating solution is explored across the range of 756 unique house archetypes, which are selected to represent the housing stock of the North-East region of England. The data used to model the selected housing stock is derived from the national English Housing Survey (EHS), with the included house archetypes covering a wide range in built form, size and age of construction, the age of construction, in particular, resulting in various levels of fabric insulation and states of repair. The constructed house models are suitable to be studied using the

EnergyPlus dynamic simulation engine and the adopted modelling approach is verified through an inter-model comparison technique. An AWHP model coupled with auxiliary electric heating is integrated in each house archetype to meet its heating demand throughout the entire heating season, with the AWHP model being representative of actual AWHP systems that are available in the UK market. The heating performance of the AWHP retrofit is assessed across the range of the modelled housing stock for both current and future weather scenarios, the future weather scenarios incorporating probabilistic climate change projections for 2050 and 2080 under different carbon emissions scenarios. A novel graphical representation of the simulation outputs is employed aiming to make the results communicable to consumers, stakeholders and policy-makers and support retrofit decision-making. The results obtained from this thesis allow for the distribution of the system's energy use and overall effectiveness, level of under-heating and degree of thermal discomfort to be identified across the stock. In addition to that, as a result of this novel visualisation way of the simulation outputs, the AWHP retrofit can be assessed in conjunction with fabric retrofit targets for dwellings under current and future heating requirements.

The results reveal that the simulated Seasonal Performance Factor (SPF) of the AWHP itself is around 3.0 across the stock. The contribution of supplementary electric heater to the dwellings' total heating demand reduces the overall effectiveness of the system at 2.0-2.5. Generally, the need to provide supplementary heating is found to be significant for all dwellings due to employed controlled strategy of the system. Using a current weather scenario, indoor temperatures are found to be within acceptable limits for most houses. However, only few houses manage to achieve an average annual Predicted Mean Vote (PMV) within the comfort band, these mainly being highly insulated semi-detached and mid-terrace houses with floor area lower than ~160 $m^2$ as well as medium-insulated mid-terrace houses with floor area lower than ~72 $m^2$. Under the future weather scenarios, the applicability of AWHPs is found to become more favourable across the modelled stock from both an energy use and thermal comfort perspective. As a result of the milder outdoor air temperatures, the need for supplementary electric heating reduces by 40.0 % on average for the 2050 weather scenarios (compared to the current weather scenario), while this reduction is in the range 55.0 % - 66.0 % for the 2080 weather scenarios (depending on the carbon emissions level). Nevertheless, although thermal discomfort is more limited across the stock for the 2050 weather scenarios (compared to the current weather scenario), the AWHP retrofit still fails to maintain indoor comfort for a significant number of houses across the stock. These cover all houses with uninsulated walls (independently of size and built form) as well as those medium-insulated houses being either detached (independently of size) or having a floor area greater than ~160 $m^2$ (independently of built form).

# Acknowledgements

I would like to take this opportunity to thank and express my appreciation to all those people, who were by my side all these years and contributed to the accomplishment of this work.

First, and foremost, I would like to thank both my supervisors Dennis Loveday and Jonathan Wright. Dennis, for always being available to provide his valuable advice and emotional support. His scientific contribution and encouragement, especially during the writing-up period, gave me strength and confidence to complete my Thesis. Jon, for always being an inspiration for me with his creative ideas. His caring, support and advice were all more than important for me. I feel lucky to have Dennis and Jon as my PhD supervisors and grateful for having the opportunity to work with them.

I would like to sincerely thank the funder of my PhD studies, Jim Atack. This work could not have been completed without his valuable contribution.

I wish to express a very special thanks to Elli Nikolaidou for being such a good friend all these years for me. Elli was always there to support me, give me strength, encourage me and make me laugh. Thanks to Elli, all these stressful periods during my PhD were made easier and more enjoyable. I am very glad to meet Elli and have her in my life.

My warmest thanks should go to Kostas for his constant patience and love all these years and especially during the writing-up period of my Thesis. You have always been there for me to encourage me all the way, bear with me and deal with all my ups and downs. Your support was an integral part of this journey.

I would like to truly express my greatest gratitude to my parents, Petros Vatougios and Stella Dimisianou, and my grandmother Paraskevi Dimisianou, for their emotional and financial support from the very beginning of my studies. Their unconditional love and caring have been always a constant for me and helped me pursue my dreams.

Finally, I would like to exceptionally thank Konstantinos Chatzikypraios for helping me handle all those challenging times with his continuous support as well as all those people that I met in Loughborough and become good and valuable friends; George Vaskantiras, Dr Marianna Imprialou, Dr Vasilis Bagiatis, Dr Konstantinos Mourkos, and Dr Giovanni Pipitone.

# Table of contents

# List of figures

# List of tables

# Abbreviations

**AAHP**: Air-to-Air Heat-pump

**AR5**: Fifth Assessment Report

**ASHP**: Air-Source Heat-pump

**ASHRAE**: American Society of Heating, Refrigerating and Air-Conditioning Engineers

**AWHP**: Air-to-Water Heat-pump

**BEIS**: (Department) for Business Energy & Industrial Strategy

**BPS**: Building Performance Simulation

**BRE**: Building Research Establishment

**BREDEM**: Building Research Establishment Domestic Energy Model

**BS**: British Standards

**CCC**: Committee on Climate Change

**CFC**: Chlorofluorocarbon

**CHM**: Cambridge Housing Model

**CHP**: Combined Heat and Power

**CIBSE**: Chartered Institution of Building Services Engineers

**COP**: Coefficient Of Performance

**DBT**: Dry-Bulb Temperature

**Defra**: Department for Environment, Food and Rural Affairs

**DHW**: Domestic Hot Water

**DSM**: Demand-Side Management

**DUKES**: Digest for UK Energy Statistics

**E7:** Economy 7

**E10:** Economy 10

**EFUS**: Energy Follow-Up Survey

**EHPA**: European Heat-pump Association

**EHS**: English Housing Survey

**EN:** European Standards

**ESP-r**: Environmental Systems Performance-Research

**EPC:** Energy Performance Certificate

**EPS**: Expanded polystyrene

**EST**: Energy Saving Trust

**E+:** EnergyPlus

**GHG**: Greenhouse Gas

**GIS**: Geographic Information System

**GWP**: Global Warming Potential

**GSHP**: Ground-Source-Heat-Pump

**HEED**: Homes Energy Efficiency Database

**HIS**: Household Integrated Survey

**HP**: Heat-Pump

**HVAC**: Heating Ventilation and Air-Condition

**IDF**: Input Data File

**IES-VE:** Integrated Environmental Solutions-Virtual Environment

**IPCC**: Intergovernmental Panel on Climate Change

**ISO**: International Standard Organization

**MHCLG**: Ministry of Housing Communities & Local Government

**MIS**: Microgeneration Installation Standard

**NCM**: National Calculation Methodology

**NE**: North-East

**NEED**: National Energy Efficiency Data

**NREL:** National Renewable Energy Laboratory

**Ofgem**: Office of Gas and Electricity Markets

**ONS**: Office for National Statistics

**ODP**: Ozone Depletion Potential

**PF**: Phenolic Foam

**PIR**: Polyisocyanurate

**PLF**: Part-Load Fraction

**PLR**: Part-Load Ratio

**PMV**: Predicted Mean Vote

**PPD**: Predicted Percentage of Dissatisfied

**PUR**: Polyurethane rigid foam

**RES**: Renewable Energy Sources

**RHI**: Renewable Heat Incentive

**SAP**: Standard Assessment Procedure

**SH**: Space-Heating

**SPF**: Seasonal Performance Factor

**SPSS**: Statistical Package foe the Social Sciences

**TES**: Thermal Energy Storage

**ToU**: Time of Use

**TRNSYS**: Transient System Simulation Tool

**UKCP**: UK Climate Projections

**VBA**: Visual Basic for Applications

**WHO**: World Health Organization

**WSHP**: Water-Source-Heat-Pump

# Chapter 1

# Introduction

## 1.1 Background knowledge and problem statement

Following the recommendations of the Committee on Climate Change (CCC), the UK Government has set a ground-breaking target of net-zero Greenhouse Gas (GHG) emissions by 2050 (i.e. at least a 100.0 % reduction relatively to 1990 levels) (CCC, 2019b). To achieve this, emission reductions is an imperative across all sectors (power, buildings, transport, agriculture, industry, bioenergy); power sector, in particular, is one of the top priorities, with the electricity generation market currently being under a fundamental transformation. Further, in line with the CCC's advice (CCC, 2019b), the UK Government also focuses on increasing the energy efficiency of the built environment, this being one of the most cost-effective ways to reduce carbon emissions and as such, it should be prioritised and carefully planned (BEIS, 2019c).

The domestic sector attracts much attention due to its large share in the total energy consumption and GHG emissions. More specifically, based on provisional national statistics for 2018, it is estimated that residential buildings are responsible for about 18.0 % of the total GHG emissions in the UK (BEIS, 2019a). Additionally, in 2018, the domestic sector itself accounted for almost 30.0 % of the total energy use in the

UK (41.2 million tonnes of oil equivalent) having the second largest share after transport (BEIS, 2019b). Space and water heating, in particular, cover approximately 80.0 % of the final domestic energy consumption (BEIS, 2018c). According to the same source, 64.4 % of the energy used in residential buildings is being provided by natural gas, which has been by far the dominant fuel in the UK for the last four decades.

Considering that 70.0 % - 80.0 % of the houses that will exist in the UK in 2050 have already been built, a deep national energy retrofit of the existing building stock has to be urgently put into practice (Timperley, 2018). A very recent report by the CCC highlighted that the UK Government should focus on making the 29 million existing houses low-carbon, low-energy and resilient to climate change (CCC, 2019c). The undertaking of energy efficient measures to limit residential space-heating and hot water demand is of vital importance for the UK in order to not only reduce carbon emissions to desired levels, but also limit fuel poverty[1], which appeared to affect 10.3 % of the total households in England in 2018 (BEIS, 2020). These measures include the upgrade of building fabric (e.g. upgrade of insulation levels, increase of air tightness) as well as the integration of renewable energy technologies. The latter, in particular, is highly promoted by the UK Government through legislative incentives such as the Renewable Heat Incentive (RHI) scheme, which provides income to households for the use of low carbon heating technologies (Ofgem, 2019). The technologies, which are considered to be eligible for householders to claim support through the domestic RHI, are: biomass boilers, biomass pellet stoves with integrated boilers providing space heating, Ground-to-Water-Heat-Pumps (GWHPs), Air-to-Water-Heat-pumps (AWHPs) and solar thermal panels for Domestic Hot Water (DHW) (Ofgem, 2019). Other low-carbon heating technologies (which, however, are not listed as eligible for the RHI) are micro-CHP (combined heat and power) and hydrogen boilers.

Currently, around 1 million houses in the UK are served by low-carbon heating technologies, with most of them using biomass boilers and wood stoves (CCC, 2019c). Nevertheless, although the replacement of conventional fossil fuels with biomass can

[1] The English definition for fuel poverty adopts the Low-Income-High-Cost indicator. Based on that, a household is considered to be fuel poor if its required fuel costs are above the national median level and if by spending this amount, it would be left with a residual income below the official poverty line (BEIS, 2020).

contribute to meeting the UK's emissions targets, an extensive use of biomass for domestic applications is not considered to be consistent with the long-term best utilization of the limited bioenergy resources (CCC, 2018). Generally, biomass (when it comes from sustainable sources) is recommended to be used only in cases where other low-carbon alternatives do not exist (e.g. in aviation or industrial high-grade heating processes) (BEIS, 2010; CCC, 2018). Furthermore, in terms of cost, biomass boilers are not considered to be the optimal replacement of gas boilers (Dodds, 2014). Instead, a substantial electrification of the domestic heating (as well as transportation services) is strongly believed to be the key element for reducing GHG emissions (CCC, 2019a); this is further supported by the fact that renewables' share in electricity production is getting more and more significant with a record of 33.3 % in 2018 (BEIS, 2019d).

In this context, the wide deployment of electrically driven AWHPs (and electric vehicles) is an integral part of the UK's 2050 decarbonisation pathway (CCC, 2019a). However, compared to other European countries with similar climatic characteristics, AWHPs have had a limited uptake in the UK market. The increased electricity prices compared to other available fuels as well as the inadequacy of policy to effectively drive the adoption of low carbon heating are attributed as the main reasons for the low penetration of heat-pumps in the UK market (Nowak, 2018a). Especially when it comes for the heat-pumps to be used for dwelling refurbishment in the UK, their effectiveness (most commonly expressed by the Coefficient of Performance, COP) drops due to the high heating demand of the existing houses. In fact, the existing UK housing stock constitutes one of the oldest and least energy efficient stocks across Europe (Nicol *et al.*, 2014a). Based on the same source, in 2014, the UK appeared to have the largest percentage of old houses and one of the lowest percentages of new-built houses across Europe. More specifically, 37.8 % of UK houses have been built before 1946, while the average percentage of those houses equals 22.3 % for the entire Europe. Further, only 6.9 % of the existing UK houses have been built after 2000, while for the whole of Europe, the figure is 9.8% (Nicol *et al.*, 2014b).

Although AWHPs have been generally proven to be more effective when installed in new-built and well-insulated houses (Fawcett, 2011), recent field studies and policy reports have highlighted its promising potential to play a significant role in the refurbishment of the existing UK residential buildings. The Energy Saving Trust (EST) monitored the heating performance of a large number of AWHPs in both new-built and existing houses across the UK and concluded that their average effectiveness[1] can be as high as 2.45±0.11; this, however, is being highly dependent on the correct sizing and wise operation of the installed system (Dunbabin *et al.*, 2013). Nevertheless, heat-pumps cannot compete gas boilers in terms of running costs due to the significant electricity to gas price ratio, with this making the technology a less appealing heating solution in the eyes of consumers (Le *et al.*, 2019). On the other hand, the same authors showed that retrofitting an AWHP to typical Irish Hard To Treat[2] houses (previously heated by gas-boilers) has the potential to reduce annual carbon emissions in the range of 6.0 % to 33.0 % depending on the control of the retrofitted system. Compared to GSHPs, the significantly lower capital and installation cost as well as the convenience in both installation and maintenance make AWHPs to be regarded as a preferable solution (McMahon *et al.*, 2018).

In order for the AWHP technology to be widely accepted as a viable solution for the refurbishment of the UK housing stock, policymakers and researchers should work together to overcome the issues associated with the current low uptake of AWHPs in the UK. As highlighted in a recent CCC report, UK Government policy should focus on raising the awareness of both installers and consumers about low-carbon heating (CCC, 2019c). The same source draws special attention to the provision of appropriate training to installers and designers in order to create a mature heat-pump market and limit common faults often occurring during the design and installation stage. In the same direction, the UK Government should prioritise the introduction of effective schemes through which consumers can see a real benefit for switching to low-carbon heating. Unfortunately, the current RHI (which will be in force until 2022) "*has*

---

[1] This accounts for the heating output and electric input of all the components of the system including any source of supplementary electric heating

[2] BRE defines a "Hard To Treat" house as follows: "*one that, for whatever reason, cannot accommodate 'staple' or cost-effective fabric energy efficiency measures".* For example, these could be houses with solid walls, no loft, high-rise flats, etc. (BRE, 2008).

*significantly underperformed on the Government's expectations"* (BEIS, 2018a). To support policy development, research must be oriented to explore the performance of heat-pumps and other low-carbon heating technologies at scale and gather more evidence from in-situ operation. To date, most of the existing studies in the field focused on investigating the applicability of AWHPs from a single-building perspective. Although findings from previous studies are optimistic for AWHP's suitability to be used in the retrofit of UK houses (Arteconi *et al.*, 2013; Kelly *et al.*, 2014; Le *et al.*, 2019), the viability of AWHPs should be further investigated and this should be conducted at housing stock level. This is a gap in knowledge that requires attention. Currently, the development of Housing Stock Energy Models (HSEMs) coupled with high-resolution Building Performance Simulation (BPS) tools has received increasing attention for producing decarbonisation pathways and informing policy. This approach may offer a means for addressing the question of AWHPs' viability by consideration at the housing stock level. To the author's knowledge, such an approach has not been taken before in the evaluation of heat-pumps for residential applications in the UK.

In this thesis, a methodology is developed to assess the applicability of AWHPs using dynamic BPS at the stock level based on current and future heating requirements. The methodology is then applied to evaluate the effectiveness of AWHPs to be used as a retrofit heating solution for 756 house archetypes that have been selected to represent the housing stock of the North-East (NE) region of England. The simulation results are being presented in a novel way and are suitable to be communicated to both experts and non-experts in the field including policy-makers, stakeholders and consumers. The findings of this thesis will establish a deeper understanding of the potential of AWHPs to be used across the range of UK domestic buildings and drive future policy.

## 1.2 Aim and objectives

The *aim* of this thesis is to develop a methodology for using stock-level building energy modelling to evaluate the extent to which a heating technology (in this case applied to AWHP) is an effective retrofit solution when applied across the range of

UK houses in terms of both the system's energy use and the extent to which occupant thermal comfort can be maintained; the developed methodology will be used to assess heating system retrofit linked with fabric retrofit targets at the housing stock level based on current and future heating requirements.

The above research aim will be addressed through five individual *objectives*, which are:

1. to verify the suitability of a dynamic bottom-up HSEM to be used for representing the diversity of the energy demand across the housing stock

2. to model an AWHP coupled with thermal energy storage using a previously established dynamic BPS engine; the configuration and control of the AWHP model will be representative of actual AWHP systems that are available and sold in the UK market

3. to investigate the size (represented by nominal heating capacity) of the AWHP that should be retrofitted in various houses covering a wide range in physical characteristics

4. to investigate the distribution of the energy use, level of under-heating and degree of thermal discomfort across the housing stock as a result of the AWHP retrofit

5. to investigate the impact of future weather scenarios on the distribution of the energy use, level of under-heating and degree of thermal discomfort across the housing stock (as a result of the AWHP retrofit) and to discuss implications for future retrofit policy design; the future weather scenarios result from detailed weather files incorporating data for various climate change projections.

## 1.3 Thesis outline

This section provides an outline of the structure of the thesis. The content of the included chapters is summarized as follows.

**Chapter 1** outlines the background knowledge, makes the problem statement and declares the aims and objectives of the thesis.

**Chapter 2** presents a literature review on AWHPs and HSEMs within the UK context. Firstly, the AWHP technology is introduced and the metrics used to evaluate its heating performance are reviewed. Drawing evidence form previous research studies and standards, Chapter 2 then focuses on reviewing the architecture (configuration) and sizing of AWHP systems used for domestic applications. Following that, the trends of the UK heat-pump market within the last decade are discussed and the reasons for the low uptake of heat-pumps in the UK compared to other countries with similar climatic characteristics are summarized. Finally, Chapter 2 provides a review on the different types of HSEMs and data sources used, with the focus being on models developed for the UK housing stock.

**Chapter 3** outlines the methodology developed in the thesis, starting with the description of the employed bottom-up HSEM and the data used to construct it. Further, it provides a description of the modelled house archetypes (representing the existing housing stock of the NE region of England) and explains how these have been categorized in different groups for the purpose of the analysis of the thesis results (based on this categorisation, the results of this work will be presented in Chapter 4 and Chapter 5). Finally, Chapter 3 focuses on presenting the characteristics, configuration and control of the AWHP system that has been modelled to meet each house’s space-heating and DHW demand.

**Chapter 4** presents the analysis of the annual heating performance of AWHPs at the stock level using a current weather scenario. Firstly, the chapter investigates AWHP’s size selection based on house’s physical properties. Then, the impact of AWHP size on the overall performance of the heating system is analysed and discussed. Finally, the distribution of energy use, need for supplementary electric heating, level of under-heating and degree of thermal discomfort (as a result of the AWHP retrofit) is explored across the modelled stock.

**Chapter 5** evaluates the impact of various future weather scenarios on the heating performance of AWHPs for the housing stock of the NE region of England under the assumption that houses are at their current state (no fabric energy efficiency interventions are considered). The different weather scenarios incorporating probabilistic climate change projections for 2050 and 2080 (under different carbon emissions levels) are presented. The distribution of the system's energy use and degree of thermal discomfort is then explored across the stock and for the different future weather scenarios.

**Chapter 6** provides a discussion on how the research addressed the aim and particular objectives of the thesis, discusses the applications of the developed methodology and implications of the simulated results, makes clear the contribution to knowledge and summarizes the limitations of the research.

**Chapter 7** presents the key conclusions of the thesis and provides recommendations and extensions of this work for future research in the field.

# Chapter 2

# Literature review

## 2.1 Introduction

The aim of this chapter is to review the current literature in order to identify research gaps, formulate research questions and justify the importance of this study. It is mainly organized in two parts with the first part exploring heat-pump technology and its heating performance in UK domestic buildings using findings from field, monitoring and simulation studies. A particular focus is given on the coupling of AWHPs with Thermal Energy Storage (TES) water tanks including systems' configurations and sizing and this is achieved through the review of academic literature, regulatory and industrial guides. All these data are necessary for developing a detailed AWHP system model suitable to be studied using dynamic BPS tools. This first part of the literature review concludes with highlighting the reasons for the current inadequate uptake of heat-pumps in the UK compared to other European countries with similar climatic characteristics. In the second part, housing stock energy models developed within the UK context are reviewed including their data sources, followed by the criteria and standards that are recommended to be used to assess thermal comfort conditions in domestic environments.

## 2.2 Heat-pump technology

Based on the second law of thermodynamics, heat is spontaneously transferred from a region of higher temperature to another region of lower temperature. A Heat-pump (HP) is a device that transfers heat from a lower temperature heat source to a higher temperature heat sink using a relatively small amount of external energy such as electricity, gas or waste heat. In other words, HPs absorb low-grade heat from a source and converts it to high-grade heat to be used for space-heating and hot water applications. The important benefit of HPs is that the amount of heat that they are able to transfer is much greater than the amount of energy required to drive them. In this context, HP is considered to be a very cost-effective technology to be used as heating and/or cooling system in both residential and commercial applications. Furthermore, it is argued that a wide use of HPs can significantly contribute to the reduction of Greenhouse Gas (GHG) emissions, as HPs simply transfer heat rather that burn fuel to create it (Gagneja and Pundhir, 2016).

Based on the heat source, which can be the air, ground or water, HPs are divided into Air-Source-Heat-Pumps (ASHPs), Ground-Source-Heat-Pumps (GSHPs) and Water-Source-Heat-Pumps (WSHPs), respectively. In addition, they are further divided in Air-to-Air-Heat-Pumps (AAHPs), Air-to-Water-Heat-Pumps (AWHPs), Ground-to-Water-Heat-Pumps (GWHPs), etc. depending on the type of heat sink used. AWHPs are by far the most common type of HP used for domestic applications in the UK. HPs operate either on heating or cooling mode and their operation is most commonly based on a vapour-compression or absorption cycle, with absorption HPs being outside the scope of the thesis. Typical examples of HPs operating on cooling mode are refrigerators and air-conditioning units.

The volatile substance or alternatively, the working fluid, which circulates inside the components of a HP and is responsible for transferring, absorbing and releasing heat is called *refrigerant*. In the past decades, the most common refrigerants for HP applications were chlorofluorocarbons (CFCs). However, since CFCs have been strongly criticized for their significant contribution to the depletion of the ozone layer, they have been banned and replaced with other products such as hydrofluorocarbons.

Among the most widely used refrigerants are R-134a and R-410A, which are non-toxic, non-flammable and have zero Ozone Depletion Potential (ODP). Nevertheless, both R134a and R-410A present relatively high values of Global Warming Potential (GWP), with these values being 1430 and 2088, respectively (Makhnatch, 2013; Nyers *et al.*, 2015)[1]. It is evident that HP technology will move towards the replacement of conventional refrigerants with natural ones, such as ammonia, propane, etc. (Rony *et al.*, 2019).

### 2.2.1 Heating mode operation

The main components of a HP unit are as follows:

**Compressor:** a unit that compresses the refrigerant, which is in the form of a gas, to increase its pressure and temperature

**Condenser:** a heat exchanger, through which the circulating refrigerant releases its heat to the indoor environment and becomes liquid

**Expansion valve:** a valve that reduces the pressure and temperature of the refrigerant when leaving the compressor

**Evaporator:** an air heat exchanger, where the liquid refrigerant extracts heat from the outside environment and is boiled to become a low temperature vapour.

*Figure 2.1 (a)* illustrates the main components of a HP and *Figure 2.1 (b)* depicts an ideal vapour-compression cycle based on which a HP operates. As shown in *Figure 2.1* (b), **A→B process** represents the adiabatic compression of the refrigerant. In this stage, the low-pressure and low-temperature refrigerant passes through the compressor, where its molecules are compressed and becomes a superheated vapour of high pressure and high temperature. This process obviously requires external work to be completed, as heat does not spontaneously flow from low to high temperatures. Then, the saturated vapour leaves the compressor and enters the condenser (**B→C process**), through which it releases its heat to the environment (e.g. indoor space of a building) (**C→D process**). In **D→E process (expansion)**, the condensed and liquid refrigerant

[1] GWP is a metric showing how much heat is trapped in the atmosphere by 1.0 ton of a greenhouse gas over a specific period of time compared to the heat trapped by 1.0 ton of $CO_2$.

passes through an expansion valve, which drops its pressure and temperature. Finally, in **E→A process (evaporation)**, the low-pressure and low-temperature refrigerant enters the evaporator heat exchanger as a mixture of liquid and vapour, where it absorbs heat (e.g. from outdoors). In this stage, the refrigerant has lower temperature than ambient air, and therefore heat can be spontaneously transferred from the warmer outside environment to the colder refrigerant. In the evaporator, the liquid-vapour refrigerant is now completely vaporized and becomes a low-pressure and low-temperature saturated vapour again. After that, the vapour-compression cycle starts again (Staffell *et al.*, 2012).

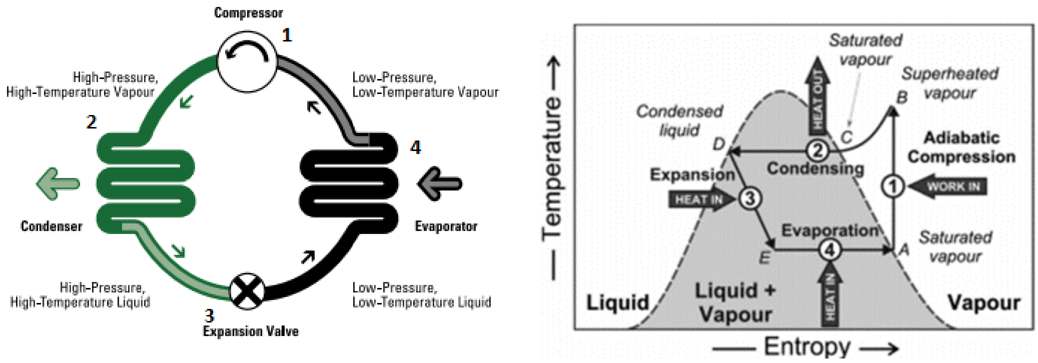



**Figure 2-1: (a) HP components, adapted from: Gagneja and Pundhir (2016) (b) temperature-entropy graph for an ideal vapour-compression cycle of a heat-pump.**

*Figure derived from:* Staffell *et al.* (2012)

All the above refer to an *ideal* vapour-compression cycle. The effectiveness of this ideal system only depends on the temperature of the condenser ($T_{cond}$) and evaporator ($T_{evap}$), as follows:

$$\eta_{ideal\text{ - }heating} = \frac{Tcond}{(Tcond - Tevap)}, \quad \text{(Equation 2-1)}$$

*Equation (2-1)* provides the theoretical maximum effectiveness of a HP and assumes that the system has no losses. In practice, a vapour-compression HP cycle presents extra heat losses due to:

- fluid and mechanical frictions causing pressure drops

- irreversibility during the compression process (as seen in *Figure 2-1(b)*, the compression process is considered isentropic in the ideal vapour-compression cycle)
- non-ideal gas behaviour (Staffell *et al.*, 2012)

*Equation (2-1)* clearly shows that the effectiveness of a HP operating on heating mode is higher than 1.0 and decreases as the temperature difference between the condenser and evaporator increases. Assuming a standard condenser temperature ($T_{cond}$), the effectiveness of the HP decreases as $T_{evap}$ decreases, with $T_{evap}$, in the case of ASHPs, being equal to air temperature. This fact explains why GSHPs usually perform more effectively compared to ASHPs as ground temperatures do not present significant fluctuations throughout the entire year. In the UK, the mean ground temperature at 100.0 m depth varies between 7.0°C–15.0°C (Gale, 2005), with this being generally higher than ambient air temperature during winter and lower than ambient temperature during summer. As a result, GSHPs are expected to be more effective to provide heating during winter and cooling during summer. However, ASHPs are much easier to be installed compared to GSHPs and further, their capital and maintenance cost is significantly lower (Cabrol and Rowley, 2012) and as such, ASHPs are considered to be a more appealing heating solution in the eyes of consumers.

### 2.2.2 Evaluation of performance

The main energy exchanges taking place within a vapour-compression HP cycle are the heat transferred to the warmer location ($Q_h$), the heat removed from the cooler location ($Q_c$) and the work needed to operate the compressor ($W$). Rather than using the theoretical maximum effectiveness of an ideal HP system ($\eta_{ideal-heating}$), the Coefficient of Performance (COP) is used instead as a more representative metric to assess the thermal performance of an actual HP. It is defined as the ratio of *the heat output of the HP itself* to the *amount of electricity supplied to drive the HP itself.*

$$\boldsymbol{COP = \frac{Useful\ heat\ output\ of\ the\ HP}{Electric\ input\ to\ the\ HP} = \frac{Q_h}{W}}, \quad \text{(Equation 2-2)}$$

It should be mentioned at this point that the COP refers to the effectiveness of the HP unit itself (excluding any other additional heaters operating to provide supplementary heating) and may or may not include the consumption of condenser's pump or evaporator's fan.

As seen in *Equation (2-2)*, COP is dimensionless. It expresses the effectiveness of the HP in such a way that as COP increases, the effectiveness of the HP increases as well. For example, a HP with a COP of 3.0 needs 1.0 unit of energy (e.g. electricity input) to produce 3.0 units of heat. In the UK, COP typically ranges from 1.0 on extremely cold winter weather conditions to 3.0 during autumn or spring (Etude, 2018). The COP and heating capacity of HPs are subject to ambient air and condenser water temperature variations. The COP of an AWHP, in particular, is likely to decrease at a range 2.0 % - 4.0 % when ambient temperature decreases 1.0 K or the delivered water temperature has to be increased 1.0 K (Welch, 2009).

Based on BS EN 14511, the performance of AWHPs should be tested under various combinations of heat source and heat sink temperatures and this information should be provided by manufacturers in order to enable the comparison of the different devices that are available in the European market. More specifically, manufacturers' technical guides should include the nominal heating capacity and nominal COP of each HP device accompanied by supplementary data showing how these nominal values vary with the variations of outdoor air and water temperature. Nominal heating capacity and COP are most commonly provided under the specification *A2/W35 or A7/W35*, which means that they have been measured for ambient and water temperatures equal to 2.0°C and 35.0°C or 7.0°C and 35.0°C respectively. BS EN 14511 recommends testing AWHPs and measuring their COP and heating capacity under the combination of five inlet air temperatures with four condenser water outlet temperatures (British Standard Institution, 2013)[1]. The data for COP and heating capacity variations are usually provided by HP manufacturers in the form of performance curves.

[1] Ambient temperature: -15.0°C (A-15), -2.0°C (A-2), 2.0°C (A2), 7.0°C (A7) and 12.0°C (A12) and condenser water temperatures: 35°C (W35), 45°C (W45), 55°C (W55) and 65°C (W65)

ASHPs should not operate under very low ambient temperatures due to the possibility of frost accumulation on the evaporator side of the device, which results in decreasing the rate of air flow and inevitably leads to COP degradation (Changqing and Liang, 2006). After a period of 4.0 h of frosting, the COP of an ASHP can be reduced by up to 0.7 units (Hewitt and Huang, 2008). To avoid the formation of frost, ASHPs are controlled to perform reverse/defrost cycles. In this case, the refrigerant performs a reverse cycle, where the evaporator becomes the condenser, and the condenser becomes the evaporator. In other words, the refrigerant absorbs heat from the interior spaces of the building and rejects it to melt the ice periodically. Mitsubishi Electric recommends the application of defrosting operation when ambient temperature falls below 2.0$^{o}$C (Mitsubishi Electric, 2015). Other methods to defrost ASHPs include direct use of electric energy and hot gas defrosting (Dunbabin *et al.*, 2013).

Another metric used to evaluate the thermal performance of a HP is the Seasonal Performance Factor (SPF). This is defined as the ratio of the annual amount of heating delivered by the HP to the annual amount of electricity used to produce it.

$$\boldsymbol{SPF = \frac{Annual\ heat\ output\ of\ the\ heat{-}pump}{Annual\ electric\ input}}, \quad \text{(Equation 2-3)}$$

As seen in *Equation 2-3*, SPF is similar to COP. However, when it comes to assess the annual performance of HPs, the SPF term is used instead. It should be noted at this point that SPF can be evaluated for different boundaries. This means that apart from the HP unit itself, the expression of SPF may or may not include other parts of the system such as fan, supplementary heaters, circulation pump, etc. (Dunbabin *et al.*, 2013).

The EST carried out a series of heat-pump field trials (both ASHPs and GSHPs) for domestic buildings (new-built and older houses) located in various regions across the UK. The monitoring of 15 ASHPs showed that the average SPF of the ASHP unit including fan’s consumption (referred as $SPF_{H2}$) was 2.68 with this varying from 2.20 to 4.00. When it comes to the effectiveness of the whole system (including energy consumption of auxiliary electric heater, DHW immersion heater, circulation pump and fan), the average SPF (referred as $SPF_{H4}$) was found to reduce at 2.45 with this varying from 2.00 to 3.60 (Dunbabin *et al.*, 2013). Based on a meta-analysis study, the SPFs reported by the EST were found to be very low when compared with similar field trials of other European countries (Gleeson and Lowe, 2013). The same authors mentioned that the inconsistency in performance for the UK HPs (resulting from the wide range of performances between the monitored houses) can be attributed to installation and sizing faults, proving that the UK HP industry is immature compared to other European countries such as Denmark; this will be discussed later in this chapter (see Section 2.5.1).

### 2.2.3 Comparison with conventional heating systems

This section presents the findings from previous works investigating the impact of replacing conventional heating systems with heat-pumps in existing houses located in the UK or countries with similar climatic conditions.

Kelly and Cockroft (2011) investigated the effectiveness of AWHPs to replace gas boilers and direct electric heaters in terms of energy use, associated carbon emissions and energy cost for an existing Scottish house using the ESP-r (Environmental Systems Performance-Research) dynamic simulation engine. The AWHP retrofit was found to reduce annual energy use and carbon emissions by 12.0 % and 69.0%, respectively compared to the gas boiler, while it was found to increase energy cost by 10.0 %. The energy cost penalty associated with the AWHP retrofit is due to the high electricity to gas price ratio. More specifically, electricity price is approximately 3.5 times higher than that of gas in the UK (the impact of the high electricity to gas price ratio on the roll-out of heat-pumps within the UK context will be more extensively discussed in Section 2.5.1). However, when compared with the direct electric heaters, the AWHP was found to reduce both carbon emissions and energy use by 55.0 %. In the same direction, Le *et al.* (2019) used TRNSYS (Transient System Simulation Tool) dynamic simulation engine to evaluate the economic and environmental impact of replacing gas boilers with high temperature AWHPs coupled with TES in two hard-to-treat mid-terrace houses located in Northern Ireland. The results showed that carbon emissions can reduce by 6.6 % - 33.0 % depending on the efficiency of the gas boiler (the highest reduction corresponds to a new 90.0 % efficient condensing boiler and the lowest reduction to an older 60.0 % efficient boiler were considered). However, the total energy costs were found to increase in the range of 18.0 % to 36.6 % for the AWHP retrofit. On the other hand, Kelly et al. (2016) carried out an economic evaluation of replacing fossil-fuel based heating systems with ASHPs for the Irish housing stock. The performed analysis revealed that there is a significant economic and environmental benefit if consumers switch from oil-boilers to ASHPs with energy costs, in particular, reducing up to €600 per year (Kelly *et al.*, 2016). This confirms that heat-pumps can more effectively compete with oil than gas boilers (although oil price is lower than that of electricity, their difference is not as high as in the case of gas).

Finally, Asaee *et al.* (2017) evaluated the techno-economic feasibility of AWHPs to be used as a retrofit heating solution across the range of the Canadian housing stock (some 17,000 unique properties were studied) using the ESP-r simulation tool. In their study, the AWHP was considered to be an eligible retrofit solution only for those houses that had a basement or were previously heated by a system that requires a mechanical room (~71.0% of the studied houses including those with gas and oil-fired boilers as well as some with wood-fuelled systems or other electrified heating systems). The modelled AWHP unit was coupled with an auxiliary gas fired-boiler and a thermal energy storage tank. The results showed that if all eligible houses were retrofitted with AWHPs, energy consumption could reduce up to 36.0 % resulting in 15.16 Mt GHG emissions savings across the entire stock. However, the AWHP was not found to be a cost-effective alternative for all cases. More specifically, there are provinces across Canada, where the high electricity price in comparison with that of gas does considerably increase payback period with this being a deterring factor for such an investment. Although this particular study was not carried out within the UK context, it revealed the high potential of moving towards the large-scale deployment of AWHPs. This, however, requires significant support from the government through profitable incentives that will effectively persuade consumers to switch to low carbon heating systems such as heat-pumps.

## 2.3 Thermal Energy Storage (TES)

TES refers to the concept of storing thermal energy and utilizing this stored energy at a later time for domestic and industrial thermal applications. Thermal energy can be stored as *sensible*, *latent* or *thermochemical*. More specifically, sensible TES refers to systems in which heat is accumulated in the mass of a storage medium such as water and rock due to its temperature differences. Latent heat storage involves the mechanism of storing thermal energy when a material (e.g. water, salt hydrates, etc.) changes phase (from solid to liquid, liquid to gas or vice versa). Last, thermochemical heat storage relies on the energy stored as a result of a completely reversible chemical reaction (Hasnain, 1998). In each case, the storage medium is situated in specific containers (usually tanks) equipped with necessary input and output devices.

This section focuses on providing a description of sensible TES (Section 2.3.1) and reviewing previous works combining AWHPs with water storage tanks as a heating system for the case of UK residential buildings (Section 2.3.2).

### 2.3.1 Sensible TES

The amount of heat stored by a sensible TES system is calculated as follows:

$$\boldsymbol{Q = m * Cp * \Delta T}, \quad (\boldsymbol{in\,Joules}), \quad \text{(Equation 2-4)}$$

where m and Cp is the mass (kg) and specific heat capacity (J/kgK) of the storage medium respectively, and ΔT is the difference between the input and output temperature of the storage medium. Gasses are not recommended for sensible TES applications due to their low density. A key factor in the design of a TES system is the utilization of strong and well-insulated tanks to withstand the weight of the water and minimize heat losses. The rate of heat losses through TES tank is calculated as follows:

$$\boldsymbol{q = S * Uvalue * \Delta T}, \quad (\boldsymbol{in\,Watts}), \quad \text{(Equation 2-5)}$$

where S is the area of the tank in $m^2$, U-value is the thermal transmittance of the storage tank in $W/m^2K$ and ΔT is the difference between the input and output temperature of the storage medium in K. Water is among the most well-known thermal energy storage mediums. It can store a relatively high amount of heat per unit of weight due to its high specific heat capacity. In addition to that, it is free and available (in most cases), easily pumped, nontoxic, nonflammable and mildly corrosive in the absence of oxygen (Kaygusuz, 1999).

The most typical sensible TES systems used for domestic applications include *mixed* or *stratified* water tanks. As seen in *Figure 2-2*, stratified tanks separate cold and hot water volumes in the bottom and top of the tank, respectively. The intermediate region between the two different water volumes is called a thermocline. Water is a naturally stratified medium as it has different values of density at different temperatures. Thus, hot water, which has lower density than cold water, moves to the top of tank and cold water remains in the bottom. Water stratification is achieved through the utilization of relatively tall tanks supplied with diffusers, which are located in the inlet of the tank (Eames *et al.*, 2014). Storage tanks operate by either *direct* or *indirect* heating mode. In a direct TES system, the storage medium itself has the role of the storage mechanism, while indirect systems include additional heat exchangers providing supplementary heating when needed (Arteconi *et al.*, 2012).

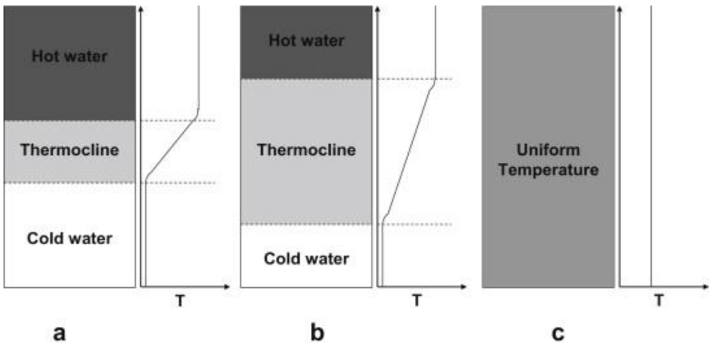



**Figure 2-2: Stratification level of a water thermal energy storage tank (a) highly stratified, (b) moderately stratified and (c) mixed**

*Figure derived from:* Arteconi et al. (2012)

### 2.3.2 Coupling AWHPs with TES

The coupling of TES with renewables and low-carbon technologies is considered to be a powerful Demand-Side Management (DSM) strategy [1] to increase demand flexibility by shifting electricity loads to off-peak periods and balancing the mismatch of energy supply and demand, thus maintaining the stability of electricity grid (Dincer, 2002). In this context, TES can be short-term or long-term ranging from diurnal to seasonal load-shifting e.g. from summer to winter (Hesaraki *et al.*, 2015). Further to that, the combination of load-shifting strategies with suitable pricing schemes (providing peak and off-peak electricity rates throughout the day) can also contribute to the reduction of consumers' electricity bills (Krajačić *et al.*, 2011).

Many previous studies focused on investigating the required storage volume in order to effectively shift heating loads from high-tariff to low-tariff periods of the day as determined by electricity tariffs that are available within the UK context. Nevertheless, load-shifting was not always found to be a viable solution for the following two reasons. Firstly, the required storage volume for an effective load-shifting was found to be significant when water storage tanks were considered with this being a restriction for many existing UK houses that have very limited available space. In addition to that, the most recognized electricity tariffs (e.g. E7 and E10 [2]) do mainly offer low prices at night. However, operating an AWHP during nighttime (where ambient temperature is usually lower than daytime) results in COP degradations and consequently, in increased energy use and costs. Eames *et al.* (2014) investigated the required TES volume to shift morning and evening peak heating loads (7-9 am and 4-7 pm, respectively) for a large detached house located in Derby, UK. Their work showed that a 560.0 L water tank was needed when the house was considered to comply with the 2010 Building Regulations, while if the house was built before 1980, the required storage volume was found to exceed 2,500 L. Similar results were also reported by

[1] Gellings and Smith define DSM as follows: "*the planning and implementation of utility activities designed to influence the time pattern and/or the amount of electricity demand in ways that will increase customer satisfaction and coincidentally produce desired changes in the utility's load shape"* (Gellings and Smith, 1989).

[2] E7 and E10 stand for Economy 7 and Economy 10 electricity tariffs with E7 offering reduced electricity prices from midnight to 7.00 am and E10 from midnight to 5.00 am, from 1.00 pm to 4.00 pm and from 8.00 pm to 10.00 pm. The low-tariff hours do slightly vary from one region to another.

Kelly *et al.* (2014), who assessed the load-shifting potential of an AWHP coupled with a phase-change enhanced tank for a typical UK detached house using the low-tariff hours provided by the E10 electricity tariff. In this case, energy use was found to increase by 60.0 %, while a storage volume in the range of 500.0 L to 1000.0 L was required depending on the volume of the utilized phase-change material. In this context, the employment of dynamic Time-of-Use (ToU) tariffs, which are increasingly penetrating the UK electricity market, might be a means to overcome problems associated with conventional electricity tariffs and make the coupling of AWHPs with TES a viable and cost-competitive heating solution (Renaldi *et al.*, 2017).

## 2.4 Design of AWHP systems

Through the review of academic papers, manufacturers' guides and UK Standards, this section provides guidelines regarding the design of AWHPs. More specifically, Section 2.4.1 includes examples of AWHP system configurations and Section 2.4.2 discusses different approaches for selecting AWHP's size.

### 2.4.1 System configuration

AWHPs can be located either outdoors or indoors, with indoor installations requiring extra ductwork to draw in outdoor air. Focusing on outdoor installations (being the most common for the case of domestic buildings), AWHP devices are mounted on an exposed wall of the building and draw ambient air using a fan. Depending on the location of the condenser heat exchanger, AWHPs are divided into *all-in-one* and *split* types. All-in-one AWHPs have all their components in the outdoor unit, while split types include an additional indoor unit containing the condenser heat exchanger. Thus, in all-in-one systems, the vapour-compression cycle of the refrigerant takes place solely in the outdoor unit, whereas in split systems, the refrigerant cycles between the indoor and outdoor units through pipes (see *Figure 2-3*).

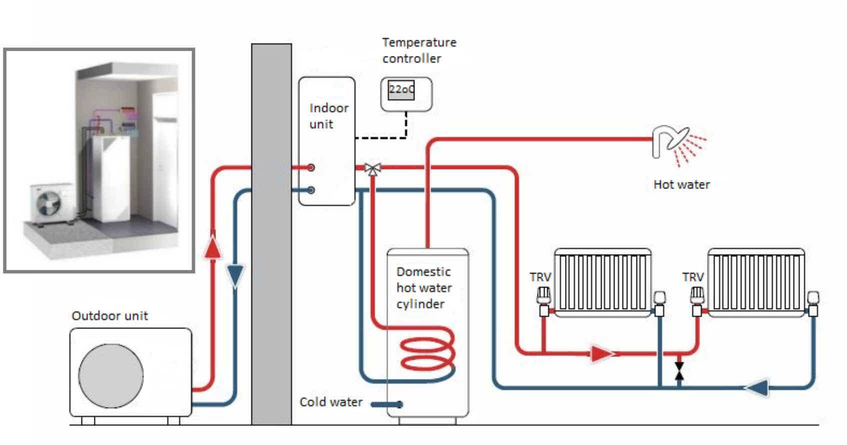



**Figure 2-3: DAIKIN split type air-to-water-heat-pump**

For the case of AWHPs serving both the dwelling's space heating and hot water demand, the DHW (used for shower, cooking, etc.) should be separated from the water circulating inside radiators or under-floor heating systems. Therefore, two different circuits, the central-heating and DHW circuit, are connected in parallel and controlled using valves, which determine which of the two circuits must be fed with hot water. As seen in the following figures, the heat produced by the AWHP can either pass directly to the DHW tank of the house (Dunbabin *et al.*, 2013) (see *Figure 2-4*) or pass to the TES tank through which is then transferred to the DWH tank and wet hydronic distribution heating system of the house (Kelly *et al.*, 2014) (see *Figure 2-5*).

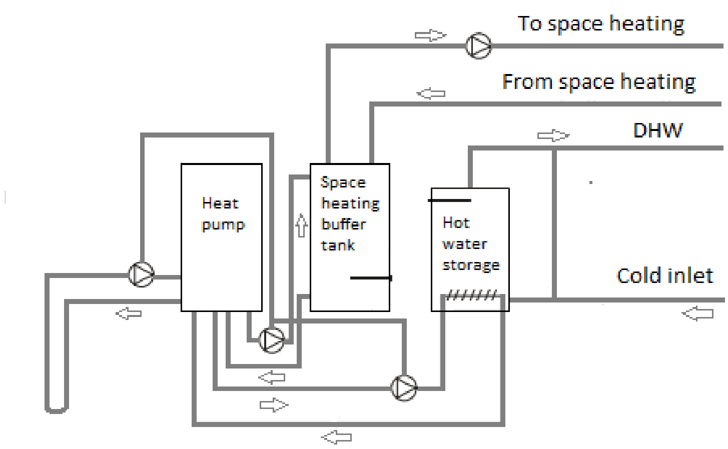



**Figure 2-4: Configuration of AWHP with TES system retrofitted in UK residential buildings**

*Figure adapted from:* Dunbabin *et al.* (2013).

*Figure 2-5* illustrates an AWHP coupled with a TES water tank that was modelled to be retrofitted in a typical detached UK house to meet its space-heating and DHW demand. As seen, the heat produced by the AWHP is transferred to the water storage tank using an indirect heating coil. The hot water is then transferred through the TES tank to the DHW tank and radiators of the building using a circulation pump (Kelly *et al.*, 2014).

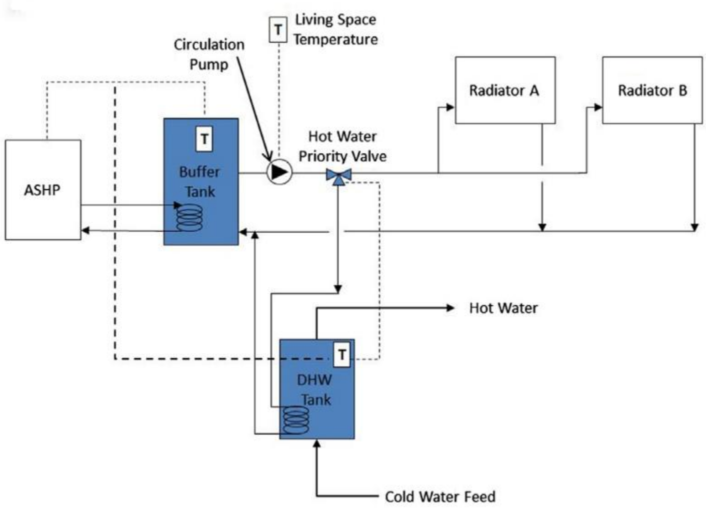



**Figure 2-5: Configuration of AWHP coupled with TES system modelled for a typical UK house**

*Figure derived from:* Kelly et al. (2014)

### 2.4.2 Sizing

The Microgeneration Installation Standard 3005 (MIS 3005) states as follows: "*A heat-pump shall be selected that will provide at least 100% of the calculated design space-heating power requirement at the selected internal and external temperatures…, the selection being made after taking into consideration the flow temperature at the heat-pump when it is doing space-heating… Heat-pump thermal power output for the purposes of this selection shall not include any heat supplied by a supplementary electric heater*" (BEIS, 2017). In this case, the calculation of the design space-heating power requirement follows the methodology recommended in BS EN 12831:2017 assuming steady-state conditions. Internal and external design temperatures are provided in Table 1 and Table 2 of the MIS 3005-issue 5.0 (p.14-15) based on BS EN 12831:2017, the external design temperatures, in particular, being criticized for being higher than those usually used for designing purposes and thus, resulting in 75.0 % power coverage as opposed to the aforementioned 100.0 % power coverage "rule" (Dunbabin and Wickins, 2012).

Since there is a limited range of HP capacities in practice, the exact matching of HP's capacity with the design heating load of the building is not always possible. The high fabric heat loss of existing UK dwellings might mean that many installed HPs will have insufficient capacity during some periods of the heating season, with the result that thermal discomfort and consequently, need for supplementary electric heating will increase. Considering the above, the installation of an under-sized HP might increase the overall operational cost due to the increased utilization of back-up electric heating with this limiting both the economic and environmental potential associated with the replacement of conventional heating systems with HPs (Renaldi *et al.*, 2017). On the other hand, the installation of an over-sized HP might increase capital cost and result in operating the system under part-load conditions for a significant amount of time, which, in turn, leads to the degradation of COP (Madonna and Bazzocchi, 2013). In this context, the adoption of HPs with variable-speed rather than on-off compressors can effectively limit the drawbacks associated with part-load operation (Adhikari *et al.*, 2012).

A significant proportion of actual heat-pump installations were found to fail due to the selection of the incorrect size (EST, 2013), this being significantly associated with the lack of a trained installers network further delaying the roll-out of heat-pumps. In an attempt to investigate the suitable AWHP's heating capacity for a single family house located in Padua, Italy, Bagarella *et al.* (2016) varied the AWHP's nominal heating capacity in successive simulations so that the AWHP was capable of meeting different proportions of the dwelling's peak heating load (from 33.5%-94.0%). The results showed that the system achieved the highest SPF when peak space-heating load coverage was in the range of 59.0%-72.0%, this being significantly lower than the 100% coverage suggested by the MIS 3005. Asaee *et al.*, (2017) assessed AWHPs to be used as a retrofit heating solution for the Canadian housing stock (the content of this study was explicitly described in Section 2.2.3). In their work, the characteristics and nominal heating capacity of the retrofitted AWHP in each individual house were selected based on the existing heating system of the house. More specifically, three different AWHP sizes were used with each reflecting on houses with existing heating system's capacity >21 kW, 11-16 kW and <11 kW, respectively. The authors mentioned that the retrofitted AWHP was capable of satisfying major part of the dwelling's design heating load without further specifying the range of this coverage.

Based on the literature, there is not a best practice yet regarding the selection of the correct size for heat-pumps. The present thesis adopts the recommendations of the MIS3005 based on which the heat-pump itself should be capable of meeting 100% of the house's design heating load without the contribution of any supplementary electric heater. However, it should be acknowledged that this practice might result in over-sized systems.

## 2.5 Heat-pumps in the UK

In an attempt to draw evidence for best practice of heat-pumps' deployment, this section reviews the trends of HP market in several European countries, compares the situation in the UK with other countries having similar climatic conditions and finally, indicates the reasons for the low uptake of heat-pumps within the UK context.

### 2.5.1 Heat-pump market trends

The graph in *Figure 2-6* illustrates the total number of HP sales in Europe within the last decade. It should be noted that data refers to those European countries that are members of the European Heat Pump Association (EHPA) (22 countries in total as depicted in *Figure 2-7*). Based on EHPA statistics, the European HP market presented an annual growth of more than 10.0 % in 2015, 2016 and 2017 reaching to 1.1 million installations in 2017. This fact led to 29.8 Mt $CO_2$ reduction and 148.0 TWh final energy reduction compared to 2016 levels (Nowak, 2018a).

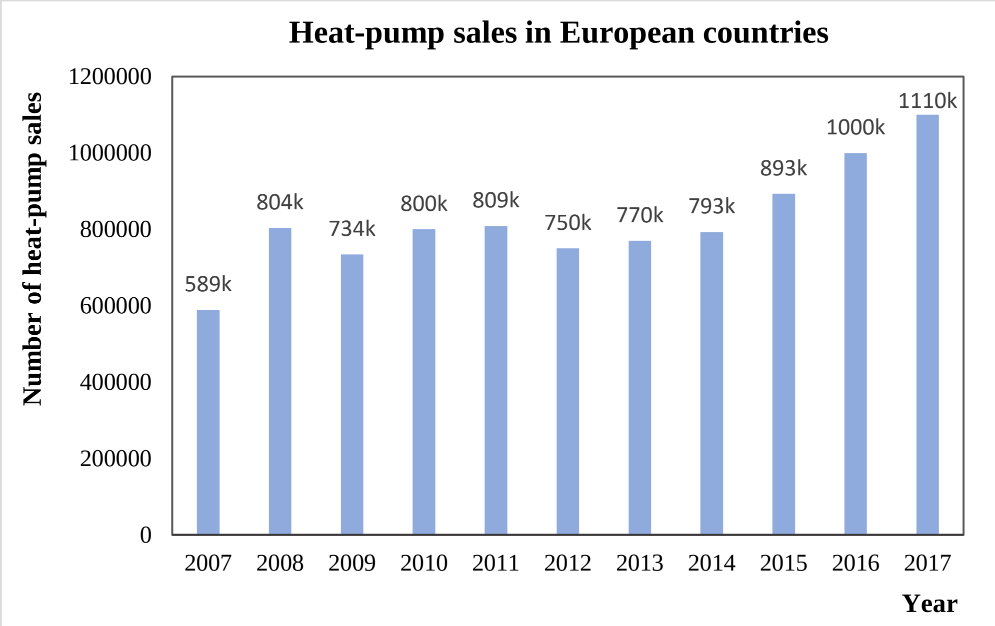



**Figure 2-6: European heat-pump market development 2007-2017. Source: European Heat-pump Association.**

*Graph adapted from:* Nowak (2018a)

*Figure 2-7* illustrates the number of HPs being in operation by country. As seen, the deployment of HPs varies across Europe with the UK having one of the least developed markets.

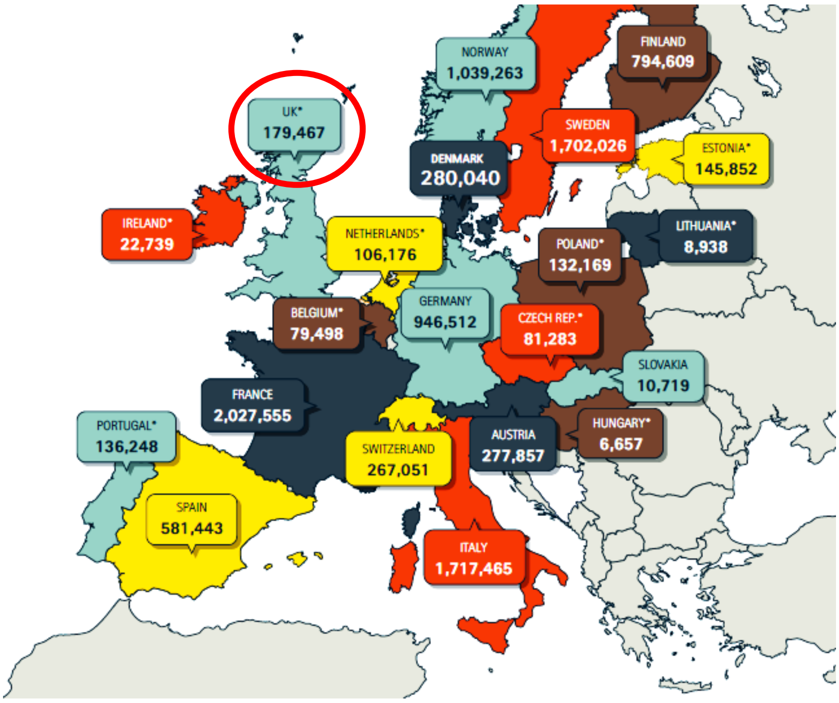



**Figure 2-7: Number of heat-pumps in operation in several European countries in 2018. Source: European Heat-pump Association**

*Figure derived from:* Nowak (2018a)

Nowak (2018a) identified the possible reasons why countries such as France, Italy, Norway and Switzerland have more developed HP markets compared to the UK as follows:

- Energy supply in countries without gas distribution infrastructure (such as Sweden and Switzerland) mainly relies on coal, oil, electricity or biomass and this makes the adoption of HPs easier for multiple reasons. Firstly, HPs gain ground against direct electric heating systems as they reduce operational costs due to their higher effectiveness. The high HP installation costs compared to direct electric heaters are effectively balanced by the significantly lower operational costs of HPs. In addition to that, compared to oil-fired heating systems, the utilization of HPs does not include costs for the maintenance of chimneys. Thus, provided that electricity prices are not too high in these countries (compared to oil), HPs can also compete with oil boilers from an economic perspective. Finally, one of the most significant problems associated with HPs is the fact that they require enough space to be installed. This is a major concern for UK houses, which have very limited free spaces. However, in houses with oil burners, HP retrofit will be simply located where the oil tank is.

- In Scandinavian countries as well as in France, electricity has already a significant share in the overall heating energy use. Therefore, the transition from conventional electric heaters to HPs is smooth mainly due to the fact that users do not suspect electricity as being an ineffective fuel, this being the case for those countries mainly relying on fossil-fuel-based heating systems such as Germany and the UK.
- Governments play a crucial role in establishing electricity as a competitive fuel for heating and thus, in accelerating the penetration rate of HPs in the market. This can be achieved through the adoption of suitable schemes encouraging and financially supporting people to switch to renewable energy systems. An example of this is the UK's RHI, which, however, was found to have significantly underperformed based on the UK Government's expectations (BEIS, 2018a). For the case of the UK, government policies should learn from the misapplication of previous practices and address the significant installation costs of HPs in a way that is of real benefit for consumers.
- Finally, the official ban of conventional fuels, such as coal, oil and gas can significantly contribute to a faster adoption of HPs. For example, Denmark banned the use of oil and gas boilers in new buildings, and later on, oil boilers were also banned for those existing buildings, which could be connected to the gas grid or have access to district energy. Similar actions have been taken by Swedish, Norwegian and Dutch governments. Lately, following the suggestion of the CCC, the UK Government announced that new buildings will be banned from the gas grid by 2025 and this is a very significant step for the development of the HP market.

*Figure 2-8* illustrates the share of the different HP types to the overall HP sales in each of the 22 European countries being members of the EHPA. The prevailing type is ASHPs with AWHPs in particular being almost the only HP type used in the UK. Based on the EHPA statistics, exhaust air HPs have an increased uptake in the

European market and are expected to play a vital role in the future (Nowak, 2018b). Moreover, the adoption of technologically advanced ASHPs such as two-stage compressor units (Safa *et al.*, 2015) or bivalent heating systems consisting of ASHP units supported by condensing gas boilers (Di Perna *et al.*, 2015; Klein *et al.*, 2014) have already drawn the attention of many recent research studies as alternatives to the conventional heat-pumps.

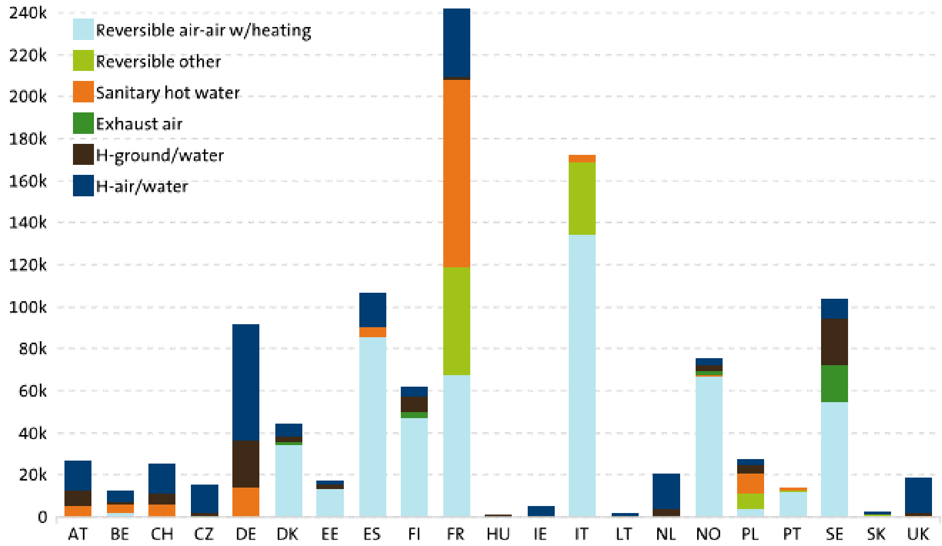



**Figure 2-8: Heat-pump sales by heat-pump type.**

*Figure derived from:* Nowak (2018b)

### 2.5.2 Factors affecting the uptake of heat-pumps in the UK

As discussed in the previous section, HPs have had a low penetration in the UK market so far compared to other European countries. Apart from the installation costs, which are comparatively high in all countries, electricity price in the UK is about 3.5 - 4.0 times higher than gas depending on fuel suppliers. More specifically, although the UK electricity price itself is comparable with that reported for most of the European countries, the price of gas in the UK is the lowest after Romania across Europe. Thus, gas is considerably more appealing in the eyes of consumers from a price perspective. The following paragraphs address other factors that further limit the uptake of HPs in the UK.

HPs are low-inertia heating systems and as such, they operate much more effectively at lower supply temperatures than conventional boilers. Thus, AWHPs should ideally serve underfloor heating systems or low-temperature radiators designed to operate at temperatures varying between 35.0$^{o}$C–45.0$^{o}$C (Fawcett, 2011). However, the common practice followed in UK heat-pump retrofit applications is to integrate the heat-pump to the existing distribution heating system of the building as the retrofit of the distribution heating system will significantly increase cost and cause disturbance to occupants. Most of the existing UK houses have high-temperature radiators (with design flow and return temperature of 75.0$^{o}$C and 65.0$^{o}$C, respectively), which have been originally sized to serve gas boilers. When these radiators are used with typical HPs, their actual flow temperature is significantly lower than the design value with this resulting in reducing their heat emission capacity. More specifically, the heat output of radiators with design flow temperatures at 75.0$^{o}$C might decrease around 40.0% when the flow temperature reduces to 55.0$^{o}$C with the result that thermal comfort will significantly deteriorate (Shah and Hewitt, 2015). These authors monitored the heating performance of AWHPs supplying water at 76.0$^{o}$C. These high-temperature AWHPs were selected to be retrofitted in two hard-to-treat test houses located in Northern Ireland. The results showed that when the retrofitted AWHP was configured to directly supply the radiators of the house (no storage tank was considered in this case), it was capable of achieving  a COP of 2.38.

Another factor that affects the penetration of heat-pumps in the UK is the condition of the existing housing stock. Heat-pumps operate much more effectively when installed in new-built and well-insulated houses (Fawcett, 2011). The existing UK housing stock is one of the oldest and least energy efficient housing stocks in Europe. A significant percentage of existing houses present high fabric heat losses mainly due to insufficient levels of wall and loft insulation. Based on data provided by the English Housing Survey (EHS), around 23% of the existing dwellings in the UK were built before 1920 (MHCLG, 2015). In addition, noise and aesthetic factors have been reported to delay the penetration of heat-pumps in the UK (Singh *et al.*, 2010).

As discussed in the previous section, the UK does mainly rely on the utilisation of gas. As a result, people are not familiar with low carbon heating technologies and generally, the low carbon living concept. The UK Government in conjunction with research institutes should contribute to this direction by gathering and publishing more evidence from in-situ performance of heat-pumps and other low carbon technologies in the UK and other countries with comparable climates. Nevertheless, this cannot be done without investing towards the creation of a mature heat-pump market including a trained and certified installers network in order to eliminate the common faults reported during the design and installation stage of heat-pumps. To conclude, the concerted effort from the government, research, installers and manufacturers is now a priority in order to reverse the bad publicity that heat-pumps have received so far in the UK.

### 2.5.3 Summary

The market trends have shown that from 2015, there is a low but stable growth in heat-pump sales across the UK. In this direction, it is expected that heat-pumps will be widely used within the next few decades and play an important role in the decarbonisation of the UK domestic sector. More specifically, based on provisional estimations, heat-pump sales are expected to double by 2025 (reaching around 48,000 installations) across the UK (Pieterse, 2019). Nevertheless, although several previous studies focused on assessing the employment of AWHPs as a retrofit heating strategy for UK domestic buildings, most of them examined its effectiveness from a single building perspective. However, if heat-pumps are going to become a major part of UK's residential energy evolution, then it is very important to evaluate their applicability at the stock level.

## 2.6 Housing stock energy models (HSEMs)

HSEMs can be constructed at local, regional, national, international or global level to estimate the overall energy use and associated carbon emissions at the stock level. Although the first HSEMs appeared in the UK in the mid-1970s (Sousa *et al.*, 2017), they have recently received attention, as they are considered to be effective tools for helping to achieve the ambitious decarbonisation targets set by the UK Government.

HSEMs are used to inform policies and encourage investments through the exploration and prioritisation of suitable interventions, such as fabric upgrades, integration of renewables and low-carbon technologies, smart metering and others, that can contribute to the reduction of domestic energy demand (Dodds, 2014). To represent reality and reliably predict the impact of energy strategies within a HSEM, the model should include all the information required to achieve satisfactory levels of accuracy. A house comprises a complex system in terms of both housing (geometry, constructions, heating system) and household characteristics (income, socio-economic status, age), the combination of which may be unique amongst the population.

Sousa et al., (2017) carried out a systematic literature review on the existing UK HSEMs focusing on the different model data sources and adopted modelling approaches, the modelling approaches, in particular, varying with the scope, quantity of available data and required level of detail. In this context, the creation of a HSEM can follow either a house-by-house (Steadman *et al.*, 2020) or an archetype-based modelling approach (Rosser *et al.*, 2019; McCallum *et al.*, 2020) or alternatively, a sampling modelling approach (Taylor *et al.*, 2013). The adoption of a house-by-house modelling approach requires time, human resources and increased computational effort, which are not always available or feasible. The use of theoretical building archetypes instead does significantly reduce simulation time and at the same time, facilitate and allow for the targeting of those houses that e.g. are eligible for an energy efficiency measure or require attention from policy. A house archetype represents all those houses amongst the entire population that share similar characteristics. More specifically, each particular house characteristic (e.g. built form, level of wall insulation, total floor area) is clustered in various groups and for each group, a representative value is assigned, with the number of groups being dependent on the scope of the HSEM. In other words, a house archetype does not match any real building, but it is considered to have an average behaviour of all the dwellings that are represented by that archetype (Loga *et al.*, 2016). Lastly, a sampling modelling approach requires the study of a significant number of real houses included in a database, with the selection of house samples being random or systematic (Sousa *et al.*, 2017). Both archetype-based and sampling modelling approaches use weighting factors to aggregate results (e.g. energy demand) at the stock level (Buckley and King-Hele, 2014).

Another important aspect of HSEMs is the quantity of data required to model each dwelling, this depending on the type of the HSEM (e.g. steady-state, dynamic) as well as the level of detail included in the available data sources. One could expect that as the number of input data increases, the capability of a model to make reliable predictions increases. However, HSEMs using very detailed input data are neither economically and timely feasible (in most cases) nor necessarily advisable. As the number of input data increases within a HSEM, the possibility of input errors increases as well (Chapman, 1991). In cases where more data are required than available, a way of filling the missing values is to make suitable assumptions (imputations), which should be consistent for the entire stock and based on manufacturers' datasheets and recognised guidelines such as the Standard Assessment Procedure (SAP), National Calculation Methodology (NCM), Chartered Institution of Building Services Engineers (CIBSE), etc. (Sousa *et al.*, 2017).

The reliability and accuracy of a HSEM is subject to various sources of uncertainty, with these resulting from input data manipulation, heat flow calculation methods, nature of the sampling and archetyping approaches, weather data used, representation of occupancy-related factors, assumptions made for gapping missing values, errors in surveys and measurements, etc. Thus, HSEMs should quantify the impact of these multiple uncertainties on model estimates through the identification of the uncertain input data on which the HSEM is sensitive and the assessment of the simultaneous impact of these inputs on model outputs (Hughes *et al.*, 2013). The following sections focus on different categories of HSEMs and provide an overview of the existing UK HSEMs.

### 2.6.1 Top-down and bottom-up HSEMs

Generally, HSEMs can be broadly categorized as top-down and bottom-up based on the level of input information, adopted calculation and simulation methods and applicability of results provided (Swan and Ugursal, 2009). More complex and sophisticated HSEMs can combine aspects of both top-down and bottom-up modelling techniques (hybrid HSEMs).

***Top-down HSEMs*** work at an aggregated level and are typically used to explore the relationship between energy related variables and macroeconomic factors. More specifically, they use historical data of energy use estimated at the stock level to assess how this varies in relationship with e.g. fuel prices. However, these models rely on past trends and thus, they are not appropriate to deal with climate-change issues and evaluate the impact of future technologies aiming to reduce energy demand of the housing sector. Top-down HSEMs are further divided in econometric and technological with econometric accounting for factors such as income, fuel prices, unemployment rates, gross domestic product, climatic conditions, etc. and technological accounting for saturation effects, technological progress and structural evolution (Swan and Ugursal, 2009; Kavgic *et al.*, 2010). The present work does not focus on top-down HSEMs and thus, a further discussion about existing top-down HSEMs is beyond the scope of the thesis.

***Bottom-up HSEMs*** work at disaggregated level and are used to calculate the energy consumption of individual groups of houses, which are then suitably weighted to estimate energy consumption at the stock level (Swan and Ugursal, 2009). The construction of these particular HSEMs is based on building engineering principles (building physics) and/or statistics. More specifically, bottom-up models can be used to assess the impact of particular house properties (e.g. type of constructions, geometry, insulation levels, air tightness, Heating Ventilation and Air-Condition (HVAC) system) and occupancy-related factors on the energy consumption and associated carbon emissions of the built environment. Bottom-up models utilise data sets including information derived from multiple sources such as Energy Performance Certificates (EPCs), national census, Geographic Information Systems (GIS), surveys, interviews, smart meter data, etc. Depending on the scope of the model, building physics-based HSEMs do employ either steady-state or dynamic calculation methods.

### 2.6.2 Sources of information – English Housing Survey (EHS)

In the UK, an official national census regarding housing stock characteristics and household composition is carried out every ten years, this being updated on an annual basis using regional data, local surveys and estimates from electricity bills and gas sales (BEIS, 2018b; Office for National Statistics, 2018). The UK census contains data for the entire UK housing stock consisting of around 29 million houses. Other sources including UK housing data, as presented by Sousa et al., (2017), are the Energy Follow Up Survey (EFUS) (~ 2.5k samples) being derived from the English Housing Survey (EHS), Homes Energy Efficiency Database (HEED) (~15.0M samples), National Energy Efficiency Data (NEED) framework (~25.0M samples) and Digest for UK Energy Statistics (DUKES) (~27.0M samples).

***English Housing Survey (EHS)***

EHS is a national survey commissioned by the Ministry of Housing, Communities & Local Government (MHCLG) about the condition and energy efficiency of housing and household composition in England. Although this survey has run since 1967, it was firstly composed in its current form in 2008-09. Since then, it is consisted of two separate surveys, these being the English House Condition Survey and the Survey of English Housing (MHCLG, 2017). The survey runs on a continuous basis as part of the Office for National Statistics (ONS) Household Integrated Survey (HIS) and its findings are provided annually in the form of detailed reports (Office for National Statistics, 2017). The EHS is conducted in three stages as follows:

1) annual questionnaire-based interviews of around 16,000 English houses concerning household characteristics, this being the **full survey sample**
2) annual follow-up physical inspections of a sub-set sample of the initial full survey sample (around 8,000 dwellings) to evaluate their condition and energy efficiency, this being the **dwelling sample** and
3) market value survey of the dwelling sample (only physically inspected houses).

As seen, although the full survey sample is based on *household* characteristics, both the follow-up physical inspection and market value surveys are based on *dwelling* characteristics. The MHCLG defines "household" as follows: *one person or a group of people, who have the accommodation as their only or main residence and (for a group) either share at least one meal a day or share the living accommodation, that is, a living or sitting room.* On the other hand, a "dwelling" is defined as: *a self-contained unit of accommodation (normally a house or flat) where all the rooms and amenities (i.e. kitchen, bath/shower room and WC) are for the exclusive use of the household(s) occupying them* (MHCLG, 2009).

The EHS data are available to the public through the website of the MHCLG in the form of two separate data sets. The first data set (EHS Household Data) includes information about household conditions and refers to the full survey sample (all interviewed households). The second data set (EHS Housing Stock Data) includes data about the condition of the physically inspected dwellings and covers a two-year period sample. For example, the 2009 Housing Stock Dataset includes data covering the period between April 2008 and May 2010. The Housing Stock Dataset includes the *primary* data gathered by the interviewer, surveyor and valuer as well as the *derived* and *time-series* data, which are provided in the form of SPSS (Statistical Package foe the Social Sciences) files. The derived data in particular, which are used for the purposes of this thesis, have been created by calculating or recoding the primary data and are mainly organized in three SPSS files (General, Physical and Interview data files). More specifically, information such as tenure type, nature of area and region is included in the *General* data file, while information such as built form (detached, semi-detached, terrace, flat), wall construction type, levels of loft insulation, usable floor area, main heating system type, etc. is included in the *Physical* data file. Finally, the *Interview* file includes data related to occupancy, such as number of adults, number of children, etc (MHCLG, 2009).

At this point, it should be noted that sample sizes used in the EHS may change every year. The size of the household and dwelling samples mentioned before, refers to the EHS of 2008-09, this being the version used for the purposes of this thesis. Each separate house included in the dwelling sample will be referred to hereafter as *house* *archetype*. For each house archetype, a weighting factor is provided by the EHS, this corresponding to the number of "real" English houses that are represented by this respective house archetype. The weighting factors are used to aggregate results and derive estimates of energy use and associated carbon emissions at the stock level.

The EHS data sets have been used (in combination with others) as the input data for many UK housing stock models such as the Building Research Establishment's Housing Model for Energy Studies (BREHOMES) (Shorrock and Dunster, 1997), Johnston's model (Johnston *et al.*, 2005), Domestic Energy and Carbon Model (DECM) (Cheng and Steemers, 2011), UK Domestic Carbon Model (Natarajan and Levermore, 2007) and the Cambridge Housing Model (CHM) (Hughes *et al*., 2013). All these models perform steady-state calculations and use the Building Research Establishment Domestic Energy Model (BREDEM) as the core module for calculating buildings' energy use and associated carbon emissions. The following sections provide a brief description of the CHM and BREDEM calculation methodology. It should be noted at this point that although the present thesis is based on the dynamic simulated performance of houses, some of BREDEM's assumptions about zoning, occupancy and heating patterns will be used. In addition to that, the results obtained by the CHM will be used to verify the modelling approach adopted for the purposes of the present thesis (see Section 3.3).

### 2.6.3 BREDEM methodology

BREDEM, which is consistent with BS EN ISO 13790 Standard, is a steady-state month-to-month calculation methodology that is used to estimate annual energy consumption of UK dwellings (Anderson *et al.*, 2008). Version 9 of BREDEM is also the basis for the Standard Assessment Procedure (SAP), which is the UK's primary methodology adopted to evaluate the energy performance of dwellings.

BREDEM requires a number of input data regarding dwelling's location, fabric, HVAC system, controls, occupancy, lighting, electric and cooking appliances. The model employs a combination of analytical and empirical techniques to perform a simple heat balance calculation, where heat losses are balanced against heat gains and their difference is multiplied by the temperature difference between inside and outside temperature to calculate heating (or cooling) demand on a monthly basis.

BREDEM recommends that dwellings should be divided in two thermal zones as follows: one *living zone* including the main living-room of the house (Zone 1) and one *non-living zone* including the rest of the house (Zone 2) (Anderson *et al.*, 2008). As shown in *Figure 2-9*, BREDEM suggests the application of different heating durations and set-point temperatures between zone 1 and zone 2. More specifically, zone 1 is heated at 21.0$^{o}$C for 9.0 h during a typical weekday and for 16.0 h during the weekend , while zone 2 is heated at 18.0$^{o}$C for 7.0 h per weekday and 11.0 h during the weekend (Anderson *et al.*, 2008).

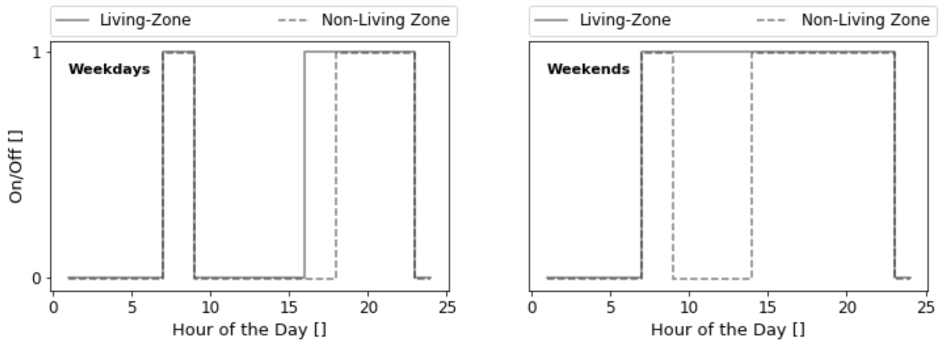



**Figure 2-9: BREDEM Heating Regimes for living and non-living zones of a dwelling during weekdays and weekends**

*Figure adapted from:* Anderson et al. (2008)

Although, the above heating patterns can be valid and reasonable for a "typical" working family with children, it is far from the expected for elderly people tending to remain at home all day or for young couples without children. The variations of households' composition and the fact that people have different heating preferences are neglected by BREDEM and most of the existing HSEMs. This means that many HSEMs do not account for variations of occupants' behaviour such as variations in the number of rooms that occupants choose to heat during the day, duration of heating and set-point temperatures. However, all these are important factors that might significantly affect the heating energy use of a dwelling. For example, by increasing the heating set-point from 20.0$^{o}$C to 22.0$^{o}$C, the heating energy use can increase by

15.0 % (Firth & Wright, 2008). Thus, while current HSEMs can be effectively used to compare different design and retrofit scenarios, they often fail to precisely predict the actual energy use (or associated carbon emissions) of buildings. Another weakness of the BREDEM methodology is the simplified equations that are employed to calculate energy consumption for lighting and electric equipment, with these two depending only on usable floor area of the house and total number of occupants. Such a simplification implies that energy consumption is not influenced by peoples' lifestyle and socio-economic group.

### 2.6.4 The Cambridge Housing Model (CHM)

One of the most recognised BREDEM-based HSEMs is the CHM developed by Cambridge Architectural Research to support the UK Housing Energy Fact File (HEFF) (Palmer and Cooper, 2013) and the Energy Consumption in the UK (ECUK) (BEIS, 2018c). The following paragraphs focus on providing a description of CHM, the data set of which is used for the purposes of this thesis.

CHM ranks among the most transparent and functional UK HSEMs, as it provides a clear and detailed explanation of the calculations and assumptions performed within the model (Sousa *et al.*, 2017). It is an archetype-based HSEM using a data set derived from the national EHS to estimate the energy consumption and associated carbon emissions of the entire UK Housing Stock [1] (BRE, 2011). The core of CHM is BREDEM 8 and SAP 2009 calculation methodologies (Anderson *et al.*, 2008; BRE, 2011). Nevertheless, CHM relatively improves the geometric representation of the modelled dwellings (by also modelling individual house storeys, basements and attics) and accounts for different ventilation types (Sousa *et al.*, 2017). CHM Version 2.7 is used in this thesis, with its data set being derived from the 2009 EHS (Hughes *et al.*, 2013). *Figure 2-10* illustrates the structure of CHM.

[1] Although the main input data of the CHM is the EHS datasets, variables are appropriately scaled (England-to-GB and GB-to-UK scaling factors) based on the number of houses located in England, GB and UK in such a way that the CHM can be also used to calculate the total energy consumption and carbon emissions of the GB and UK, respectively (Hughes *et al*., 2013)

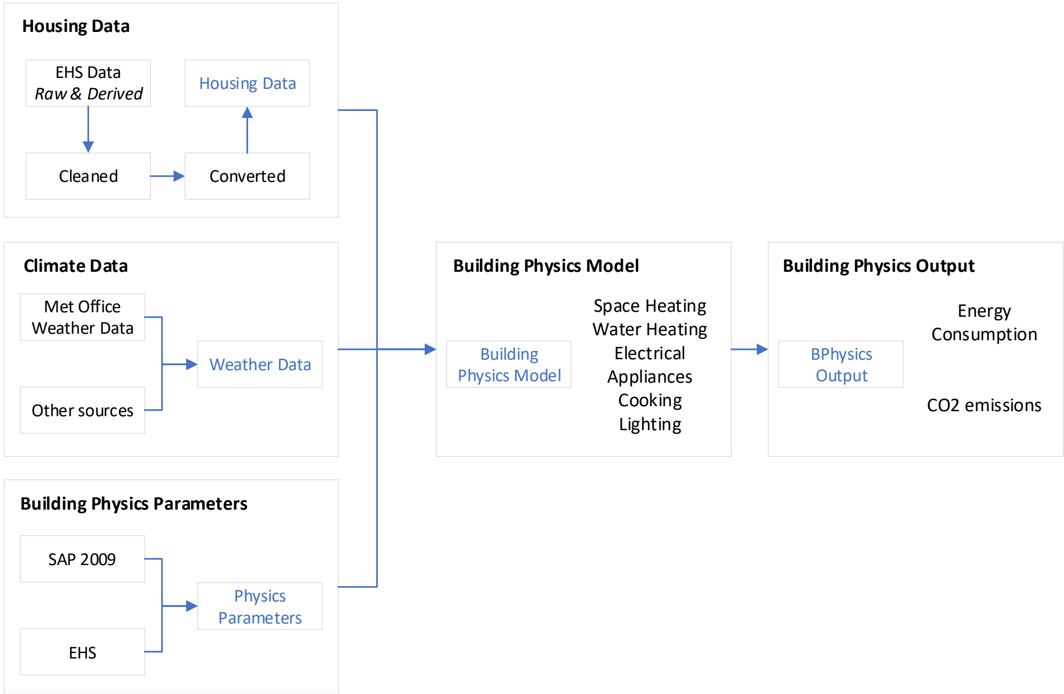



**Figure 2-10: Structure of Cambridge Housing Model (CHM)**

*Source: Hughes et al. (2013)*

The CHM model is built in Microsoft Excel worksheets and runs through Visual Basic for Applications (VBA) macros (Hughes *et al.*, 2013). It contains a total of eight spreadsheets as follows:

*Housing Data* spreadsheet contains all the required house characteristics used to describe the English housing stock. Selected data from various EHS datasets were "cleaned" (to remove any inconsistent elements) and ran through suitable data converters. Whilst most of the data could be directly used from the EHS, suitable converters were employed when data needed to be interpreted, combined or even assumed. After the end of this process, the selected data were copied from the converters to the Housing Data spreadsheet to construct the data set of the CHM (Hughes *et al.*, 2013). CHM Version 2.7 contains 16,150 rows and 109 columns with each different row referring to a single house archetype. Each house archetype is used to represent a certain number of "real" UK houses. As a result, the CHM data set contains information for the entire English housing stock. The information provided for each separate house archetype is as follows: age band, tenure and dwelling type, number of occupants (adults and children, separately), region, number of storeys, floor area of each separate storey, storey height, infiltration rate, type of ventilation system, total door area and door U-value, type of glazing (single, double or mixed), total glazing area of each different glazing type, type of window frame, ground-floor construction, ground-floor heat loss area, ground-floor exposed perimeter, living area fraction, external-wall construction type, total external-wall area, external-wall thickness, total roof area and roof construction type, amount of loft insulation, total party wall/floor/ceiling areas and construction types, internal wall/floor/ceiling areas and construction types, basement characteristics, DHW and main and secondary heating system.

*About the Model* spreadsheet presents a flowchart depicting the link between the different spreadsheets included in the model and briefly describes the contents of the model and the calculations performed in it. *Climate Data* spreadsheet provides monthly weather data for different regions throughout England (outdoor air temperature, wind speed and solar radiation). *Physics Parameters* spreadsheet contains an explanation of all the data included in the Housing Data spreadsheet. *Building Physics Model* spreadsheet contains all the calculations performed within the model. In this spreadsheet, the user has the possibility to input the code corresponding to a specific house archetype or choose the entire housing stock and run the model. *Physics Output* spreadsheet presents all the available outputs regarding energy consumption and associated $CO_2$ emissions for a single house archetype or the entire housing stock (based on user's selection). *Data & Assumptions* spreadsheet provides a list of data, assumptions and variables included in the model. Lastly, *Version History* spreadsheet contains a record of previous versions of the CHM model.

### 2.6.5 Conclusions

Following the shortcomings of the available UK HSEMs as described in the previous sections, there is an increasing need to move towards more sophisticated modelling approaches accounting for dynamic building responses and quantifying the impact of uncertain inputs to model outputs. Due to computational advances, HSEMs are very powerful and informative tools to support policymakers and encourage investments aiming to upgrade the thermal performance of the housing stock. However, current HSEMs lack transparency in terms of modelling algorithms and employed datasets, which might significantly limit their functionality. The lack of open-source HSEMs that can be easily interpreted and used should be addressed as it constitutes one of the most important shortcomings of current models. Secondly, it is crucial to limit model's imputations about occupancy-related factors by feeding HSEMs with information obtained from socio-economic and household surveys. Last but not least, with most of current HSEMs being based on steady-state calculations, it is important to develop models that are able to capture the dynamic interaction between building's components, systems and occupants.

## 2.7 Thermal comfort

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55 defines thermal comfort as "*that condition of mind which expresses satisfaction with the thermal environment*" (ASHRAE, 2004). The sensation of comfort varies from one person to another due to physiological, psychological or cultural factors. In an attempt to assess and quantify the conditions of users' comfort in buildings, several thermal comfort models have been developed and integrated into widely-used building design standards and regulatory documents such as ISO Standard 7730 (BS EN ISO 7730:2005), BS EN 15251:2007 [1] and ASHRAE Standard 55 (ASHRAE, 2017).

### 2.7.1 Fanger's model

The idea of quantifying thermal sensation was firstly introduced by Fanger based on a series of steady-state laboratory and climate chamber experiments. In these experiments, a relatively large group of people wearing standard clothes and

[1] This Standard has been recently replaced by BS EN 16789-1: 2019. However, at the time of the analysis carried out for the purposes of this thesis, BS EN 15251:2007 was used.

performing sedentary activities were exposed to various thermal environments. Their thermal sensation was expressed using a seven-point scale known as the Predicted Mean Vote (PMV), which ranges from -3 (cold) and +3 (hot), with 0 expressing thermal neutrality. Based on heat balance principles and the subjects' perception of comfort, Fanger concluded that the conditions of thermal comfort can be evaluated through the combination of six individual factors as follows: *indoor air temperature*, *mean radiant temperature*, *air velocity*, *relative humidity*, *metabolic rate* and *clothing value (clo)*. Fanger developed another equation to relate PMV index with the percentage of people that are not satisfied within a specific environment, this being expressed with the Predicted Percentage of Dissatisfied (PPD) index (Fanger, 1970).

Fanger's PMV/PPD model does not account for thermal adaptation. This refers to the fact that people make their own conscious or unconscious decisions to adapt within a thermal environment, with thermal adaptation being broadly categorized as physiological, behavioural and psychological (De Dear and Brager, 2001). In other words, people interact with the building, change their behaviour and adapt their expectations to match the thermal environment (De Dear and Brager, 1998). In this context, previous studies have shown that Fanger's PMV/PPD model applies more effectively to buildings with a steady-state environment; these are sealed and mechanically cooled/heated buildings, usually offices, where users' metabolic rate and clothing insulation are usually standard or vary within a narrow range (Peeters *et al.*, 2009). For free-running and naturally ventilated buildings, adaptive thermal comfort models should be used instead. Most of the current comfort models, which are included in reputed building design standards have incorporated adaptive comfort criteria.

### 2.7.2 Standards for assessing thermal comfort in domestic buildings

The World Health Organization (WHO) recommends that during daytime, air temperature should not fall below 21.0$^{o}$C and 18.0$^{o}$C in living-rooms and bedrooms, respectively. At night, room temperatures should be approximately 2.0$^{o}$C - 3.0$^{o}$C lower than daytime. More specifically, the heating system of each house should be designed to reach a minimum air temperature of 21.0$^{o}$C in bathrooms and living-rooms, 18.0$^{o}$C in bedrooms and 16.0$^{o}$C in kitchens and all other circulation areas, when outdoor temperature is 0.0$^{o}$C (Ranson, 1988). It should be noted that these recommendations are valid only in case where the difference between air and wall temperature is less than 3.0$^{o}$C, as low radiant temperatures can reduce indoor comfort by causing events of local discomfort. In this case, the operative air temperature, which is defined as the average of air and wall temperature, should be considered instead. The Cold Weather Plan for England also mentions that indoor temperatures of no less than 18.0$^{o}$C do not pose a significant health risk for a sedentary person wearing comfortable clothes (Katiyo *et al.*, 2015). The following paragraphs review current comfort criteria incorporated in building design standards that can be used to assess thermal comfort conditions in mechanically heated domestic environments.

As shown in *Table 2-1*, BS EN 15251:2007 standard establishes four building categories based on PPD/PMV ranges. Although category IV is considered to be outside comfort criteria, it might be acceptable for limited periods. The building categories I, II and III are also referred in ISO 7730 Standard as A, B and C, respectively (BS EN ISO 7730:2005, 2006). The lowest PMV value for each category is recommended to be considered as the lowest acceptable limit when designing mechanically heated buildings. In a similar way, highest PMV values should be used as limits when designing mechanically cooled buildings. *Table 2-1* also reports the optimum operative temperature for each different building category.

**Table 2-1: Recommended ranges of PMV/PPD and operative indoor temperature for the design of mechanically heated and cooled buildings (BS EN 15251:2007)**

| **Category** | **Thermal Comfort** | | **Operative Temperature (ºC)** | | **Level of Comfort/ Description** |
|---|---|---|---|---|---|
| | **PPD (%)** | **PMV (-)** | **Living spaces** | **Other spaces** | |
| **I** | <6 | 0.2<PMV<0.2 | 21.0 | 18.0 | **High** vulnerable occupants |
| **II** | <10 | 0.5<PMV<0.5 | 20.0 | 16.0 | **Normal** new buildings |
| **III** | <15 | 0.7<PMV<0.7 | 18.0 | 14.0 | **Moderate (acceptable)** existing buildings |
| **IV** | >15 | PMV<-0.7 or PMV>0.7 | - | - | **Outside comfort criteria** acceptable only for limited periods |

*Table 2-2*, provides the metabolic rate (met), clothing insulation value (clo) and optimum operative air temperature for various rooms of the house based on CIBSE Environmental Guide A (CIBSE, 2006). As seen, operative air temperatures required by CIBSE are generally higher compared to the EN 15251 standard.

**Table 2-2: Recommended operative temperature ranges for standard activity and clothing in different dwelling rooms (CIBSE, 2006)**

| Room Type | Activity: Metabolic Rate (met) | Clothing: Clothing Insulation (clo) | Operative Temperature Range (°C) |
|---|---|---|---|
| **Living room** | 1.1 | 1.0 | 22-23 |
| **Bedroom** | 0.9 | 2.5 | 17-19 |
| **Kitchen** | 1.6 | 1.6 | 17-19 |
| **Bathroom** | 1.2 | 0.25 | 20-22 |
| **Toilet** | 1.4 | 1.0 | 19-21 |
| **Circulation areas** | 1.8 | 0.75 | 19-24 |

## 2.8 Chapter summary

Chapter 2 was organized in two parts covering the following areas: a description of the AWHP technology and its application in UK domestic buildings; and an overview of the different housing stock modelling approaches (with a focus on UK HSEMs).

Firstly, the AWHP technology was introduced and its operational mechanism was described from a component viewpoint. Then, the practicality of coupling AWHPs with TES was discussed and the most common system configurations were identified drawing evidence from academic literature and similar systems that are available and sold in the UK market. Following that, the penetration of heat-pumps in the UK market was discussed and compared with other European countries having similar climatic characteristics. For the purposes of this chapter, previous works in the field (simulation, monitoring, field studies) were reviewed and discussed with their findings being promising for the future of AWHPs in the UK. Finally, the second part of this chapter focused on describing existing housing stock modelling approaches adopted within the UK context.

In contrast to most previous works evaluating the AWHP retrofit from a single-building perspective, the present thesis aims to investigate their applicability at the stock level using dynamic BPS.  The number of houses studied and the fact that these houses  have been modelled using data from real UK houses will help establishing a deeper insight into the heating performance of AWHPs. The findings form this thesis can then be used to inform policies and retrofit decision making for the applicability of AWHPs in combination with fabric retrofit targets for UK dwellings in a way that hitherto has not been possible.

Chapter 3

# Methodology

## 3.1 Introduction - overview of the methodological approach

Chapter 3 presents the data, methods and tools that are employed to address the aim and individual objectives of the present thesis (as presented in Section 1.2). The developed methodology is based on the simulated performance of a number of house archetypes (selected to represent the housing stock of the NE region of England), which are used to explore the variation of AWHPs' heating performance between buildings presenting a wide range in physical properties. *Figure 3-1* illustrates a schematic diagram of the developed methodological approach.

The selected housing stock is modelled using data that are derived from the data set of the CHM (Hughes *et al.*, 2013), with the CHM using information from the national EHS of 2009 (2009 EHS) (MHCLG, 2009) (the contents and structure of both EHS and CHM were described in Section 2.6.2 and Section 2.6.4, respectively). An in-house building generation tool, referred to hereafter as IDF (Input Data File) creator, reads the data set of the CHM and automatically generates house models suitable to be studied using a dynamic simulation engine, which in the case of this thesis is EnergyPlus ($E^+$). In Section 3.2, the structure of the IDF creator is described combined with the assumptions required in order to make CHM data suitable to be used for the case of constructing dynamic house models. The adopted housing stock modelling approach is *verified* using an inter-model comparison technique, which focuses on investigating whether the created house models can effectively represent the distribution of the heating energy demand across the modelled stock (Section 3.3). The composition of the selected housing stock as well as the categorisation of the included house archetypes is presented in Section 3.4. An AWHP unit coupled with supplementary electric heating is then modelled for each individual house archetype as a retrofit heating solution to meet its space-heating and hot water demand throughout the entire heating season (from October to May included). The size, configuration, characteristics and control of the AWHP retrofit are selected based on AWHP systems that are available and sold in the UK market (Section 3.5). Each house model with the integrated AWHP system is simulated in $E^+$ under both current and future weather scenarios (Section 3.6) Finally, the characteristics of the performed $E^+$ simulations are described in Section 3.7.

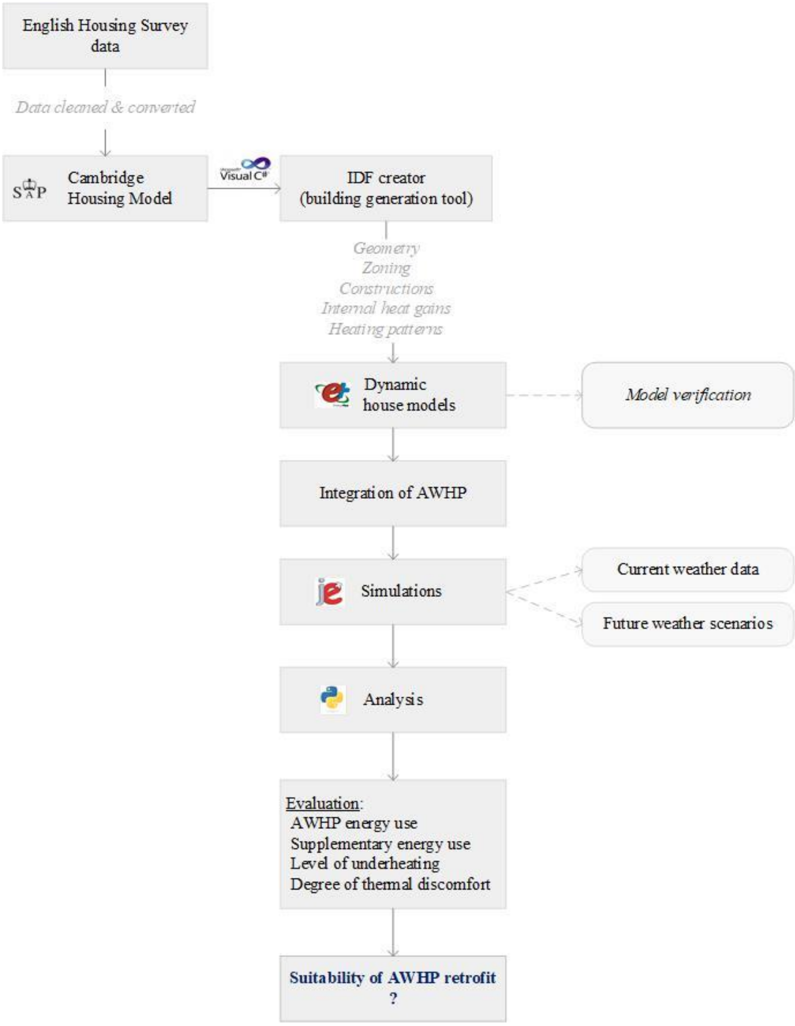



**Figure 3-1: Methodological approach**

## 3.2 Housing stock representation

Excluding flats (which are outside the scope of the present thesis), the housing stock of the NE region of England is represented in the CHM data set by 756 unique house archetypes with each archetype representing a number of real houses located in this region. The level of detail used to represent each house archetype in the CHM data set is not sufficient to construct dynamic house models suitable to be studied using a dynamic simulation engine. $E^+$, in particular, requires an increased amount of data compared to most of the existing steady-state models developed for UK buildings (Badiei, 2018). Section 3.2.1 describes how the data set of the CHM is exploited in order to construct dynamic house models and Section 3.2.2 presents the additional data used to define the full three-dimensional geometry of the selected house archetypes as well as some further assumptions that needed to be made regarding zoning, constructions and internal heat gains.

### 3.2.1 IDF creator

The IDF creator is an *in-house* building generation tool developed in Visual Studio using C# programming language. The C# code processes the data set of the CHM to automatically generate house models that can be simulated using the $E^+$ simulation engine (He *et al.*, 2014). More specifically, to run the IDF creator, three separate text files (txt) are required with the first including the house data as derived from the CHM data set and the second and third including user-defined $E^+$ objects. For each separate run, the IDF creator processes all the house data included in the first txt file to create $E^+$ objects, which are then combined with the user-defined $E^+$ objects included in the second and third txt files to create comma delimited *Input Data Files (IDFs).* The number of IDFs generated per each run depends on the number of houses included in the first txt file (each row contains data for one house). Each generated IDF contains all the required information to perform an $E^+$ simulation for a particular house. The contents of the three txt files are described in the following paragraphs.

It should be noted that IDF creator runs separately for all those houses that have the same number of storeys, with the number of storeys determining the number of thermal zones (zoning will be explained in detail in Section 3.2.2). For the case of the housing stock of the NE region of England, the 756 included house archetypes might have one, two or three storeys and therefore, the IDF creator should be used three times to generate all the required $E^+$ house archetype models.

The **first txt file** used by the IDF creator contains selected house data from the *Housing Data* spreadsheet of the CHM (see Section 2.6.3) as well as some additional data directly derived from the original EHS data set. The included data for each house archetype are processed through the C# code to generate the geometry of each house archetype, distribute the windows and doors to its building envelope, create constructions for its exposed-walls, floors, roof, etc. and assign infiltration rates, number of occupants etc., to each different house archetype. In other words, the first txt file includes all these data that vary from one house to another and need to be processed through the C# code in order to be appropriately assigned to each house archetype. Through the C# code, suitable $E^+$ objects are created, which are automatically integrated in the final IDF of each house archetype.

The second and third txt files contain user-defined $E^+$ objects that are applied *as they are* to every separate house archetype. In other words, the user-defined $E^+$ objects included in the second and third txt files are not processed through the C# code, but they are directly integrated in the final IDF of each individual house archetype. More specifically, in the **second txt file**, the user can define all those $E^+$ objects that are common for all the house archetypes and are not associated with thermal zones such as schedules, simulation parameters (e.g. timestep, run-period), location-related factors (e.g. longitude, latitude), requested output variables, etc. The **third txt file** contains all the zone-dependent $E^+$ objects with the number of objects depending on the number of thermal zones. For example, a two-storey house has three thermal zones and thus, it contains three baseboards heaters, which are represented by three different E+ objects. Similarly, a three-storey house with four thermal zones contains four baseboard heaters, which are represented by four E+ objects.

To conclude, for each house archetype, the $E^+$ objects created by the process of the first txt file plus the user-defined $E^+$ objects included in the second and third txt files are put together by the IDF creator to form an IDF file including all the required information in order for each house archetype to be simulated using $E^+$.

### 3.2.2 Assumptions

#### *Geometry*

Dynamic energy modelling requires the definition of the full three-dimensional geometry of a building. The data set of the CHM only provides for each house archetype the number of storeys, the height and floor area of each storey and the external perimeter of the ground-floor. To generate the full geometry of the selected house archetypes, additional data were extracted from the original EHS Housing Stock Datasets; these data include the shape of the building, the width and depth of its external-walls as well as the width and depth of the living-room.

All houses are assumed to be either rectangular or L-shaped. For the case of L-shaped dwellings, the EHS data sets also provide the location of the additional rectangle in relationship with the main one. There are in total twelve possible locations of the additional rectangle, with these being in the middle, left or right corner of any of the four sides of the main rectangle. However, for simplicity reasons, the additional rectangle is modelled to be attached in the right-back side of the main rectangle for all the L-shaped house archetypes with this being its actual location in most cases (He *et al.*, 2014).

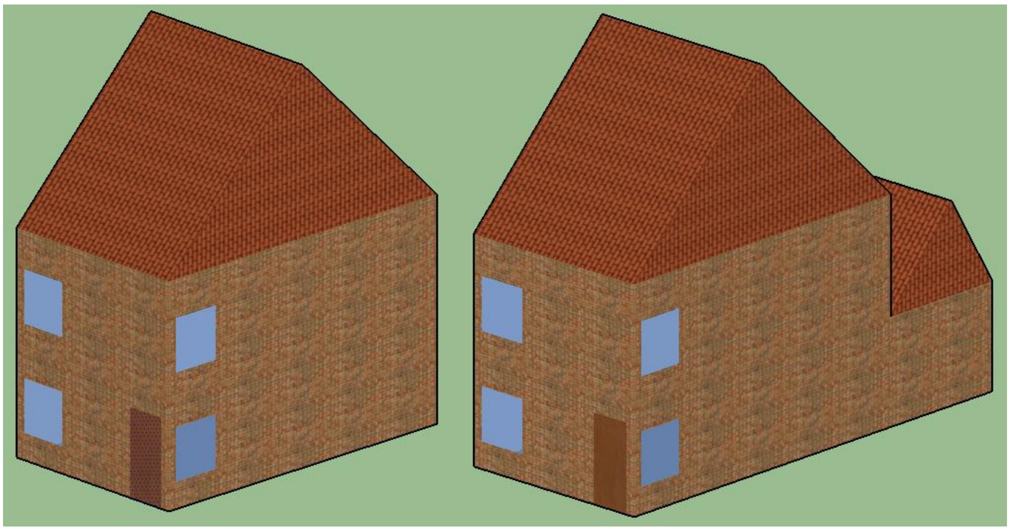


**Figure 3-2: Geometry of rectangular and L-shaped house archetypes**

The living-room is considered to be a separate thermal zone located in the ground-floor of each house. Based on the dimensions of the living room and dimensions of the external-walls of the house, there are five and four possible locations of the living-room for the L-shaped and rectangular dwellings, respectively. The different ground-floor layouts are illustrated in *Figure A-1* and *Figure A-2* in the *Appendix A*.

***Zoning***

In the context of building energy modelling, a thermal zone is defined as follows "*an air volume at a uniform temperature plus all the heat transfer surfaces bounding that air volume* (external-walls, roofs, floors) a*nd the heat storage surfaces inside that air volume* (e.g. partitions separating spaces that have the same temperature) (EnergyPlus, 2016a). In $E^+$, the user has the possibility to implement as many thermal zones as desired. Based on the definition of thermal zone, the number of thermal zones in a building model could depend on its heating regime in a such a way that all rooms following the same heating pattern could be modelled as a separate thermal zone.

SAP recommends to divide a house into two thermal zones, these being the *living zone* containing the largest room of the house (living-room or lounge usually following a different heating regime compared to the other rooms of the house) and the *non-living zone* containing the rest of the house (SAP, 2014) (see also Section 2.6.3 for BREDEM methodology). Nevertheless, thermal zones cannot be extended to more than one floor (Anderson *et al.*, 2008). Therefore, the ground-floor of each house archetype is divided into two thermal zones, one living and one non-living zone, while each upper floor is assumed as a separate non-living thermal zone. For the case of the present thesis, the 756 modelled houses have up to three storeys. Thus, all the one-storey houses are modelled to have two thermal zones, all the two-storey houses are modelled to have three thermal zones and all the three-storey houses are modelled to have four thermal zones.

The living zone of each house is considered to include only the living-room. The non-living ground-floor zone is assumed to include the kitchen, dining-room and a corridor, while bedrooms and bathrooms are located in the upper floors of the house. For the case of one-storey dwellings, bedrooms are considered to be accommodated in the non-living zone of the ground-floor. The internal heat gains (due to the occupancy, lighting and electric appliances) will be applied in each separate thermal zone of the house based on the type of the rooms that it accommodates.

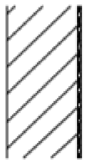
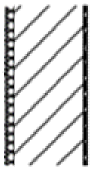
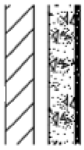
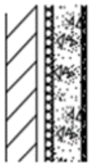
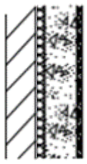
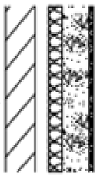
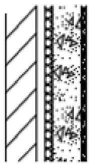
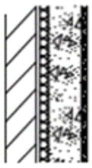
***External-wall constructions:***

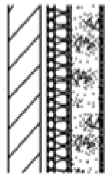
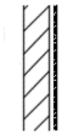
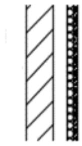
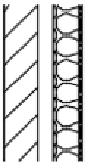
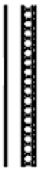
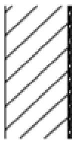
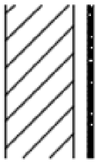
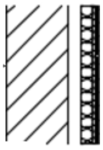
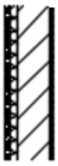
The CHM data set specifies the external-wall type for each house archetype as: *solid brick*, *cavity* (no insulation), *filled cavity* (cavity wall filled with insulation), *timber frame*, *system build* (with no or external insulation) or *metal frame*. However, it does not include any further information regarding the particular materials used for each construction with this being a required input for generating $E^+$ models. This issue was resolved using the recommendations given by the UK Government's Standard Assessment Procedure in Appendix S: *Reduced Data SAP for existing dwellings* (RdSAP). RdSAP, in particular, was developed to be used for existing dwellings in case that their available data is not sufficient to perform a SAP calculation (SAP, 2014).

Table S6 of RdSAP recommends the U-value for various external-wall types based on the age band of the house. In this work, the external-wall construction type (e.g. "filled-cavity") and the age band of the house (as both reported in the CHM data set) are used to select the U-value of external walls, the U-value then being used as an indicator to assign the different material layers in each case. In other words, the different materials combined with their thermal properties are selected in such a way that the overall U-value of the wall matches the given RdSAP value. *Table 3-1* illustrates the external-wall constructions used for the case of this thesis.

For example, if the construction of the external-wall is specified as "unfilled cavity" in the CHM data set and the age band of the house is E, the simulated U-value of external-walls is considered to be equal to 1.67 W/m$^2$K. In this case, the materials used are modelled to be as follows: exposed brick (0.105m), airspace (0.050m), concrete (0.100m) and dense plaster (0.013m). It should be noted that the *system build* construction type refers to non-traditional wall constructions being built using some type of systemized process (not directly built on the construction site) and consisting of 200.0 mm heavy concrete blocks (SAP, 2014). *Table 3-2* illustrates the different SAP age bands.

**Table 3-1: External-wall constructions**

| Wall type | Age band | Material layers (from outside to inside layer) | Simulated U-value ($W/m^2K$) |
|---|---|---|---|
| **Solid brick** | A-D |  0.225m brick<br>0.013m dense plaster | 2.06 |
| | I |  0.020m external render<br>0.050m EPS<br>0.225m brick<br>0.013m dense plaster | 0.44 |
| **Cavity wall (unfilled)** | A-E |  0.105m brick<br>0.050m airspace<br>0.100m concrete<br>0.013m dense plaster | 1.67 |
| | F |  0.105m brick<br>0.030m airspace<br>0.020m mineral wool<br>0.100m concrete<br>0.013m dense plaster | 0.92 |
| | G, H |  0.105m brick<br>0.050m EPS<br>0.100m concrete<br>0.013m dense plaster | 0.54 |
| | I, J |  0.105m brick<br>0.050m airspace<br>0.050m PF<br>0.100m concrete<br>0.013m dense plaster | 0.39 [1] |
| **Filled cavity wall** | A-E |  0.105m brick<br>0.025m airspace<br>0.025m PUR<br>0.010m concrete<br>0.013m dense plaster | 0.64 [2] |
| | F |  0.105m brick<br>0.050m PUR<br>0.010m concrete<br>0.013m dense plaster | 0.40 |

| | | | | |
|---|---|---|---|---|
| | G-J |  | 0.105m brick<br>0.025m airspace<br>0.025m PUR<br>0.050m mineral wool<br>0.100m concrete<br>0.013m dense plaster | 0.36 |
| | C |  | 0.105m brick<br>0.019m plywood<br>0.013m plasterboard | 1.85 |
| **Timber frame** | E |  | 0.105m brick<br>0.050m airspace<br>0.020m mineral wool<br>0.013m plasterboard | 0.80 |
| | G, H |  | 0.105m brick<br>0.050m airspace<br>0.080m EPS<br>0.013m plasterboard | 0.39 |
| **Metal frame** | D |  | 0.006m LW metallic cladding<br>0.050m airspace<br>0.030m EPS<br>0.013m dense plaster | 0.88 |
| **System built/solid wall** | D |  | 0.200m concrete<br>0.013m plasterboard | 2.06 |
| | E |  | 0.200m concrete<br>0.050m airspace<br>0.013m plasterboard | 1.70 |
| | F |  | 0.080m concrete<br>0.050m EPS<br>0.100m concrete<br>0.013m dense plaster | 1.00 |
| **System built/external insulation** | D, E |  | 0.020m external render<br>0.025m PIR<br>0.100m concrete<br>0.013m plasterboard | 0.57 |

[1] Based on RdSAP, for age bands I and J, U-values should be considered equal to 0.45 $W/m^2K$ and 0.35 $W/m^2K$, respectively. An average U-value of 0.39 $W/m^2K$ is considered here for both age bands I and J

[2] Based on Table S6 RdSAP, the U-value for filled cavity walls being built before 1983 should be considered equal to 0.50 $W/m^2K$. In this thesis, this is adjusted to 0.65 $W/m^2K$ based on CHM following DECC's request (Hughes *et al*., 2013)

**Table 3-2: SAP Age Bands**

| Period of Construction | SAP Age Band |
|---|---|
| Before 1900 | A |
| 1900-1929 | B |
| 1930-1949 | C |
| 1950-1966 | D |
| 1967-1975 | E |
| 1976-1982 | F |
| 1983-1990 | G |
| 1991-1995 | H |
| 1996-2002 | I |
| 2003-2006 | J |
| 2007- | K |

***Ground-floor construction:***

The CHM data set specifies the construction of ground-floor for the selected house archetypes as *solid* (slab on ground, screed over insulation) or *suspended timber* (insulation between joists). However, the insulation thickness (if present) used for each construction is not specified. Following a similar approach as for the case of external walls, the insulation thickness of the modelled ground-floor constructions is determined based on the age band of the house as recommended in Table S11 of RdSAP.

***Loft insulation:***

The modelled house archetypes have either pitched or flat roofs. For those houses with pitched roofs, insulation (if present) is considered to be located in the upper ceiling level (insulation at joists). A unique construction with varying insulation levels is used for the upper ceiling of all the selected house archetypes. The CHM data set provides the loft insulation thickness for most of the selected house archetypes. Thus, for houses, in which the insulation thickness is known, Table S9 of RdSAP recommends that the U-value of loft construction varies between 2.30 $W/m^2K$ (no loft insulation) and 0.11 $W/m^2K$ (insulation layer of more than 300.0 mm). In cases where loft insulation thickness is not known, the upper ceiling of the house has been modelled so that it achieves the U-value recommended in Table S10 of RdSAP based on the age band of the house (SAP, 2014).

***Windows:***

The CHM data set provides the total single and double-glazed area for each house archetype without further specifying the percentage of glazing area facing east, west, north or south. There are house archetypes that are partly double-glazed and thus, they have both single and double-glazed windows.

For house archetypes that have either only single-glazed windows or only double-glazed windows, it is assumed that the total glazing area is equally distributed in the exposed walls of the house. On the other hand, for house archetypes with both single and double-glazed windows, the fraction of the single-glazed to total glazed area is calculated and each individual window is divided into single and double-glazed area accordingly. For example, if the total single-glazed and total double-glazed area of one house are equal, then each window of that house is modelled as 50.0 % single-glazed and 50.0% double-glazed. In all cases, window height is modelled to be equal to 1.20m.

***Internal Heat Gains***

The CHM data set provides the number of adults and children for each house archetype. It is assumed that occupants' presence in each thermal zone of the house follows space-heating patterns in such a way that occupants are modelled to be active during those periods that the heating system is ON in that zone. For those periods that the heating system is ON in more than one zone, occupants are equally distributed in these specific zones.

Space-heating patterns have been derived from BREDEM for the living and non-living zones of the house (see *Figure 2-10* in Section 2.6.3). It should be noted that all occupants are assumed to be away from home between 9 am and 4 pm during weekdays, while for the rest of the week (including the weekends), the house is considered to be fully occupied. Sleeping period is assumed to be from 11 pm to 7 am for the entire week, where all occupants are modelled to be in their bedrooms (and the heating system is modelled to be OFF).

Regarding heat gains from artificial lighting and electric equipment, the CHM dataset does not contain any measured data for the modelled house archetypes. To address this issue, the database of the National Calculation Methodology (NCM) was used; this specifies design values for lighting and electric equipment heat gains for the different rooms of the house in Watts per square metre. It also contains schedules accounting for the hourly variation of design values during the day with these schedules being different for weekdays and weekends. Lighting and electric equipment heat gains were applied to each separate thermal zone of the house based on the specific use of the rooms that it accommodates. Thus, the living zone follows the daily patterns provided for the lounge in the NCM database and non-living zones of the upper floors follow the daily patterns provided for bedrooms. Similarly, the internal heat gains for the non-living ground-floor zone are considered to be a weighted average of the internal heat gains provided in NCM for kitchen, dining room and corridors (plus bedrooms in the case of one-storey dwellings).

## 3.3 Inter-model comparison – model verification

An *inter-model comparison* technique between $E^+$ and CHM is employed in this thesis as a model verification technique to assess the suitability of the developed $E^+$ house models to represent the variability of the heating energy demand across the modelled stock. Generally speaking, the inter-model comparison involves the direct comparison of the outputs obtained by two or more models, which use equivalent inputs. This technique does not require the use of real (measured) data in order to evaluate the validity of a model (Judkoff *et al.*, 2008). The main drawback of applying comparative testing as a model verification technique is the absence of a *truth model*. The inter-model comparison should be ideally applied between models that are based on completely different modelling or solution approaches. For example, when the comparison between a steady-state and dynamic modelling approach shows good agreement, it is quite possible that the building is adequately modelled and described by both the steady-state and dynamic model (Judkoff *et al.*, 2008). In addition to that, comparative tests are inexpensive and quick and do not involve any significant input uncertainty as modellers can control the accuracy of every single input and eliminate the sources of external errors; these include any error that is not dependent on the internal workings (calculations) of the simulation and is linked to user’s inputs and assumptions (weather data, occupancy pattern and behaviour, etc.).

In this thesis, the space-heating energy demand as obtained by the $E^+$ simulations is compared for the modelled 756 house archetypes against CHM predictions. More specifically, the CHM predictions are used here as a benchmark against which the $E^+$ model predictions can be compared. In CHM, the space-heating energy demand of each individual dwelling is given explicitly as *space-heating requirement*. In $E^+$, the space-heating energy demand of each individual house archetype can be easily obtained by assuming that space-heating is provided using an *ideal air load* heating system with infinite capacity and 100.0 % efficiency.

The purposes of this model verification technique are:

- to confirm that the automatically created $E^+$ models result in an appropriate distribution of heating energy demand across the modelled housing stock (Section 3.3.1)
- to compare the magnitude of the predicted heating energy demand between $E^+$ and the CHM (Section 3.3.2)

The latter was the scope of a previous work focusing on the development of house models suitable to be simulated with $E^+$ using SAP equivalent input data (Badiei, 2018). Having matched the input data between the two models, this author applied an inter-model comparison between the outputs (space-heating energy demand and indoor air temperatures) obtained by $E^+$ and SAP for 83 semi-detached houses. The results showed that the differences of the space-heating energy demand between the two models were in the range of 1.0 % – 17.0 % implying that the dynamic nature of the building physics cannot be fully captured by steady-state models. The effect of thermal mass was found, in particular, to have the greatest impact on models' predictions.

For the case of this thesis, matching the input data between $E^+$ and CHM is outside the scope of the research. It is true that each of the 756 house archetype is defined by a large number of input parameters (heat gains from occupants/lighting/electric appliances, occupancy and heating patterns, heating set-point temperatures, infiltration/ventilation rates, weather data, etc.); the interpretation of these parameters as well as their relationship to the CHM and $E^+$ model input parameter values is different in each case and therefore, difficult to compare. However, the magnitude of the predicted heating energy demand between the two modelling approaches is compared in Section 3.3.2 and the implications of the difference between the two for the simulations results will be discussed later in the thesis (Section 6.2.2).

### 3.3.1 Distribution of the heating energy demand

The shape of the probability distributions for the two modelling methods (CHM and $E^+$) can be compared if the space-heating energy demand of each house archetype is normalised. In this case, for each modelling method, the normalisation is based on the following equation:

$$\chi_{normalised} = \frac{\chi - \chi_{min}}{\chi_{max} - \chi_{min}} \quad \text{(Equation 3-1)},$$

where $\chi$ is the *actual* space-heating demand of the house, $\chi_{min}$ is the minimum space-heating demand found among all house archetypes and $\chi_{max}$ is the maximum space-heating demand found among all house archetypes (with separate maxima and minima identified for the CHM and $E^+$ results). This normalisation method scales all data to have values between 0.0 and 1.0 (*feature scaling*).

*Figure 3-3* illustrates that the (normalised) space-heating energy demand across the housing stock has almost identical frequency distribution when houses are modelled by either the CHM (blue) or $E^+$ (green). This conclusion is further supported by the similarity in the cumulative probability curves shown in *Figure 3-4*.

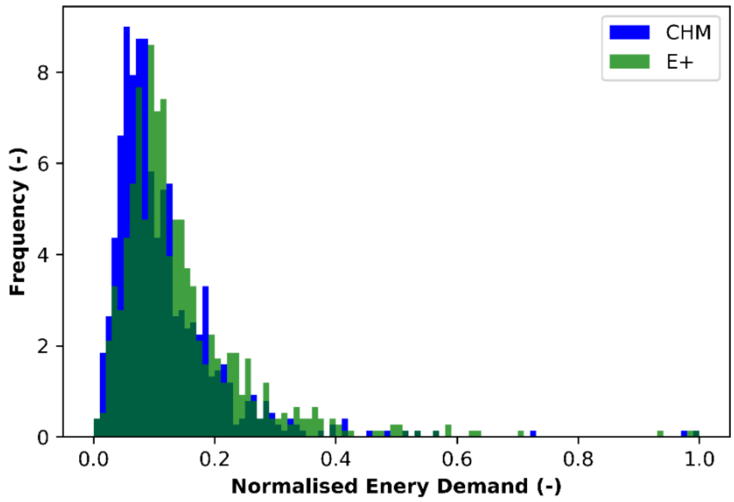



**Figure 3-3: Frequency distribution for the normalised space-heating energy demand (bins=100)**

The cumulative probability is used to predict the probability that a value has to fall within a specific range. As it can be seen in *Figure 3-4*, the probability of a house's space-heating energy demand to be less than or equal to the first 50.0 % of the range of all houses' space-heating energy demands is almost the same for both modelling methods.

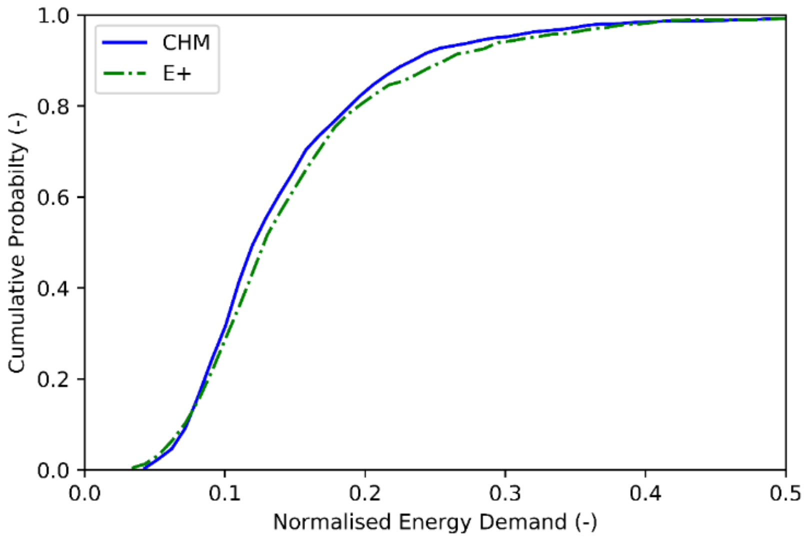



**Figure 3-4: Cumulative probability distribution of the space-heating energy demand of the modelled housing stock**

*Figure 3-5*, illustrates the annual space-heating energy demand of all the modelled house archetypes for both $E^+$ and CHM. The *Spearman Rank Correlation coefficient (R)* for the two predicted space-heating energy demands is 0.94 with this revealing a very close positive correlation between the results obtained by the CHM and $E^+$. The Spearman Rank Correlation coefficient (R) is calculated based on *Equation 3-2*:

$$\boldsymbol{R} = \frac{\mathbf{1}-(\mathbf{6}*\sum \boldsymbol{d}^{\mathbf{2}})}{\boldsymbol{n}^{\mathbf{3}}-\boldsymbol{n}} \quad \text{(Equation 3-2),}$$

where $\Sigma d^2$ is the sum of the square difference of the CHM and $E^+$ heating energy demand of each house archetype and $n$ is the total number of the house archetypes (756).

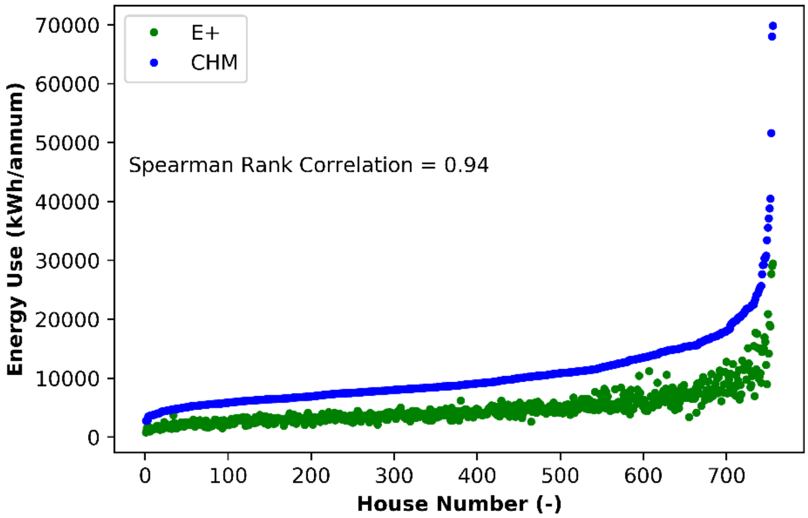



**Figure 3-5: Rank-ordered predicted energy demand**

To conclude, the fact that the distribution of the space-heating energy demand across the modelled stock is similar for both the $E^+$ and CHM models gives confidence that the adopted $E^+$ modelling approach is suitable for representing the diversity of the energy demand across the stock. This conclusion is considered to be valid following the definition and principles of the inter-model comparison technique; this indicates that in the absence of a “true” model, comparative tests between different models can be used instead to increase the level of confidence that a model is suitable for a specific purpose (in this case, to represent the diversity of the energy demand across the stock).

### 3.3.2 Magnitude of the heating energy demand

Although the CHM and $E^+$ house models result in the same shaped distribution, $E^+$ gives a lower predicted space-heating energy demand than the CHM. As shown in *Figure 3-6*, the mean difference between the two models is 54.0 % with a standard deviation of 8.0 %.

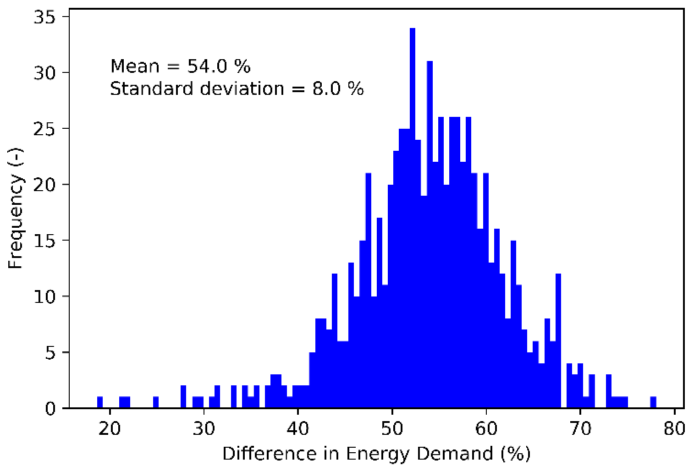



**Figure 3-6: Frequency distribution of the difference between the heating energy demand of CHM and $E^+$**

A complete resolution of the cause of the heating energy demand under-prediction by $E^+$ is outside the scope of the present thesis. Section 6.2.2 will provide a discussion on possible reasons of this under-prediction by summarizing findings as included in Badiei (2018) as well as observations resulting from the present work (Section 6.2.2)

### 3.3.3 Conclusions

As shown, the distribution of the predicted heating energy demand across the modelled housing stock is very similar when the 756 house archetypes were modelled by either the CHM or $E^+$; this increases the level of confidence that the automatically generated $E^+$ models result in an appropriate distribution of the heating energy demand across the modelled stock. It should be highlighted again that the similarity of heating loads distribution obtained between the two models does not imply that both models are correct. It just *increases the level of confidence* that the models can appropriately represent the variability of the heating energy demand across the stock.

Each house's *peak space-heating demand power* as predicted by $E^+$ will be used to select the size of the AWHP (represented by nominal heating capacity) that will be integrated in each house archetype. More specifically, the nominal heating capacity of the retrofitted AWHP for each house archetype will be selected so that it is equal to or greater than the *peak space-heating demand power* of the house as predicted by $E^+$. Based on the similarity of heating loads distribution between $E^+$ and CHM, it is highly expected that $E^+$ simulation gives a good (similar to the reality) prediction of the variation of heating loads across the housing stock (even if the absolute values of theses loads might be lower than reality). As a result, matching AWHP's size to the house's peak heating load as predicted by $E^+$ will result in a good (similar to the reality) prediction of the pattern of AWHP's heating performance across the examined housing stock. For example, it is expected that the pattern of under-heating (resulting from the AWHP retrofit) will be similar to the reality as the AWHP's size is matched to the $E^+$ simulated loads, and as such, will respond to the changes in simulated load.

## 3.4 **Housing stock of the NE region of England**

The housing stock of the NE region of England consists of 756 house archetypes; these are selected to represent 978,490 real houses with flats and empty houses being excluded from this study. The modelled house archetypes cover a wide variation in size, built form (detached, semi-detached, terrace), level of infiltration, age of construction with the age, in particular, resulting in a wide range of wall and loft constructions and states of repair. This section presents the composition of the selected housing stock in terms of building characteristics (Section 3.6.1) and discusses the categorisation of the house archetypes based on which the results of the simulations will be presented in Chapters 4 and 5 of the present thesis (Section 3.6.2).

### 3.4.1 Composition

*Figure 3-7* illustrates the variations of the modelled house archetypes in terms of age band (period of construction), built form, construction of external-walls, glazing type, range of total conditioned floor area (in $m^2$), range of total conditioned volume ($m^3$), thickness of loft insulation (in mm) and range of infiltration rate (in air changes per hour, ach). The graphs depict the proportion of houses that share a specific characteristic (e.g. single-glazed windows) or belong to a specific category (e.g. have a total floor area in the range of 70-95 $m^2$). The term *mixed* in the "Glazing Type" graph refers to those houses that are reported to be partially retrofitted with double-glazed windows.

In *Figure 3-8*, the 756 modelled house archetypes are grouped based on the combination of their age band and construction type of their external walls. The colour of each box indicates the number of houses lying in each group (see colour-bar next to the figure) and the number inside each box indicates the simulated U-value for their external walls. For example, the first green box indicates that some 40-60 houses have been built before 1900 and have solid brick external walls (no insulation) with U-value of 2.06 $W/m^2K$. As seen, the lowest U-value across the modelled housing stock is 0.36 $W/m^2K$ and this is observed for houses with filled cavity walls that have been built after 1983. Further, as seen, house archetypes that have been built after 1983 and are reported to have unfilled cavity external-walls also present relatively low U-values (0.54 $W/m^2K$ for houses being built between 1983-1990 and 0.39 $W/m^2K$ for houses being built between 1991-2006). Based on Table S6 of RdSAP, all house archetypes that have been built after 1983 (unless they are reported to have solid brick walls) should be considered to have insulated walls even if they are reported to have unfilled cavity walls. This means that the external-wall construction itself does not indicate the level of insulation and thus, does not reflect the level of fabric heat losses of a specific house. Therefore, it would be more reasonable to categorise house archetypes based on their U-value rather than external-wall construction type. For the rest of the thesis, houses will be reported as having no external-wall insulation (U-value $\geq$ 1.50 $W/m^2K$), medium levels of external-wall insulation (0.50 $W/m^2K \leq$ U-value < 1.50 $W/m^2K$) and (relatively) high levels of external-wall insulation (U-value < 0.50 $W/m^2K$).

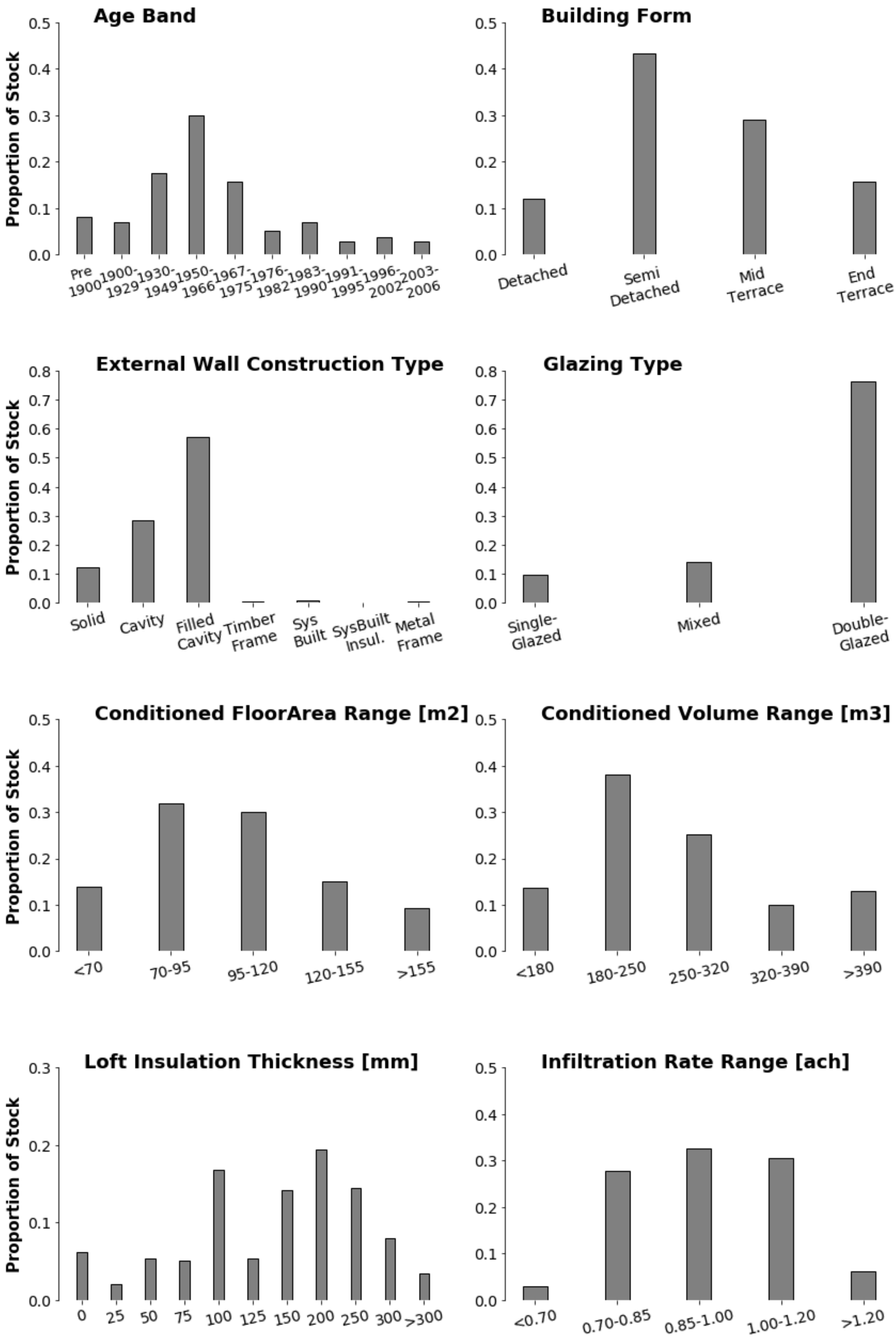



**Figure 3-7: Characteristics of the modelled housing stock**

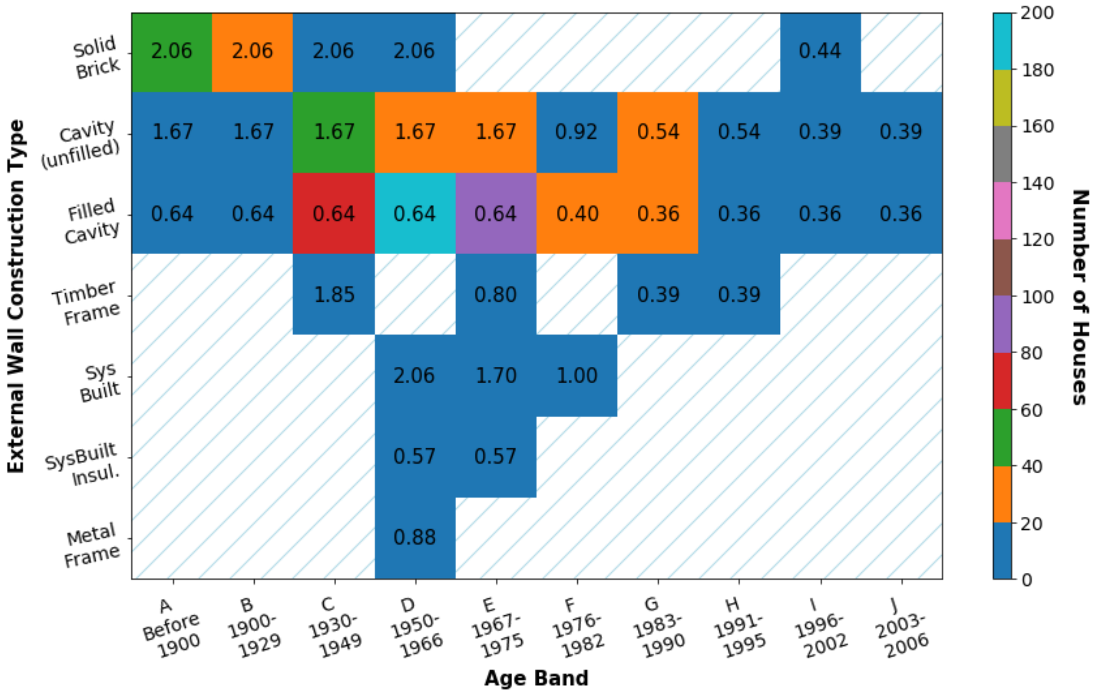



**Figure 3-8: Simulated U-value (W/m$^2$K) and number of houses per external-wall construction type and age band**

### 3.4.2 Categorisation of house archetypes

The present thesis aims to identify *which house archetypes* across the modelled housing stock are suitable for adopting an AWHP as a retrofit heating solution. In other words, this study aims to indicate the combination of those characteristics that make a house suitable or not for the AWHP retrofit. Due to the number of the examined houses (756 house archetypes), the simulation results cannot be presented for each house separately. Thus, it is necessary to categorise houses; the categorisation should be based on those house characteristics that are considered to be the most influential for the houses' thermal performance. In this work, all the house archetypes are modelled under the same weather conditions (same location) and heating regimes (same set-point temperatures and duration of heating per day). Therefore, the construction of the house itself (size, shape, materials used, built form, etc.) and number of occupants are those factors that differentiate one house from another.

*Figure 3-9* illustrates the number of house archetypes per various categories, with the categorisation being based on the U-value of external walls, built form and total conditioned dwelling's volume. More specifically, *Figure 3-9*, consists of three separate plots, with each plot including houses with no, medium and high levels of exposed-wall insulation (U-value ≥ 1.50 W/m$^2$K, 0.50 W/m$^2$K ≤ U-value < 1.50 W/m$^2$K and U-value < 0.50 W/m$^2$K, respectively). The x-axis of each plot represents different built forms; detached, semi-detached/end-terrace and mid-terrace houses (semi-detached and end-terrace houses are treated as the same building form, as their envelope is similarly exposed to the outside environment, and this means that when built at same standards and sizes, they have similar surface-to-volume ratios and thus, they are expected to present similar heat losses through their exposed walls). The y-axis of each plot represents the total conditioned volume of each house archetype, with the attic being unconditioned in most of the modelled houses (only 7.5 % of the modelled house archetypes include habitable rooms in their roof).

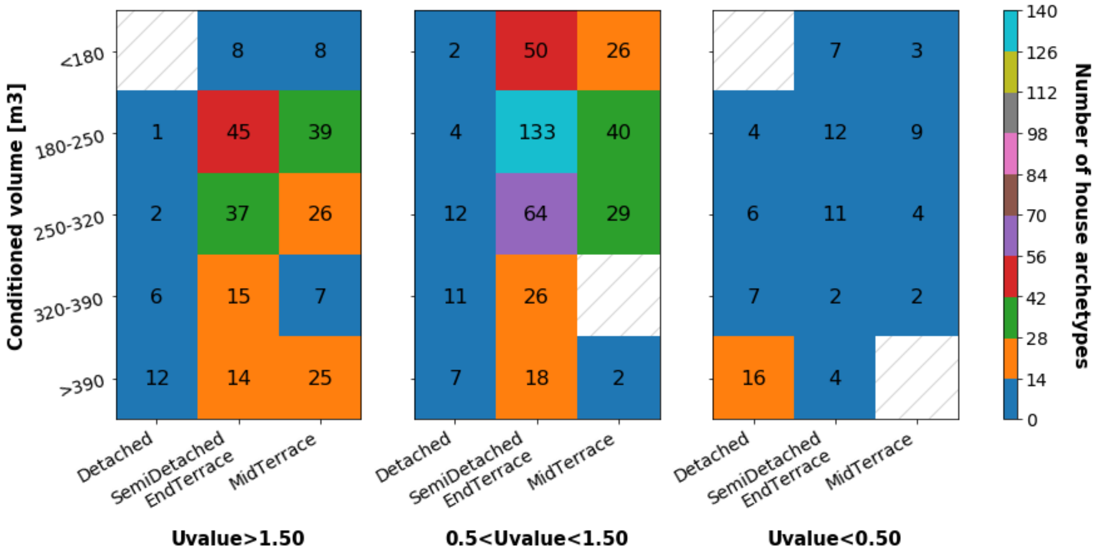



**Figure 3-9: Number of house archetypes per external-wall insulation level, built form and floor area**

Each of these **45 house categories** (**3** *U-value ranges* **x 3** *built forms* **x 5** *volume ranges*) includes house archetypes with similar characteristics in terms of exposed-wall thermal properties, level of exposed surface area and size. These 45 house categories will be mainly used to perform the analysis of the simulated housing stock in Chapter 4 and Chapter 5 of this thesis. For example, the energy consumption of a specific house category (e.g. semi-detached houses with no wall insulation and conditioned volume between 180-250 $m^3$) will be shown as the average value of the energy consumption of all house archetypes lying in this category. The categorisation of the examined house archetypes depends on the identification of those input parameters that 1) differentiate the heating demand between the selected houses and 2) are among the most influential for a house's heating demand. In this context, the selection of the above characteristics (external-wall U-value, total conditioned dwelling's volume and built form) are justified through the consideration of basic engineering principles and a previous sensitivity analysis study conducted for the CHM by Hughes *et al*. (2013).

A building's heating demand depends on the balance between its heat losses (through fabric and due to ventilation/infiltration) and heat gains (due to solar and internal heat gains). Fabric heat losses are conducted through the external-walls, roof, ground-floor, windows and pedestrian doors with the external-walls having the largest share. More specifically, in an average UK house, external-walls account for approximately 33.0 % of the house's total fabric heat losses. Thus, the **U-value** and **total surface area of external-walls** are considered to be critical parameters for the thermal performance of the house; the total surface area of the external walls, in particular, can be represented by the combination of the dwelling's built form and total conditioned volume.

The selection of the above characteristics for categorising the examined house archetypes is further supported by a sensitivity analysis that is implemented for the CHM in order to identify the most influential input parameters for the energy consumption of houses (Hughes *et al*., 2013). This sensitivity analysis is carried out to evaluate the significance of 29 input parameters by changing each parameter individually and assessing the impact of this change on the energy consumption of the house (one-at-a-time sensitivity analysis). Normalised sensitivity coefficients are extracted for each of the 29 input parameters and in descending order, the *internal demand temperature*, *effectiveness of heating system*, *external temperature*, *total floor area*, *storey height* and *daily heating hours* are found to be by far the most significant input parameters. Other parameters such as *wall U-value, wind speed, infiltration rate, window U-value* and *roof U-value* come after (in descnding order as well). However, in the case of this thesis, the internal demand temperature and daily heating hours are selected to be the same for all the examined houses. In addition to that, external temperatures are also the same across the stock, as all houses are simulated under the same weather conditions. Furthermore, an AWHP is considered to be retrofitted in each house with the effectiveness of the system (represented by nominal COP) presenting very limited differences between the houses; the nominal COP for the different AWHP units is shown in *Table 3.4* in Section 3.5.1. Thus, total floor area, storey height and also, U-value are the most influential parameters that differentiate the heating demand of the 756 modelled house archetypes used for the purposes of this thesis. The total floor area and storey height are combined and represented by the dwelling's total conditioned volume.

Further, it is evident from *Figure 3-9* that there is a significant variation in the number of houses being included in each category, ranging from 1 to 133 houses. The low number of houses lying in some categories indicates that a strictly statistical comparison of the results is not possible. So, any comparison of results between different categories is justified through consideration of engineering principles (for instance, as the U-value and floor area increase, it would be expected that the annual heating energy demand would also increase). *Figure 3-9* also shows that most of the simulated house archetypes (133 out of 756) are semi-detached houses with medium levels of external-wall insulation and total conditioned volume in the range of 180-250 $m^3$.

## 3.5 Retrofit of an AWHP heating system

The heating system that is considered to be retrofitted in each house archetype consists of an electrically driven AWHP coupled with auxiliary electric heating; both the AWHP and auxiliary electric heater are linked to a storage water tank. The system is modelled to meet the space-heating and hot water demand of each individual house archetype for the entire heating season (from October to April included).

*Figure 3-10* illustrates the configuration of the retrofitted heating system. As shown, the energy produced by the heat-pump is transferred to a storage water tank through which is then delivered to the Domestic Hot Water (DHW) tank and radiators of each house (with the radiators being modelled as convective baseboard heaters). The architecture of the retrofitted AWHP system is similar to these used in previous works (Kelly *et al.*, 2014; Asaee *et al.*, 2017).

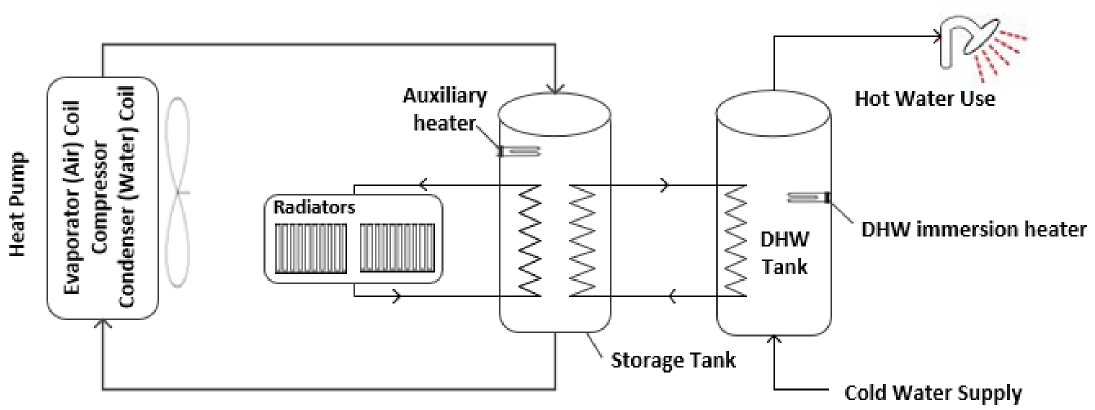



**Figure 3-10: Configuration of the retrofitted heating system**

### 3.5.1 Air-To-Water-Heat-Pump system model

The AWHP system is developed and modelled in E+ simulation engine using a compound object named *WaterHeater:HeatPump:PumpedCondenser*, which includes an ON-OFF fan (*Fan:OnOff)*, a heat-pump unit containing the evaporator, condenser and compressor (*Coi:WaterHeating:AirToWaterHeatPump:Pumped*) and a mixed storage water tank (*WaterHeater:Mixed*).

The heat-pump unit is considered to be the primary heating source, while the auxiliary electric heater located inside the storage tank is a secondary heating source operating when the heat-pump is either unable to meet the entire heating demand of the house or is scheduled to be OFF due to low ambient temperatures; the operation and control of the retrofitted heating system will be explained in detail in Section 3.5.5.

***AWHP unit***

The AWHP unit includes an air heat exchanger (evaporator), a water heat exchanger (condenser), an electric compressor and a water pump cycling ON and OFF with the compressor. The AWHP unit is considered to be located outdoors and thus, the temperature of the air entering the evaporator is modelled to be equal to the outdoor Dry-Bulb Temperature (DBT).

In actual AWHP installations, the system is controlled to perform a defrost (or reverse) cycle when the combination of DBT and relative humidity is below a specific limit. This is applied in order to avoid the accumulation of frost on the evaporator side of the AWHP. During defrost cycling, the operation of the evaporator and condenser are reversed, and the AWHP operates in cooling mode. This means that heat is extracted from indoor environment and used to defrost the evaporator. To account for the possibility of frost accumulation in this present thesis, the compressor of the modelled AWHP system is controlled to switch OFF when DBT falls below 2.0 $^{o}$C; this is employed as a *frost-protection technique* to prevent the AWHP from operating under severe weather conditions. In this case, heating is solely supplied by the auxiliary electric heater as it will be further explained in Section 3.5.5. The threshold of 2.0$^{o}$C is selected based on performance curves provided for typical AWHP units that are widely used for UK domestic applications (Mitsubishi Electric, 2015). These performance curves show that the defrost operation starts when DBT falls below 2.0$^{o}$C (the application of the frost-protection technique is considered in this thesis instead of reverse cycling as the employed AWHP $E^+$ model does not account for defrosting through reverse cycling).

Several AWHP systems that are available in the UK market have been reviewed (Viessmann, 2012; Mitsubishi Electric, 2015). The *Ecodan* AWHP units provided by Mitsubishi Electric offer a range of AWHPs suitable to be used for domestic applications in new and existing UK houses. The *Ecodan* AWHP unit comes in four different nominal heating capacities (A2/W35); 5.0 kW (AWHP Unit A), 8.5 kW (AWHP Unit B), 11.2 kW (AWHP Unit C) and 14.0 kW (AWHP Unit D). The manufacturer's technical guides contain detailed information regarding their characteristics, performance, operation and control. All this information is gathered and used to model representative AWHP heating systems, which are considered to be retrofitted in the (756) selected house archetypes. For each individual house archetype, the nominal heating capacity of the retrofitted AWHP is selected to be equal to or higher than the (annual) peak space-heating power demand of the house. The selection of AWHP's heating capacity for each modelled house archetype is further discussed in Section 3.5.2. The characteristics of the four different AWHP units are presented in *Table 3-3*.

**Table 3-3: Characteristics of the four modelled AWHP units representing *Ecodan* AWHP products (Mitsubishi Electric, 2015)**

| | | **AWHP Unit A** | **AWHP Unit B** | **AWHP Unit C** | **AWHP Unit D** |
|---|---|---|---|---|---|
| **Heat-pump (A2/W35)** | Nominal Heating Capacity (kW) | **5.0** | **8.5** | **11.2** | **14.0** |
| | Nominal COP () | 3.50 | 3.17 | 3.34 | 3.11 |
| | Power Input (kW) | 1.43 | 2.68 | 3.35 | 4.50 |
| | Pump Power Input (kW) | 0.01 | 0.046 | 0.01 | 0.02 |

The nominal values of the heating capacity and COP specified in *Table 3-3* imply that each AWHP unit is expected to achieve these respective values under a standard combination of DBT and condenser water temperature. In this case, as specified in manufacturer's guide, these DBT and condenser water temperatures are 2.0$^{o}$C and 35.0$^{o}$C, respectively. As the temperature difference between condenser water temperature and DBT increases, both heating capacity and COP of the AWHP are expected to decrease. In $E^+$, the adopted AWHP model offers the possibility to specify suitable *performance curves* that vary the heat-pump's heating capacity and COP as a function of DBT and condenser water temperature. Mitsubishi manufacturer's guide contains detailed data that can be used to construct these performance curves, the required data being included in tables showing the value of heat-pump's heating capacity and COP for various combinations of DBT and water temperature (Mitsubishi Electric, 2015).

**Table 3-4: Heating Capacity and COP Performance Curves for the four retrofitted AWHP units (Mitsubishi Electric, 2015)**

| | | |
|---|---|---|
| **Unit A** | $Q_{Heating,Max} = (1.2 + 8.5 * 10^{-3} * x - 3.4 * 10^{-4} * x^2 - 1.3 * 10^{-2} * y + 1.4 * 10^{-4} * y^2 + 1.3 * 10^{-5} * x * y) * Q_{Nominal}$ | (Equation 3-3) |
| | $COP_{Max} = (2.1 + 7.9 * 10^{-2} * x + 2.2 * 10^{-4} * x^2 - 4.4 * 10^{-2} * y + 2.0 * 10^{-4} * y^2 + 1.2 * 10^{-3} * x * y) * COP_{Nominal}$ | (Equation 3-4) |
| **Unit B** | $Q_{Heating,Max} = (0.9 + 1.1 * 10^{-2} * x - 3.4 * 10^{-4} * x^2 + 3.1 * 10^{-3} * y - 3.2 * 10^{-5} * y^2 + 3.6 * 10^{-6} * x * y) * Q_{Nominal}$ | (Equation 3-5) |
| | $COP_{Max} = (2.2 + 6.6 * 10^{-2} * x + 3.3 * 10^{-4} * x^2 - 3.9 * 10^{-2} * y + 2.0 * 10^{-4} * y^2 - 9.4 * 10^{-4} * x * y) * COP_{Nominal}$ | (Equation 3-6) |
| **Unit C** | $Q_{Heating,Max} = (1.0 + 7.0 * 10^{-3} * x - 4.7 * 10^{-4} * x^2 + 3.3 * 10^{-5} * y - 5.3 * 10^{-6} * y^2 + 2.8 * 10^{-5} * x * y) * Q_{Nominal}$ | (Equation 3-7) |
| | $COP_{Max} = (1.4 + 5.2 * 10^{-2} * x + 4.2 * 10^{-4} * x^2 - 6.7 * 10^{-3} * y - 1.5 * 10^{-4} * y^2 - 5.9 * 10^{-4} * x * y) * COP_{Nominal}$ | (Equation 3-8) |
| **Unit D** | $Q_{Heating,Max} = (1.0 + 6.4 * 10^{-3} * x - 4.2 * 10^{-4} * x^2 - 7.3 * 10^{-4} * y + 6.3 * 10^{-6} * y^2 + 7.3 * 10^{-6} * x * y) * Q_{Nominal}$ | (Equation 3-9) |
| | $COP_{Max} = (1.5 + 5.3 * 10^{-2} * x - 1.8 * 10^{-5} * x^2 - 9.0 * 10^{-3} * y - 8.4 * 10^{-5} * y^2 - 6.5 * 10^{-4} * x * y) * COP_{Nominal}$ | (Equation 3-10) |

As shown in *Table 3-4*, for each of the four AWHP units, two performance curves are employed. These vary the nominal heating capacity ($Q_{Nominal}$) and nominal COP **(**$COP_{Nominal}$**)** of each AWHP unit based on second-order polynomial equations depending on the temperature of the air entering the evaporator (x*)* and the temperature of the water entering the condenser (*y*). Therefore, for each simulation timestep, the maximum possible COP ($COP_{,Max}$) and the maximum available heating capacity

($Q_{Heating,\ Max}$) of each AWHP is calculated for the current combination of DBT and condenser water temperature based on the above performance curves. It should be noted that the additional heat generated by the condenser's pump is considered to be included in the $Q_{Heating,Max}$. *Figure 3-11* illustrates the COP variations for the four modelled AWHPs based on DBT (ambient temperature) and condenser water temperature variations.

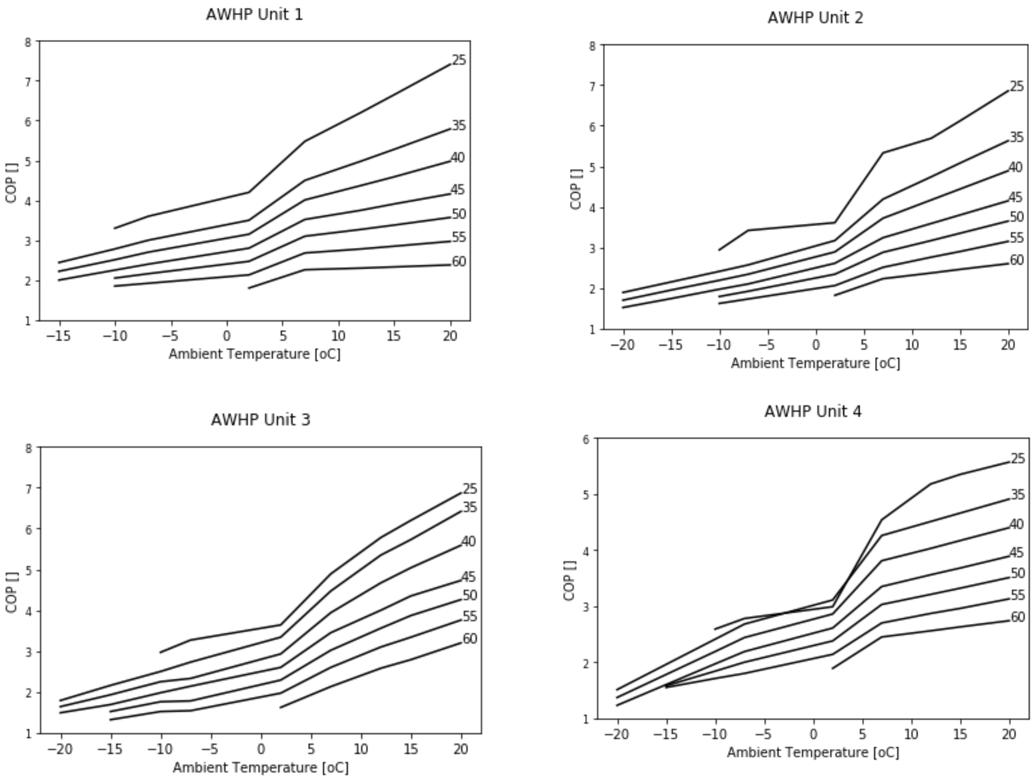



**Figure 3-11: COP Performance curves for the four selected AWHP units (Mitsubishi Electric, 2015)**

In $E^+$, the user can also specify a *part-load fraction correlation curve* accounting for efficiency losses due to the potential cycling of the compressor. In this thesis, the default curve recommended by $E^+$ has been employed to calculate the Part-Load Fraction (PLF), which is used to parametrize the variation of electrical power input to the AWHP as a function of the Part-Load Ratio (PLR) (EnergyPlus, 2016b). The PLF varies for each simulation timestep as follows:

$$\boldsymbol{PLF = 0.85 + 0.15 * PLR}, \quad \text{(Equation 3-11)}$$

$$\boldsymbol{PLR} = \frac{\boldsymbol{Q_{Heating}}}{\boldsymbol{Q_{Heating,\ Max}}}, \quad \text{(Equation 3-12)}$$

As shown in *Equation 3-12*, the PLR is defined as the ratio of the total water heating that is *actually* delivered by the AWHP ($Q_{Heating}$) to its maximum (available) water heating capacity ($Q_{Heating,\ Max}$). Both PLR and PLF are equal to 1.0 only when the AWHP operates under full-load conditions, this implying that the compressor runs continuously for a specific simulation timestep and the heat-pump delivers its maximum (available) water heating output.

To calculate the actual COP and the total electric power (electricity consumption) of the AWHP for each simulation timestep, *Equation 3-13* and *Equation 3-14* are employed by the $E^+$ simulation engine as follows:

$$\boldsymbol{COP} = \boldsymbol{COP_{,MAX}} * \boldsymbol{PLF}, \quad \text{(Equation 3-13)}$$

$$\boldsymbol{P_{Heating}} = \frac{\boldsymbol{Q_{Heating}}}{\boldsymbol{COP}}, \quad \text{(Equation 3-14)}$$

***Storage water tank***

The AWHP unit is linked to a storage water tank, through which the heat is transferred to the radiators and DHW tank of each house. The storage water tank is supplied with a capacity-limited electric heater, referred to hereafter as auxiliary electric heater, which operates as a secondary heating source and provides supplementary heating only when the AWHP is not able to meet the entire heating demand of the house. More specifically, the auxiliary electric heater operates in two cases as follows: 1) to meet the entire demand of the house when the outdoor temperature is lower than 2.0 $^{o}$C and thus, the AWHP is off due to the application of the frost-protection technique or 2) to top-up the energy supplied by the AWHP in case the latter is unable to meet the entire demand of the house.

The storage water tank is modelled as a well-mixed (no water stratification is considered) and perfectly insulated tank (no parasitic or on-off cycle losses are considered). It indirectly heats both the radiators and the DHW tank using two heat exchangers (with the heat exchangers being modelled in $E^+$ using the

*HeatExchanger:FluidToFluid* object). The storage water tank has a volume of 200.0 litres for all the selected house archetypes and the maximum heating capacity of the auxiliary electric heater is modelled to be equal to 3.0 kW.

### 3.5.2 Sizing

This section presents the method applied to size the AWHP unit that is considered to be retrofitted in each of the 756 selected house archetypes. As discussed in Section 2.4.2, based on MIS 3005, the size of the AWHP unit (represented by nominal heating capacity) shall be selected in such a way that the AWHP itself shall be capable of meeting 100.0 % of the design heating load of the house without considering the contribution of any supplementary electric heater (BEIS, 2017). It should be noted that, in this case, the design heating load shall be calculated when the AWHP operates on space-heating mode.

In the present thesis, the design space-heating load of each house archetype is considered to be equal to the hourly peak heating power (throughout the entire heating season) that should be supplied in order to meet the space-heating requirement of the house. This results from the dynamic simulation of each house archetype using the CIBSE weather file for Newcastle, UK (referring to a current weather scenario) and assuming that space-heating is supplied by an "ideal" heating plant with infinite capacity and 100.0 % efficiency. Hence, the size of the retrofitted AWHP for each house archetype is selected so that the nominal heating capacity of the AWHP matches or exceeds the peak space-heating demand power of the house.

As previously mentioned, the AWHP unit, which is selected to be retrofitted in the modelled houses, comes in four different nominal heating capacities; these are equal to 5.0 kW, 8.5 kW, 11.2 kW and 14.0 kW. *Figure 3-12* illustrates the number of house archetypes that are retrofitted with each of the four selected AWHP units. As seen, most of the houses have a 8.5 kW AWHP unit; this is the most typical AWHP size for UK domestic applications (Kelly and Cockroft, 2011; Kelly *et al.*, 2014).

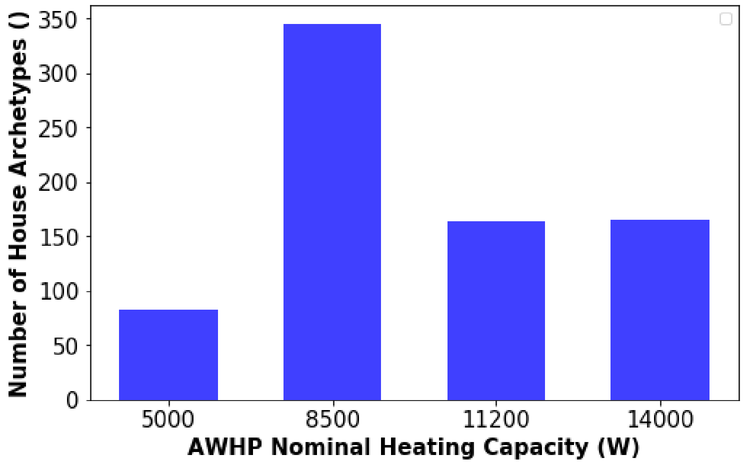



**Figure 3-12: Number of house archetypes per AWHP unit**

### 3.5.3 Domestic Hot Water (DHW) tank

A DHW tank is modelled for each house archetype in order to store the hot water, which will used by the occupants for showering, bathing, dishwashing, etc. The DHW tank is also supplied with an immersion heater operating to maintain the tank temperature in the range of 54.0 to 55.0 $^oC$ (the control of AWHP, auxiliary and immersion heater is explained in detail in Section 3.5.5).

The DHW tank is linked to the taps of the house and hot water is drawn at specified time intervals throughout the day. The daily number of the modelled draw-off events as well as their flow rate and duration vary for each separate house archetype based on the household size. The hot water draw-off events used in this thesis are derived from the Commission Delegated Regulation (EU) No 812/2013, this being developed to establish a standard regarding domestic water heaters and hot water storage tanks that are available and sold in the European market (European Commission, 2013). More specifically, domestic water heaters are categorized based on the hot water load profile (tapping cycle) of each household, which is provided in a 24-hour period. *Table 3-5* presents the characteristics of the different hot water load profiles based on different household sizes. The starting time, required flow rate, target water temperature as well as the amount of hot water energy used (in kWh) are specified for each separate hot water draw-off event in *Table 3-6*. The modelled hot water draw-off events are considered to cover cleaning, showering, bathing, dishwashing and other events described as “small” and “large”. *Table 3-6* illustrates the type and characteristics of the different draw-off events as included in the Commission Delegated Regulation (EU) No 812/2013.

**Table 3-5: Hot water profiles for various household sizes (European Commission, 2013)**

| No of occupants | Hot water load profile | No of daily draw-off events | Daily DHW energy use [kWh] |
|---|---|---|---|
| **1** | S | 11 | 2.1 |
| **2-3** | M | 23 | 5.8 |
| **4-6** | L | 24 | 11.7 |
| **More than 6** | XL | 30 | 19.1 |

**Table 3-6: Characteristics of various domestic draw-off events (European Commission, 2013)**

| Draw-off type | Energy used [kWh] | Volume [litres] | Flow Rate [litres/min] | Duration [minutes] |
|---|---|---|---|---|
| **Showering (small)** | 1.400 | 40.0 | 6.0 | 6.67 |
| **Showering (large)** | 1.820 | 52.0 | 6.0 | 8.67 |
| **Bathing (small)** | 3.605 | 103.0 | 10.0 | 10.30 |
| **Bathing (large)** | 4.420 | 126.0 | 10.0 | 12.60 |
| **Small dishwash** | 0.315 | 6.0 | 4.0 | 1.50 |
| **Medium dishwash** | 0.420 | 8.0 | 4.0 | 2.00 |
| **Large dishwash** | 0.735 | 14.0 | 4.0 | 3.50 |
| **Cleaning** | 0.105 | 2.0 | 3.0 | 0.67 |
| **Small** | 0.105 | 3.0 | 3.0 | 1.00 |
| **Large** | 0.525 | 15.0 | 5.0 | 3.00 |

Provided that the minimum timestep in an $E^+$ simulation is one minute, all draw-off events should be modelled to have an integer number of minutes as a duration. This means that, in some cases, the flow rate provided in the above table should be modified to the closest integer number in order to achieve an equivalent event in terms of energy use and hot water volume. For example, assuming a shower of 40.0 litres with a duration of 11.40 minutes and a flow rate of 3.50 litres/min, its duration is modified to 12.00 minutes and therefore, its flow rate is decreased to 3.33 litres/min. It should be noted that no hot water draw-off event is assumed to happen between 10 pm to 7 am in any of the modelled house archetypes.

### 3.5.4 Radiators

Room heaters are modelled as convective baseboard heaters using the *ZoneHVAC:Baseboard:Convective:Water* $E^+$ object. It is argued that heat-pumps are much more effective when serving low-inertia distribution heating systems such as underfloor heating systems or low-temperature radiators (Arteconi *et al.*, 2013). However, the majority of existing UK houses have high temperature radiators with flow and return water temperatures being at least 75.0$^o$C and 65.0$^o$C, respectively (BS:EN 442:2014). To limit the installation costs, the common practice in residential retrofit applications is to install the AWHP without further retrofitting the distribution heating system of the house. Nevertheless, the output of a radiator can significantly decrease when its actual flow temperature is lower than its design temperature (Shah and Hewitt, 2015). Considering all the above, this thesis considers that the distribution heating system of each house is retrofitted so that baseboard heaters are capable of delivering the maximum output of the AWHP acknowledging the fact that retrofitting the house's existing distribution heating system has important cost implications for the wide deployment of heat-pumps. The flow temperature of the modelled baseboard heaters varies between 40.0$^o$C and 50.0$^o$C based on the operation of the heating system (see Section 3.5.5). Each baseboard heater is modelled to serve one individual thermal zone of the house and its heating capacity is auto-sized by $E^+$.

The schedule of the modelled room heaters is based on the UK Government's recommendations (SAP, 2014). Thus, the living zone is heated to 21.0$^o$C from 7 am to

9 am and from 4 pm to 11 pm during weekdays and from 7 am to 11 pm during weekends, while the rest of the house is heated to 18.0$^{o}$ C from 7 am to 9 am and from 6 pm to 11 pm during weekdays and from 7 am to 9 am and from 2 pm to 11 pm during weekends.

### 3.5.5 Design and control of the modelled AWHP system

The design of an HVAC system in $E^+$ is based on the definition of one or multiple plant loops, the simulation of which is performed simultaneously with that of the building and the system to provide a physically realistic solution. Plant loops are closed loops using a liquid transport medium, which in the case of this research is water, and are divided into sub-loops for better controlling and handling the information during the simulation. More specifically, for each separate plant loop, a supply and demand sub-side loop should be defined by the user in such a way that the equipment included in the demand side sub-loop places a load, which is supposed to be satisfied by the equipment included in the supply side sub-loop. In other words, the demand side of each loop contains equipment such as baseboard heaters, coils, etc., while the supply side contains primary equipment such as boilers, chillers, heat-pumps, etc.

Sub-loops consist of a set of branches, where each branch describes one or more equipment components. For each individual branch, one inlet and one outlet node should be defined in such a way that the outlet node of one component is the inlet node of the following downstream component. Branches can be placed either in series or in parallel within a sub-loop. Parallel connection requires the definition of one splitter before the set of the (parallel) branches and one mixer connector after the set of the (parallel) branches. A splitter divides a single stream into multiple streams, while a mixer merges multiple streams into one single stream. It is recommended to include one splitter and one mixer in every separate sub-loop even if all of its branches are connected in series (EnergyPlus, 2016b). Only one splitter and one mixer is permitted in each sub-loop.

The employed AWHP system is defined in $E^+$ by creating five separate water loops, the connections and controls of which compose a representative AWHP system operating to meet the space-heating and DHW demand of each house archetype. *Figure 3-13* illustrates a schematic of the individual loops modelled.

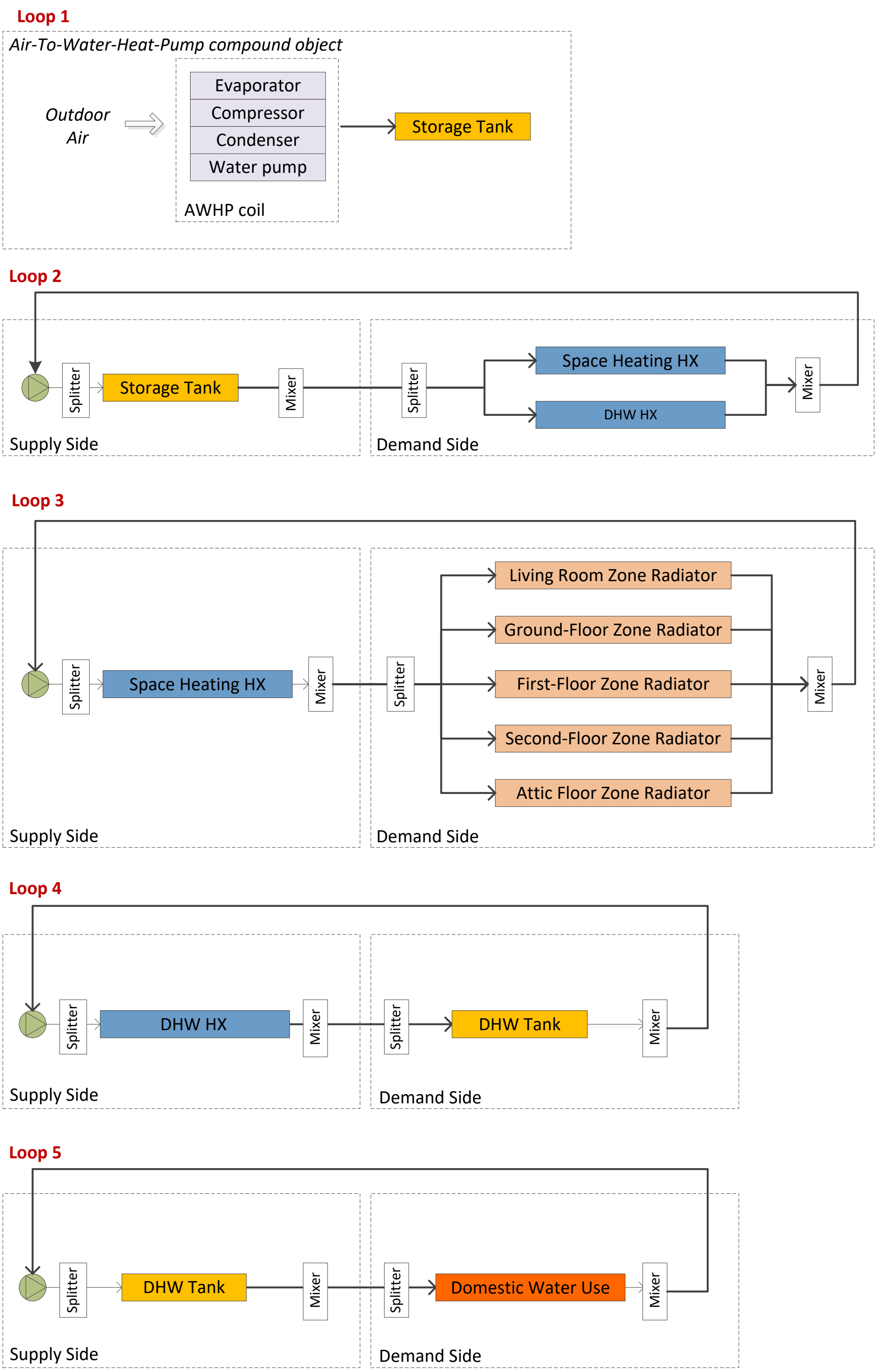



**Figure 3-13: Loops for the modelled AWHP system**

Loop 1 includes the AWHP unit providing heat to the storage water tank. Loop 2 operates the storage water tank to heat two separate heat exchangers, which are then used to provide heat to the radiators (Loop 3) and the DHW tank (Loop 4). Last, loop 5 operates to deliver hot water from the DHW tank to the taps, shower heads, etc. when needed. Adiabatic pipes have been assumed to connect the various components of the system. The following paragraphs describe the control strategies applied to each separate loop; the control of the system is representative of the operation of *Ecodan AWHP products* as described in manufacturer's technical guides (Mitsubishi Electric, n.d.).

AWHP systems that are used in actual domestic installations are recommended to operate either in space-heating or in DHW mode, which means that space-heating and hot water cannot be provided simultaneously. It is recommended to schedule the system so that the DHW tank is heated overnight or during selected periods throughout the day when the house is unoccupied. However, under extreme weather conditions, the system can be controlled so that the AWHP provides space-heating and the immersion heater located in the DHW tank water heater is used for the DHW; this, however, is not advisable under normal circumstances as it will significantly increase electricity use (Mitsubishi Operational Manual).

The modelled heat-pump and auxiliary electric heater (located in the storage water tank) (Loop 1) are controlled using an ON-OFF control strategy with the operation of the two devices being separated by their set-points and control differentials as depicted in the following figure.

*Figure 3-14* illustrates the system controls when the AWHP operates in space-heating mode. In this case, the AWHP is modelled to have a water set-point of 50.0$^{o}$C, while the auxiliary electric heater (referred as Tank Heater in *Figure 3-14*) is modelled to have a water set-point of 45.0$^{o}$C. Both devices operate with a control differential of 1.0$^{o}$C. This strategy results in three possible system operating modes: heat-pump only operating (a); heat-pump and electric heater operating (b); electric heater only operating (c). *Figure 3-14* illustrates these scenarios.

During **operating period (a)** the energy demand is low enough for the tank temperature to be maintained between 49.0°C and 50.0°C by cycling the AWHP alone. **Operating period (b)** illustrates the case where the energy demand has resulted in the tank temperature falling below the ON temperature of the auxiliary electric heater; this temperature is 44.0°C (auxiliary heater's set-point temperature minus the control differential of 1.0°C). Provided that the ambient temperature is above the frost limit of 2.0°C, the AWHP will also be ON (since its ON temperature is also higher than the tank temperature). Both the auxiliary electric heater and AWHP would operate until the tank temperature rises above the 45.0°C (set-point of the auxiliary electric heater), at which point, the auxiliary electric heater would be turned OFF; the AWHP would continue to operate alone until the tank temperature reaches its set-point of 50.0°C. The **operating period (c)** illustrates the case where the ambient temperature is below 2.0°C, and so the tank temperature is maintained (between 44.0°C and 45.0°C), by the auxiliary electric heater alone.

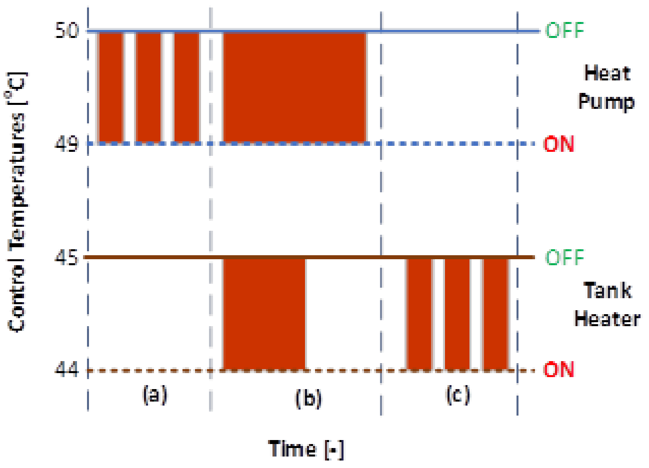



**Figure 3-14: AWHP operating in Space-Heating mode**

Although the auxiliary electric heater has a lower set-point than the AWHP, the adopted control strategy can result in significant use of the auxiliary electric heater. This is particularly expected to happen when the ambient conditions result in long periods of ambient temperature being below the frost-protection limit of 2.0°C. Extensive use of the auxiliary electric heater will reduce the annual effectiveness for the AWHP as well as annual effectiveness for the whole system; the latter is a function of not only the AWHP operation, but also the use of the electric heaters.

When the system operates in DHW mode, the heat-pump and the storage tank electric heater use the same ON-OFF control strategy as described previously, but they have different set-points. Based on WHO recommendations, the common practice in UK houses is to maintain the temperature of the DHW tank at 60.0 $^{o}$C to prevent the growth of Legionella bacteria. However, heat-pump installers across the UK market as well as previous works state that the threat of Legionella can be prevented with the occasional increase of the tank temperature to 60.0$^{o}$C. More specifically, Mitsubishi Electric recommends the operation of the heat-pump system under 'Legionella prevention mode once per 15 days. In this case, the hot water should reach the temperature of 65.0$^{o}$ C for at least 30 min (Mitsubishi Electric, n.d.). However, Legionella prevention cycle is not considered in this study as the energy use is assumed negligible throughout the year. The annual energy used to raise the temperature of the tank to 60.0$^{o}$C once per ten days using an electric heater has been estimated to be approximately 180.0 kWh in a typical UK detached house (Kelly *et al.*, 2014).

In DHW mode, the AWHP and auxiliary electric heater are modelled to have a set-point temperature of 55.0$^{o}$C and 50.0$^{o}$ C, respectively (with a control differential of 1.0$^{o}$C). The AWHP with the auxiliary electric heater provide heat to the DHW tank through a heat exchanger seven days a week from 5 am to 7 am and from 2 pm to 4 pm on weekdays, where no space-heating is required. During these periods, the immersion heater located in the DHW tank is deactivated to avoid its operation instead of the AWHP. The DHW tank's immersion heater is controlled using an ON-OFF control strategy and is ON only when the AWHP operates under space-heating mode to maintain the DHW tank temperature between 54.0$^{o}$C and 55.0$^{o}$C. In other words, the DHW tank is heated by the heat-pump only when occupants are sleeping or are away from home (and thus, space-heating is OFF), while during active occupancy, the immersion heater is ON to maintain DHW tank temperature at desired levels (54.0$^{o}$C – 55$^{o}$C).

It is worth mentioning at this point that the AWHP unit could have been alternatively modelled to provide heat directly to the heating circuit and DHW tank. In this case, the storage water tank would have been modelled to have almost zero volume (tankless system). However, this would not allow for the existence of the auxiliary electric heater with this being necessary for taking into account the impact of low ambient temperatures on the heating performance and effectiveness of the AWHP system (especially for this case that the employed model does not include a reverse cycling operation). Another alternative would be to consider that the DHW is directly drawn from the storage water tank and the same storage water tank supplies heat to the heating circuit. For this arrangement, two different circuits are required in order to ensure that the DHW is not mixed with the water circulating inside the radiators. However, this configuration would not allow controlling the set-point temperature to be different for space-heating and DHW. For these reasons, the configuration shown in *Figure 3-10* was selected acknowledging that the existence of two tanks might have space implications for the wide adoption of the proposed heating system, the latter being discussed in Section 6.3.2.

## 3.6 Weather data

To evaluate the effectiveness of the AWHP retrofit, the selected 756 house archetypes are simulated using both *current* and *future* weather scenarios. However, it should be noted that when using the future weather scenarios, the heating performance of the AWHP retrofit is assessed for the housing stock at its current condition and without considering any further refurbishment measures (such as increase of insulation levels, upgrade of windows, etc.). The implications of using future weather scenarios for the existing stock is discussed in Section 5.3 of this thesis.

The current and future weather scenarios are provided by CIBSE in the format of EPW (EnergyPlus Weather) files including a set of climatic variables such as DBT, wet-bulb temperature, relative humidity, atmospheric pressure, direct solar irradiation, diffuse solar irradiation, cloud cover, wind speed, wind direction etc. All climatic variables are reported at hourly intervals throughout an entire year. CIBSE weather files include current and future weather scenarios for 14 different locations across the UK. For the present thesis, the weather file referring to Newcastle, UK is chosen as it is considered to be the closest location to represent the weather conditions of the NE region of England.

For both current and future weather scenarios, CIBSE provides *Test Reference Year (TRY)* and *Design Summer Year (DSY)* weather files; these are suitable to be used to determine average energy use within buildings and assess the risk of overheating during summer, respectively (Virk and Eames, 2016). This thesis studies the heating performance of AWHPs throughout the entire heating season and thus, only the TRY weather files are used. The TRY weather files used are composed of twelve separate months selected to be the most average months from a 30-year baseline (1984-2013). They were morphed using the ISO methodology (BS EN ISO 15927-4:2005, 2005), based on which the most average months are selected using four daily parameters as follows: mean DBT, total global horizontal radiation, mean relative humidity (as primary parameters) and mean wind speed (as secondary parameter). However, CIBSE weather files use mean wind speed as a primary parameter rather than relative humidity (Eames *et al.*, 2016).

Based on the probabilistic UK Climate Projections of 2009 (UKCP09), CIBSE in collaboration with the UK Climate Impacts Program (UKCIP), Arup and Exeter University created detailed weather files suitable to be used for BPS (CIBSE, 2019). The future weather files were developed assuming various emission scenarios (low, medium and high), while for each different emission scenario, three probabilistic projections were included representing the 10$^{th}$ percentile, 50$^{th}$ percentile (median, central estimation) and 90$^{th}$ percentile. The selected housing stock with the integrated AWHP is simulated using 15 different future weather scenarios in total as illustrated in *Table 3-7*.

**Table 3-7: Simulated future weather scenarios**

| Year | Emission Scenario | Probability |
|---|---|---|
| 2050 | Medium | 10th percentile<br>50th percentile<br>90th percentile |
| 2050 | High | 10th percentile<br>50th percentile<br>90th percentile |
| 2080 | Low | 10th percentile<br>50th percentile<br>90th percentile |
| 2080 | Medium | 10th percentile<br>50th percentile<br>90th percentile |
| 2080 | High | 10th percentile<br>50th percentile<br>90th percentile |

The content of these future weather scenarios is further explained and discussed in Chapter 5 of this thesis (see Section 5.2).

## 3.7 Simulations

Whole building thermal simulation is a key tool for studying the complex interaction between building fabric, occupant behaviour, HVAC systems and control, thus allowing for the analysis of design alternatives and their impact on thermal comfort conditions and building's energy consumption. Thermal modelling is based on heat and mass balance mechanisms describing the main heat transfers that take place in buildings; conduction, convection and radiation (heat flow through building elements, air movement through windows and cracks of the building envelope, solar heat gain through windows, heat added to or removed from building's mass and internal heat gains from occupants/lights/electric appliances) (De Wilde, 2018). There is a number of powerful dynamic BPS tools used in both industry and academia such as EnergyPlus ($E^+$), DesignBuilder, TRNSYS, IES-VE (Integrated Environmental Solutions-Virtual Environment), ESP-r, etc. For the purpose of this thesis, $E^+$ is selected as the BPS engine to study the heating performance of the AWHP retrofit at the stock level. $E^+$ is a well-established whole building energy simulation software developed by the

National Renewable Energy Laboratory (NREL) under the United States Department of Energy (EnergyPlus, 2020). It is capable of providing a simultaneous solution for energy loads, systems and plant equipment of a building at a user-specified timestep varying from one minute to an entire year (Crawley *et al.*, 2001) and validated through analytical, comparative, sensitivity and empirical methods (Witte *et al.*, 2001; Henninger *et al.*, 2004). Jankovic (2017) mentions that $E^+$ "*has the most comprehensive list of heat transfer and HVAC models than any other building simulation software*," these being described in regularly updated documents that are available online. In addition to that, $E^+$ is an open-source simulation engine enabling the engagement of the entire building simulation community to expand the program's capabilities (Jankovic, 2017). Since its development, $E^+$ has been used in a range of different studies including the calculation of heating and cooling loads as well as the performance of advanced and complicated HVAC systems. Griffith and Crawley (2006) developed a methodology for evaluating the zero-energy potential for a fairly large number of US commercial buildings; Boyano *et al.* (2013) evaluated the impact of climatic conditions, orientation and various retrofit scenarios (improvement of lighting, upgrade of insulation and glazing properties) on the energy consumption of a European office building; Hong *et al.* (2016) used $E^+$ to develop a VRF-HP (Variable Refrigerant Flow Heat-pump) model incorporating advanced control techniques (validated using measured data).

In this thesis, $E^+$ simulations are carried out using one-minute simulation timestep for both loads and HVAC calculations, this being the shortest (available) timestep that can be used in an $E^+$ simulation. Based on that, heat balance calculations are performed every minute throughout the selected run period, which in the case of this research, is an entire year. The selection of the one-minute simulation timestep is based on the fact that the DHW draw-off events have a duration ranging from one to approximately thirteen minutes and thus, the selection of a longer timestep would not "catch" all these events. The selection of short timesteps (10 minutes or less) improves the numerical solution of the zone heat balance model as it improves the coupling of the different models used for surface temperature and zone air temperature calculations. Nevertheless, this inevitably results in increasing the run time of each simulation.

Generally, the use of short timesteps is highly recommended for $E^+$ models including one or more HVAC systems (EnergyPlus, 2016b).

Having generated the IDFs for all house archetypes (with the retrofitted AWHP system), the $E^+$ simulations are run using the JEPlus tool (Zhang, 2009). The recent version of JEPlus (version 1.7.2) offers the possibility to call Python scripts for post-processing of the $E^+$ simulation results; this is the approach adopted in this study. For the simulation of each building, several output variables were reported either in hourly or in annual interval. More specifically, output variables such as water temperatures or zone air temperatures are reported hourly throughout the year and are then post-processed using Python scripts to derive other outputs that are not directly available from $E^+$ simulations (e.g. the number of hours throughout the year that zone temperature or PMV falls below specific thresholds).

## 3.8 Chapter summary

The present thesis utilizes an existing in-house bottom-up HSEM deriving information from the national EHS and CHM to automatically generate house models that are suitable to be studied using $E^+$. The work presented in this thesis builds up on this existing HSEM by improving the representation of houses (geometry, internal heat gains) and integrating new features such as a detailed AWHP model (coupled with supplementary electric heating) to be used as the only heating source for meeting the dwelling's space heating and hot water demand.

Chapter 3 presented the approach adopted to model the housing stock of the NE region of England consisting of 756 house archetypes. This modelling approach was tested using an inter-model comparison technique and was found to be suitable for representing the distribution of the houses' heating demand across the stock. Then, the chapter presented the methods and tools used to model an AWHP heating system, this being considered to be retrofitted in each house archetype in order to meet its space-heating and hot water demand throughout the entire heating season. The chapter presented the configuration and control strategies applied in order for the modelled

AWHP system to be representative of actual systems that are used for space-heating and hot water applications of UK residential buildings. The developed methodology is generic and can be easily applied to every housing stock. For this thesis, it is applied to explore the applicability of AWHPs across the housing stock of the North-East region of England for both current and future weather scenarios. The analysis of the results will be presented in Chapter 4 and Chapter 5.

# Chapter 4

# Results 1: The applicability of AWHPs under current weather conditions

## 4.1 Introduction

Chapter 4 sets out to evaluate the heating performance of AWHPs for 756 house archetypes selected to represent the existing housing stock of the NE region of England. The AWHP heating system is considered to be retrofitted in each house archetype to meet its space-heating and hot water demand throughout the entire heating season. In this chapter, the applicability of AWHPs for the selected building stock is studied for a current weather scenario. The individual aims of this chapter are summarised as follows:

- to investigate the sizing (selection of nominal heating capacity) for the AWHP retrofit across the modelled stock (Section 4.2)
- to investigate the distribution of AWHP's energy use and annual effectiveness (Section 4.3)
- to evaluate the need for supplementary electric heating as a result of the AWHP retrofit and explore the relationship between the energy use of the AWHP (itself) and auxiliary electric heater for various house categories (Section 4.4)

- to assess the suitability of the AWHP retrofit to limit the level of under-heating across the stock (Section 4.5) *and*
- to assess the suitability of the AWHP retrofit to maintain conditions of thermal comfort across the stock (Section 4.6).

Simulation results are mainly presented as average values per various house categories with each category including a certain number of house archetypes (for the categorisation of the modelled building stock see *Figure 3.9*). In addition to that, suitable examples are used across the chapter to compare the operation and heating performance of the retrofitted AWHP system between different house archetypes.

## 4.2 Nominal heating capacity of the AWHP unit

The AWHP unit that is considered to be retrofitted in each of the 756 house archetypes comes in four different sizes (5.0 kW, 8.5 kW, 11.2 kW and 14.0 kW) with the size being represented by AWHP's nominal heating capacity. For each house archetype, the size of the AWHP is selected based on the house's peak space-heating load so that the AWHP itself (without considering the contribution of any supplementary electric heater) should have enough capacity to meet 100.0 % of this load. The method used to size the AWHP is explicitly described in Section 3.5.2.

*Figure 4-1* illustrates the peak space-heating power demand of each house archetype (house archetypes are sorted in ascending order based on their annual peak space-heating power demand). The four different colours refer to the size of the AWHP unit that is selected to be retrofitted in each house archetype. For example, all houses that are considered to be retrofitted with the 5.0 kW AWHP are depicted with blue colour. As seen, the houses with peak space-heating power demand higher than 14.0 kW (92 houses in total) are considered to be retrofitted with the 14.0 kW AWHP even if in this case, the nominal heating capacity of the AWHP is lower than the peak space-heating power demand of the house. Although these 92 houses are under-sized, this does not automatically imply that the AWHP retrofit is ineffective for them. In other words, even if the rule of the 100.0% coverage cannot be met for a particular house (due to the limited AWHPs' capacities in practice), the AWHP might still be effective if the level of under-heating and degree of thermal discomfort are within acceptable limits throughout the heating season. (The assessment of under-heating and thermal comfort conditions across the entire housing stock are discussed in Sections 4.5 and 4.6, respectively).

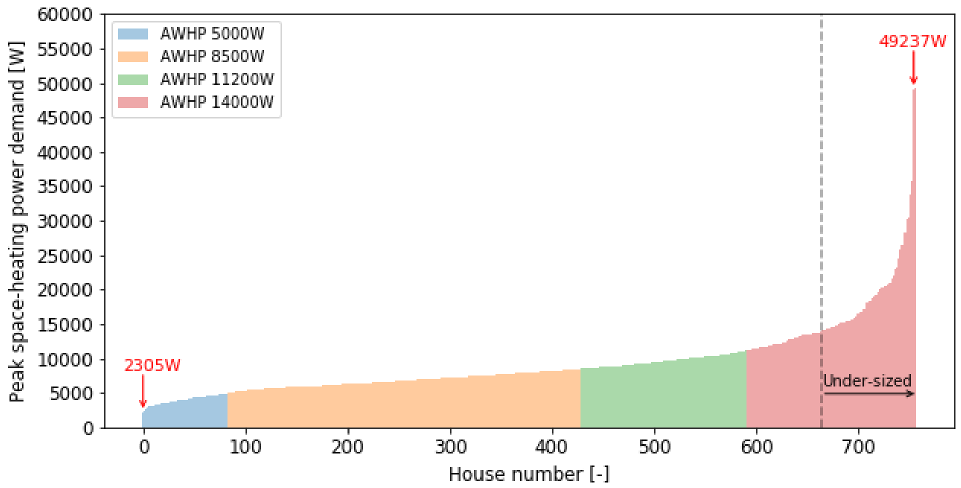



**Figure 4-1: Peak space-heating power demand (throughout the year) of each house archetype (in an ascending order)**

It is obvious that since the AWHP is sized to meet the entire peak space-heating load of the house, it will operate under part-load conditions for the rest of the time. More specifically, if the average hourly heating load of the house is significantly lower than its peak heating load, then the AWHP will operate far from its full-load conditions for a significant amount of time throughout the heating season. For example, if a particular house has a peak space-heating power demand slightly higher than 5.0 kW, then the 8.5 kW AWHP is selected to be retrofitted in that house and in this case, the AWHP will always operate far from its full-load conditions. Operating the AWHP far from its full-load conditions results in the reduction of the COP based on *Equation 3-11* and *Equation 3-12*; this is further discussed in Section 4.3 with the use of a suitable example.

However, although the AWHP is sized to meet the peak heating load of the house, supplementary electric heating might be needed even for those houses that are adequately sized. This can happen for two reasons as follows. First, as discussed in

Section 3.5.1, the AWHP is modelled to operate at its nominal heating capacity under a specific combination of DBT and condenser water temperature (2.0$^{o}$C and 35.0$^{o}$C, respectively). For different combinations of these two temperatures, the maximum heating capacity that can be achieved by the AWHP is adjusted using the equations illustrated in *Table 3-5*. As a result, when the peak heating load occurs, the DBT might be lower than 2.0$^{o}$C and/or condenser water temperature might be higher than 35.0$^{o}$C and thus, the actual heating capacity of the AWHP might be lower than its nominal value. In this case, supplementary heating will be needed to top-up the energy provided by the AWHP itself in order for the peak heating load to be entirely met. Second, if the peak heating load of a house occurs when DBT is below 2.0$^{o}$C, then the AWHP will be OFF due to the application of the frost-protection technique and heating will be entirely supplied by the auxiliary electric heater[1]. This would, however, increase the extent of AWHP's over-sizing and part-load conditions.

*Figure 4-2* illustrates the annual peak space-heating power demand per house category (for the categorisation of the 756 house archetypes, see Section 3.4.2). The value corresponding to each particular house category represents the *average* annual peak space-heating power demand of all house archetypes lying in that category. For example, all the semi-detached houses with volume lower than 180.0 m$^3$ and no wall insulation (U-value > 1.50 W/m$^2$K) have an average peak space-heating power demand of 5.5 kW. The colour of each box indicates the range to which the annual peak space-heating power demand of each category belongs (see colour-bar next to each figure). For example, if the annual peak space-heating demand for one specific category ranges between 3.0 and 6.0 kW, the colour of the box will be orange. The use of the colours makes the "reading" of the figures easier as it helps the reader identify at a glance which categories have similar behaviour. (These apply to all graphs that have the same structure and are included in this thesis). It should be noted that for the rest of the thesis, when referring to a dwelling's volume, this involves only conditioned volume. Moreover, when referring to wall insulation, this means exposed-wall insulation. It should be clarified that the simulated results presented in this thesis refer

[1] Frost-protection technique forces the AWHP to switch-off when temperature is lower than 2.0$^{o}$C to avoid frost accumulation on the evaporator side

to the 756 unique house archetypes and are not aggregated at the stock level using the weightings provided by the EHS; weightings refer to the number of real houses represented by each unique house archetype.

It is clear from *Figure 4-2* that the annual peak space-heating power demand generally increases as exposed-wall U-value and dwelling's volume increases and the house becomes "more detached". For all house categories with volume greater than 390.0 $m^3$ as well as for almost all the categories with no wall insulation (U-value > 1.50 $W/m^2K$) and volume in the range of 320.0 $m^3$ to 390.0 $m^3$, the (average) peak space-heating power demand is greater than 14.0 kW. As a result, these house categories might include a significant number of houses with under-sized AWHPs.

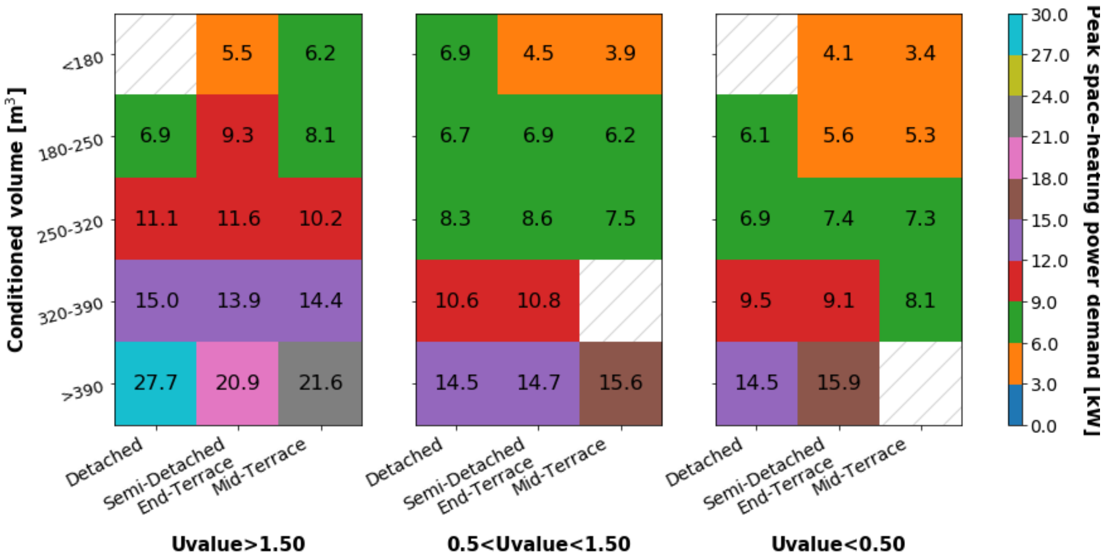



**Figure 4-2: Average peak space-heating power demand (throughout the year) per house category**

*Figure 4-3* illustrates the mode nominal heating capacity of the retrofitted AWHP per house category (above figure) as well as the percentage of houses per category having the AWHP with the mode nominal heating capacity (below figure). For example, 88.0 % of the mid-terrace houses with volume lower than 180.0 $m^3$ and no wall insulation are selected to be retrofitted with an 8.5 kW AWHP. As also seen in *Figure 4-3*, there are five categories to which two mode values correspond (see black circles). The latter means that the same percentage of houses within each of these particular categories is selected to be retrofitted with either AWHP unit. For example, half of the semi-detached houses with no wall insulation and volume lower than 180.0 m$^3$ are selected to be retrofitted with a 5.0 kW AWHP, while the other half of them with an 8.5 kW AWHP. In statistics, mode is used to describe the most frequent value of a dataset.

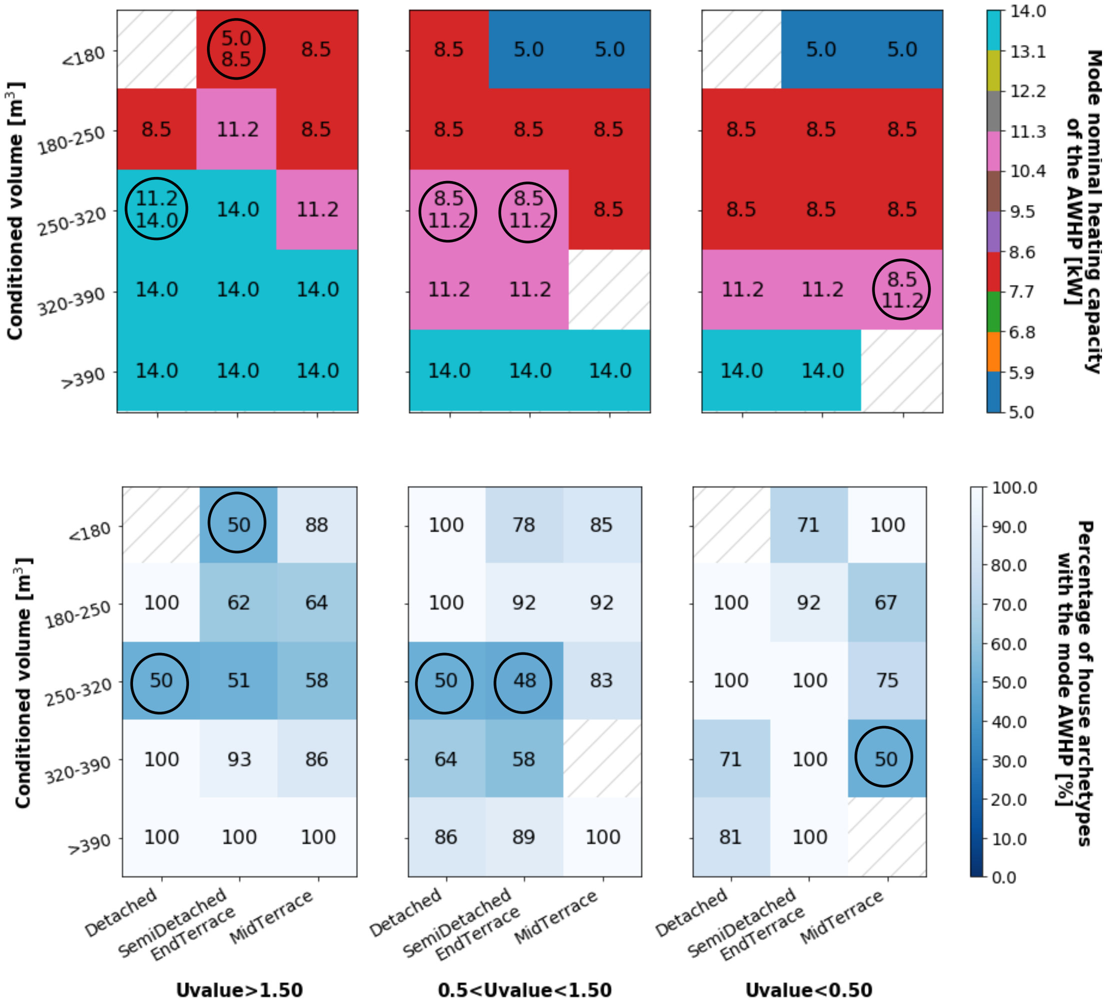



**Figure 4-3: Mode nominal heating capacity and percentage of house archetypes having the AWHP with the mode nominal heating capacity per house category**

It is important to discuss the extent to which the mode value corresponding to each separate category (as presented in *Figure 4-3*) can be considered as representative for this particular category. First and most importantly, the low number of houses included in some of the categories (see *Figure 3-9*) decreases the level of confidence for recommending these values as representative of these categories even if all the included houses have the same AWHP size. For example, all the mid-terrace houses with volume lower than 180.0 m$^3$ and high insulation level (U-value < 0.50) are selected to be retrofitted with a 5.0 kW AWHP. Nevertheless, as seen in *Figure 3-9*, this particular category contains only 3 house archetypes, which means that the sample size is too small to be used in order to determine the statistical significance of these mode values. On the other hand, 92.0 % of the semi-detached houses with medium insulation levels (0.5 $W/m^2K$ < U-value < 1.50 $W/m^2K$) and volume in the range 180.0 $m^3$ - 250.0 $m^3$ are selected to be retrofitted with an 8.5 kW AWHP with this category including 133 house archetypes in total. In this case, the large sample size coupled with the (relatively) large percentage of houses having the same AWHP increases the level of confidence for recommending the 8.5 kW AWHP as representative for this particular house category. The implementation of statistical tests (e.g. one-sample t-test) is highly suggested (where sample size permits it) in order to determine the level of confidence for using these mode values as representative.

Further, although the number of houses included in some of the categories is not low, the results show that that the size of the AWHP cannot be directly connected with the built form, insulation level and volume of the house. For example, there are in total 64 semi-detached houses with medium wall insulation level and volume in the range 250.0 $m^3$ - 320 $m^3$. Nevertheless, 30 of them were selected to be retrofitted with an 8.5 kW AWHP, 30 with an 11.2 kW AWHP and 4 with a 14.0 kW AWHP. Hence, although houses have been categorised based on the most critical characteristics for the determination of their heating demand (as described in Section 3.4.2), the analysis confirms that the range of the heating demand within each category might be large and this might lead to a wide variation of AWHP's size (within the same category). In fact, the houses within each particular category cover a wide variation in loft insulation level, glazing-type (single, double or both), infiltration, number of occupants, etc. with all these factors having an impact on heating demand and consequently on the selection of AWHP's size. Thus, this confirms that the selection of the AWHP's heating capacity cannot be based on some of the "most typical" house characteristics, but on the precise calculation of the house's demand. Many previous works confirm that a very common reason for the failure of actual AWHPs' installations is that installers fail to select the "right" size (Staffell *et al.*, 2012; Dunbabin *et al.*, 2013; Etude, 2018).

The limitations arisen due to the low number of houses included in some of the categories as well as the wide variation of AWHP's sizes within some of the categories limit the effectiveness of directly linking AWHP's size with some of the most "typical" house characteristics such as built form, level of wall insulation and volume range. However, in the present thesis, each house archetype is sized separately with its peak heating load resulting from dynamic calculations using a well-established and validated simulation engine ($E^+$). Therefore, the AWHP's size selected for each *individual* house allows for the development of a tool in the future, where the user will provide the detailed characteristics of the house to get the recommended AWHP's size. Currently, there is a number of similar tools available online that can be used to estimate the required heating capacity of the AWHP for either new-built or existing houses. In these online tools, the user usually needs to provide a small amount of data such as dwelling's age of construction, number of bedrooms, built form, location and presence of external-wall insulation (or not). Although the calculation methodology adopted by these commercial tools is not explicitly described by AWHP manufacturers, the amount of input data (provided by the user) is not sufficient for a detailed representation of the house. This means that these tools do not usually account for factors that are significant for the thermal performance of a particular house (such as dwelling's volume, glazing type, total glazed-area, number of occupants, infiltration, etc.). AWHP installers and designers are recommended to make an accurate estimation of the building's energy demand and not be based on a high-level inspection of the property in order to select system's size.

## 4.3 AWHP energy use

*Figure 4-4* and *Figure 4-5* illustrate the annual heating output and annual electric input of the AWHP itself (without considering the contribution of the auxiliary electric heater) per various house categories. The heating output involves the annual amount of heating energy produced by the AWHP to meet the heating demand of the house (space-heating and DHW), whereas the electric input involves the annual amount of electricity consumed by the AWHP. Both the heating output and electricity input of the AWHP for each separate house category are shown as average values of all houses lying in that specific category.

Comparing *Figure 4.4* and *Figure 4.5*, it can be seen that the amount of the AWHP's heating output is approximately 3x the amount of its electric input for almost all the examined house categories. This means that the annual effectiveness of the AWHP itself is around 3.0. As shown in Equation 2-3 (see Section 2.2.2), the annual effectiveness of the AWHP is expressed by the Seasonal Performance Factor (SPF). This is defined as the ratio of the annual heating output to annual electricity input of the AWHP. For each modelled house, SPF being an annual expression of COP, depends on nominal COP of the retrofitted AWHP, differences between DBT and condenser water temperature and extent to which AWHP operates under part-load conditions (throughout the year) for this particular house. The variation of SPF between the selected house categories is discussed in the following section.

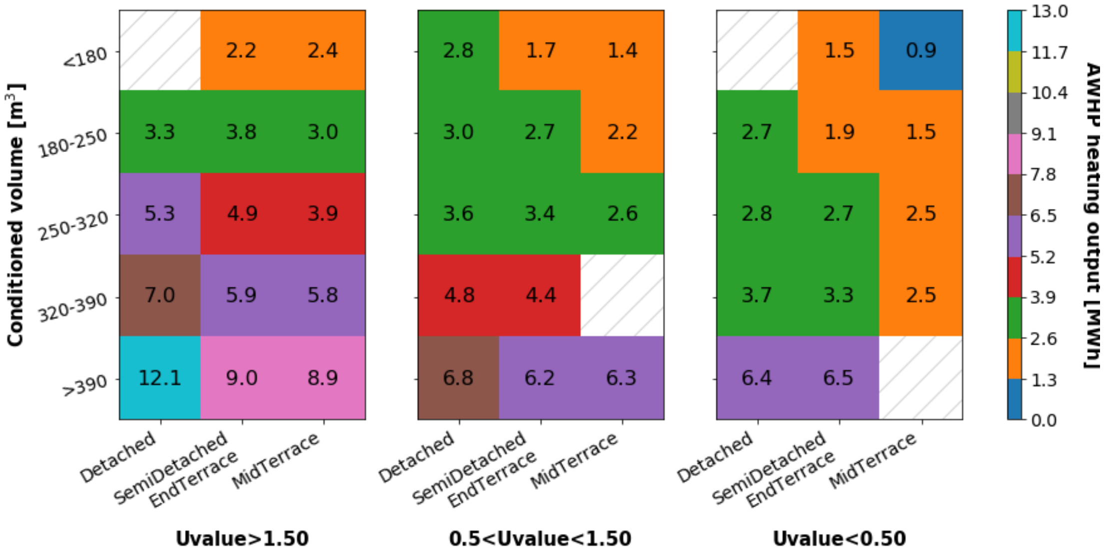



**Figure 4-4: Average annual heating output of the AWHP per house category**

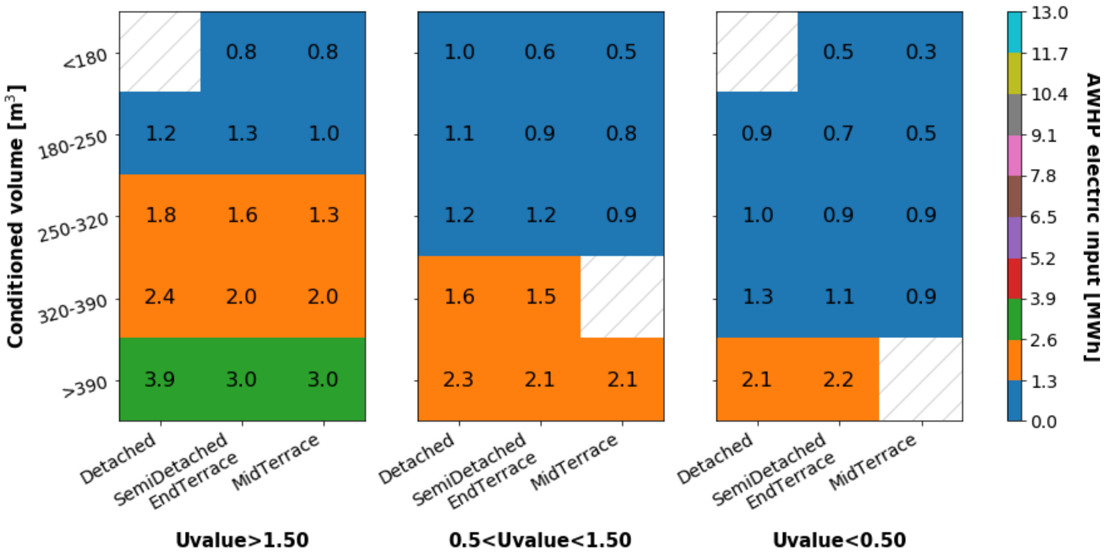



**Figure 4-5: Average annual electricity input of the AWHP per house category**

### 4.3.1 Seasonal Performance Factor (SPF)

*Figure 4-6*, *Figure 4-7*, *Figure 4-8* and *Figure 4-9* depict the average SPF of the retrofitted AWHP for the various house categories with each of these figures including house archetypes that are selected to be retrofitted with a 5.0 kW, 8.5 kW, 11.2 kW and 14.0 kW AWHP unit, respectively. The four retrofitted AWHP units vary, amongst others, in nominal COP (see *Table 3-3* in Section 3.5.1) and therefore, SPF is compared separately for house archetypes that have been retrofitted with the same AWHP unit. It should be noted that the SPF shown in the above figures does not include the electricity consumed by the AWHP's fan. The simulated SPF is found to be similar when compared with previous works. More specifically, based on EST field trials, the monitoring of several AWHPs installed in various UK regions showed that SPF might vary between 2.4 and 3.2[1] (EST, 2013).

Those house archetypes retrofitted with the 8.5 kW AWHP (see *Figure 4-7*), which presents the lowest nominal COP between the four different units, have slightly lower SPF compared to the rest house archetypes. However, it is evident from the above figures that the variability of SPF is almost negligible across the entire stock. The

[1] In EST, the SPF accounting only for the heating output and electric input of the AWHP itself is referred as $SPF_{H1}$

highest variation of SPF occurs for the house archetypes that have the 14.0 kW AWHP unit (*Figure 4-9*) with SPF ranging between 2.89 and 3.06. Whilst SPF's variability is also very limited in this case, what is notable is the fact that SPF generally increases as the heating demand of the house is expected to increase. In other words, SPF appears to increase as dwelling's volume and exposed-wall U-value increases and the house becomes more "detached". More specifically, the higher SPFs are associated with those house categories including a relatively large number of inadequately sized houses. The reasons for that are discussed in the following section through the comparison of AWHP's performance (in terms of COP) for two different house archetypes with both houses being retrofitted with a 14.0 kW AWHP.

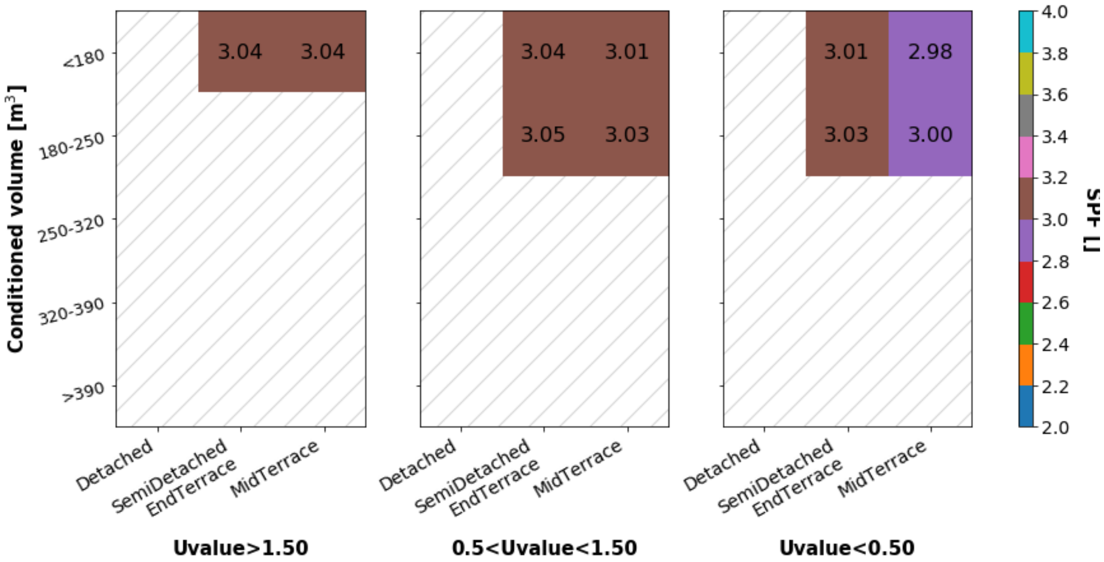



**Figure 4-6: Average SPF of the 5.0 kW AWHP ($COP_{Nominal}$ = 3.50) per house category**

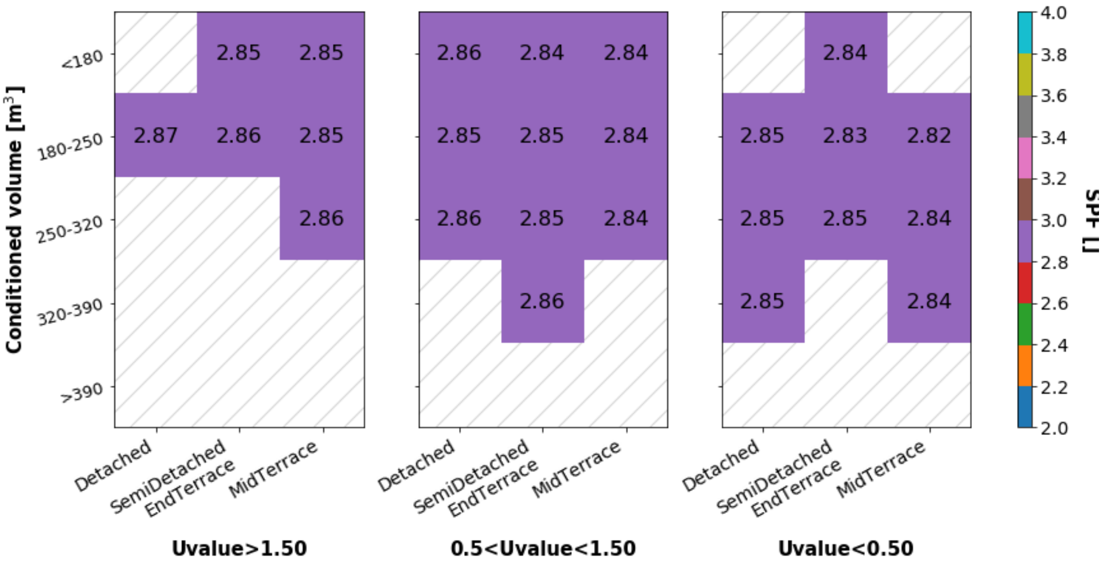



**Figure 4-7: Average SPF of the 8.5 kW AWHP ($COP_{Nominal}$ = 3.17) per house category**

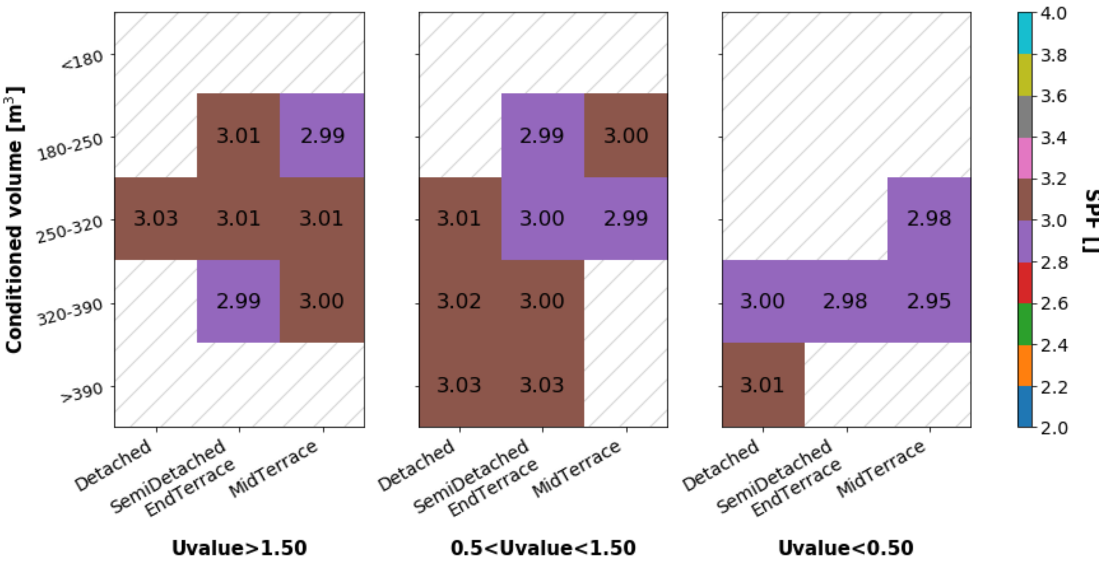



**Figure 4-8: Average SPF of the 11.2 kW AWHP ($COP_{Nominal}$ = 3.34) per house category.**

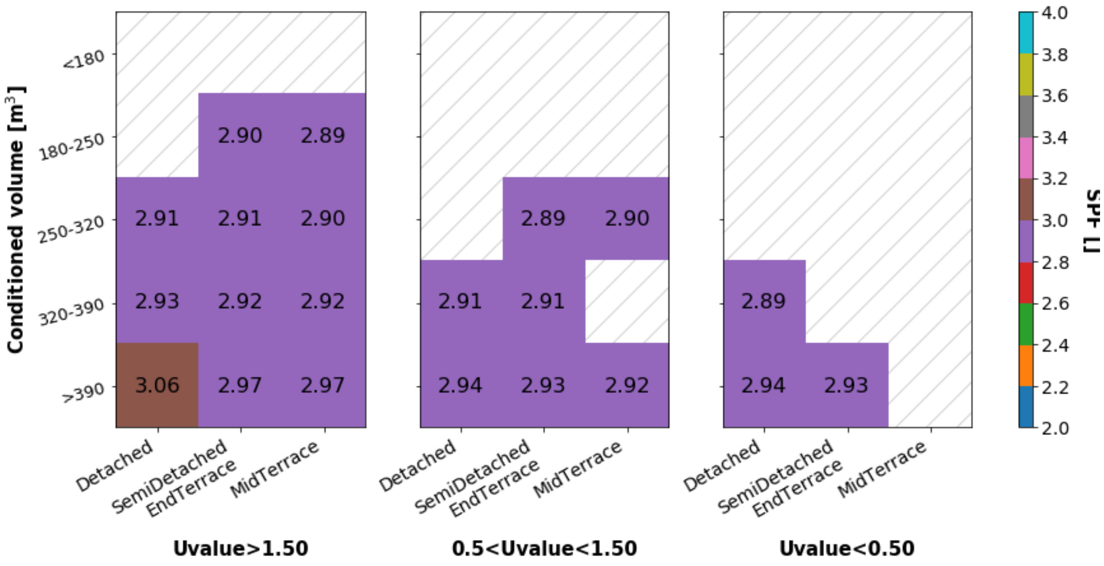



**Figure 4-9: Average SPF of the 14.0 kW AWHP ($COP_{Nominal}$ = 3.11) per house category**

### 4.3.2 Comparison of hourly COP for two house archetypes (example)

The following analysis aims to explore the variation of several parameters on which the simulated COP depends and to compare how these parameters vary for two different house archetypes (*House A* and *House B*). Both houses are retrofitted with the 14.0 kW AWHP unit. The characteristics of *House A* and *House B* are illustrated in *Table 4-1*.

**Table 4-1: Characteristics of House A and House B**

| | **House A** | **House B** |
|---|---|---|
| **Built form [-]** | Detached | Detached |
| **Total conditioned volume [m3]** | 495.82 | 1136.34 |
| **Exposed wall Uvalue [W/m$^2$K]** | 0.359 | 2.06 |
| **Loft Insulation thickness [mm]** | 300 | 100 |
| **Infiltration rate [ach]** | 0.74 | 1.21 |
| **Simulated SPF [-]** | **2.91** | **3.31** |

As seen, *House B* has significantly larger conditioned volume, lower levels of wall and loft insulation and higher infiltration rate compared to *House A*. However, the retrofitted AWHP in *House B* appears to achieve a higher SPF compared to *House A*. To identify the reasons for that, the one-minute variation of several parameters that affect the COP are compared for these two houses during a typical working-day (11 January). This particular day is selected, because outdoor air temperature is always above 2.0 °C and thus, the operation of the AWHP is not restricted due to the application of the frost-protection technique, which, as said, forces the AWHP to switch-off when DBT is below 2.0°C. The variation of DBT for the 11th of January is illustrated in *Figure 4-10*. (It should be reminded that during working days, the AWHP is modelled to operate from 5-7 am on DHW mode, 7-9 am on space-heating mode, 2-4 pm on DHW mode and 4-11 pm on space-heating mode. From 9 am to 2 pm and from 11 pm to 5 am, the AWHP system is considered to be completely switched-off).

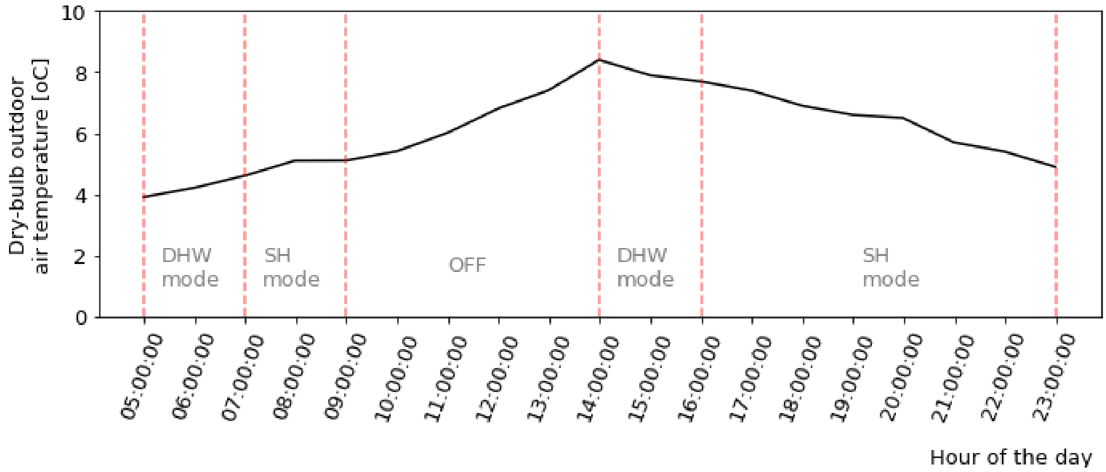



**Figure 4-10: DBT for 11 January (CIBSE Test Reference Year weather file for Newcastle, UK)**

*Figure 4-11* illustrates the one-minute variation of the simulated COP for *House A* and *House B*. During the periods that the AWHP does not operate, the COP is shown to be zero. As seen, even for periods that the AWHP is scheduled to be ON, there are timesteps that the COP is zero. This means that the energy demand is low enough for the tank temperature to be maintained at desired levels and the AWHP operates on float mode (compressor is OFF, but tank's water temperature is equal to or higher than the specified set-point temperature). It is evident from *Figure 4-11* that the simulated COP in *House B* is higher than that of *House A* for almost the entire day. The average daily COP is estimated at 2.85 and 3.59 for *House A* and *House B*, respectively. Also, it can be seen that COP has a more significant variation in *House B* compared to *House A*.

For each simulation timestep (one-minute), the COP of the AWHP is modelled to vary based on two different curves. The first curve (*COP performance curve*) is used to adapt the nominal COP of the AWHP based on the combination of DBT and condenser water temperature (see *Table 3-5*), whereas the second curve (*part-load correlation curve*) is used to reduce the COP when the AWHP operates under part-load conditions (see *Equations 3-11* and *Equation 3-13*). Hence, for each simulation timestep, the employed AWHP model uses the COP performance curve and part-load correlation curve to parametrize the nominal COP ($COP_{Nominal}$) in order to estimate the actual COP of the AWHP at the current air/water temperatures and operating conditions as follows:

$$COP = COP_{Nominal} * z_{-factor} * PLF \qquad \text{(Equation 4-1), } where$$

$$z_{-factor} = (1.5 + 5.3 * 10^{-2} * x - 1.8 * 10^{-5} * x^2 - 9.0 * 10^{-3} * y - 8.4 * 10^{-5} * y^2 - 6.5 * 10^{-4} * x * y) \qquad \text{(Equation 4-2)}$$

*z-factor* expresses the effect of the combination of DBT (x) and condenser water temperature (y) on the nominal COP, whereas the PLF expresses the effect of part-load operation on the nominal COP.

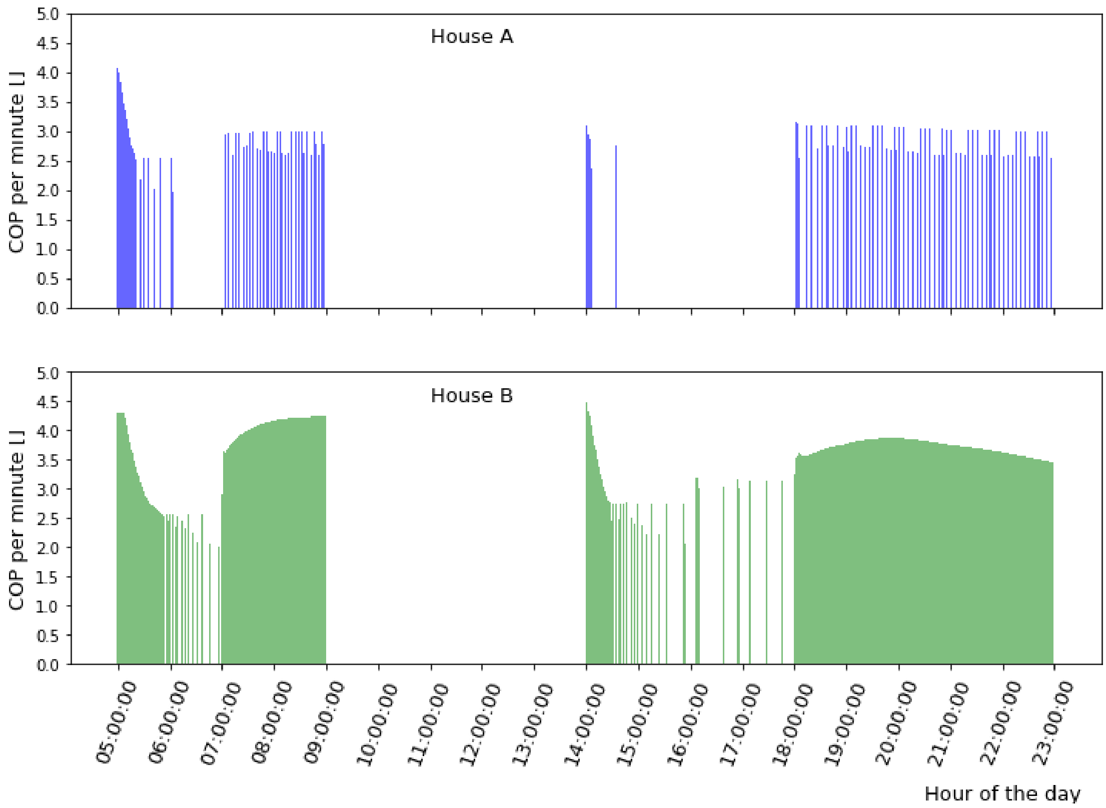



**Figure 4-11: COP variation per simulation timestep (one-minute) on 11 January for House A and House B**

*Figure 4-12* depicts the one-minute variation of the *z-factor* for *House A* and *House B*. *z-factor* reduces as the difference between condenser water temperature and DBT increases. However, since *House A* and *House B* are simulated under the same weather conditions, the temperature of the air entering the evaporator (DBT) is the same for both houses during a specific simulation timestep. Considering that, any variations of *z-factor* between *House A* and *House B* will arise due to the variations in the temperature of the water entering the condenser. And more specifically, as the temperature of the water entering the condenser increases, z-factor decreases. Therefore, it can be concluded that the house with the higher z-factor (*House B*) will have lower condenser water temperatures; this is further confirmed in the following figure.

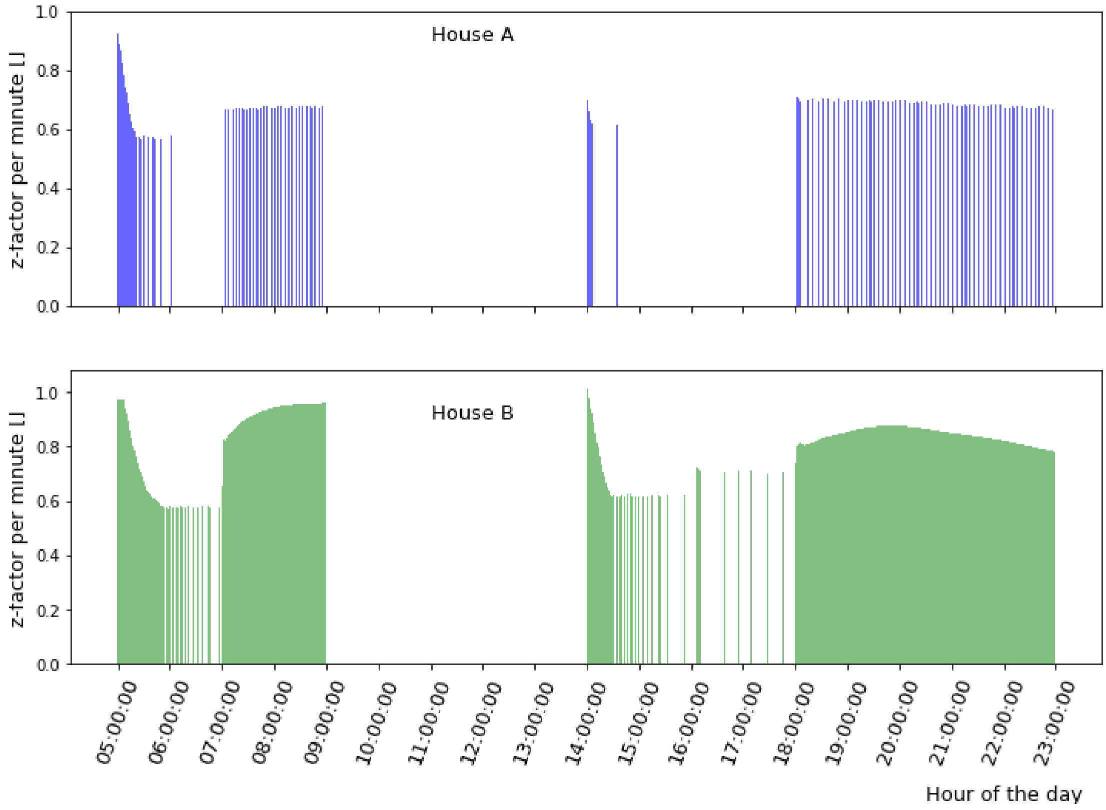



**Figure 4-12: z-factor variation per simulation timestep (one-minute) on 11 January for House A and House B**

*Figure 4-13* illustrates the one-minute variation of the temperature of the water entering the condenser for *House A* and *House B*. It should be noted that since the AWHP is linked to the storage water tank, the heat is transferred from the condenser of the AWHP to the storage tank and therefore, the storage water tank temperature is very close to the condenser water temperature. As seen, in *House A*, the AWHP achieves to reach the set-point temperature of the storage water tank, which is 55.0°C and 45.0°C, when the AWHP runs in DHW and space-heating mode, respectively. On the other hand, the temperature of the water in *House B* is quite often lower than the specified set-point temperatures (especially between 7 and 9 am). Comparing *Figure 4-11*, *Figure 4-12* and *Figure 4-13* for *House B*, it can be seen that the maxima in COP and *z-factor* correspond to minima in condenser water temperature. To summarise, one reason because of which *House B* appears to achieve higher simulated COP compared to *House A* is the fact that the retrofitted AWHP system in *House B* does not manage to reach the desired water set-point temperatures. Thus, the difference between the temperature of the water entering the condenser and the ambient air temperature is lower for *House B* and this results in operating the AWHP system "more effectively" in terms of COP compared to *House A*. In other words, the comparatively higher simulated COP in this case is connected with the ineffectiveness of the AWHP retrofit to reach the desired water temperature and meet the heating demand of the house.

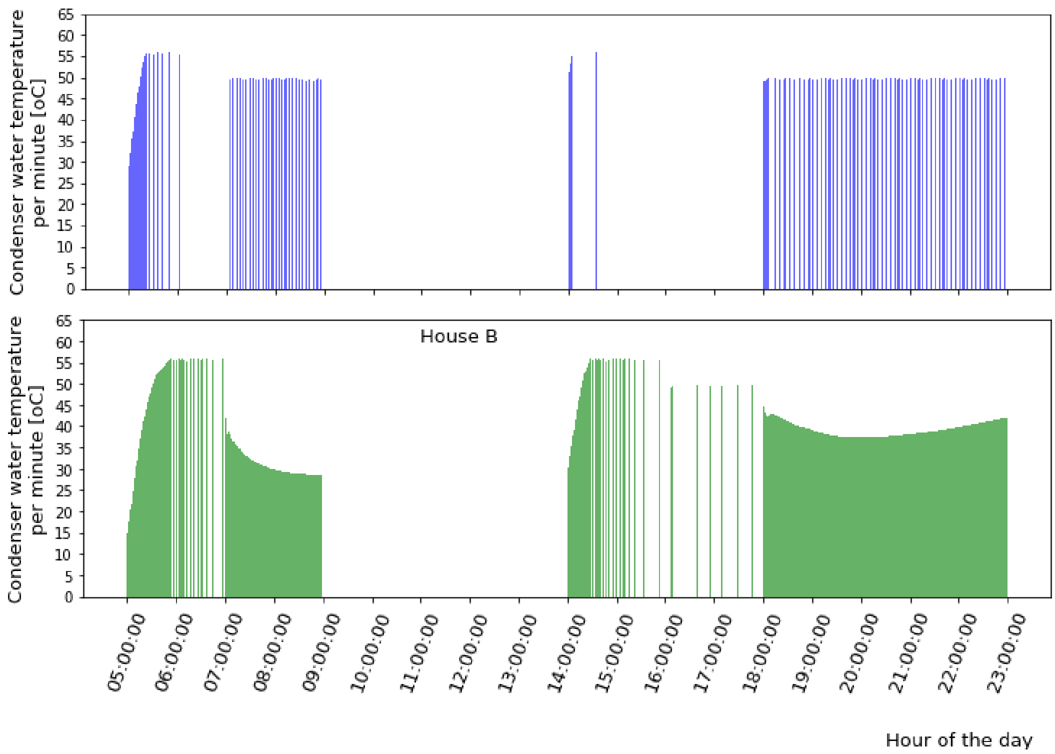



**Figure 4-13: Condenser water temperature variation per simulation timestep (one-minute) on 11 January for House A and House B**

*Figure 4-14* illustrates the one-minute variation of the PLF for *House A* and *House B*. As said, besides DBT and condenser water temperature fluctuations, the simulated COP also depends on the PLF. This is a factor ranging from 0.0 to 1.0, which is multiplied by the nominal COP to account for efficiency losses due to compressor's cycling (see *Equation 4-1*). (The calculation of PLF is explicitly explained in Section 3.5.1.) When PLF equals to 1.0 for a specific simulation timestep, this means that the AWHP operates at its maximum available capacity (full-load operation). As shown in Figure 4-14, the retrofitted AWHP in *House A* cycles on and off more often in comparison to *House B*. The PLF in *House A* is around 0.80 for a significant amount of time throughout this specific day, which results in reducing the COP of the AWHP by up to 20.0%. This means that the extent of the part-load operation in *House A* is higher compared to *House B*, which results in a more significant degradation of the simulated COP.

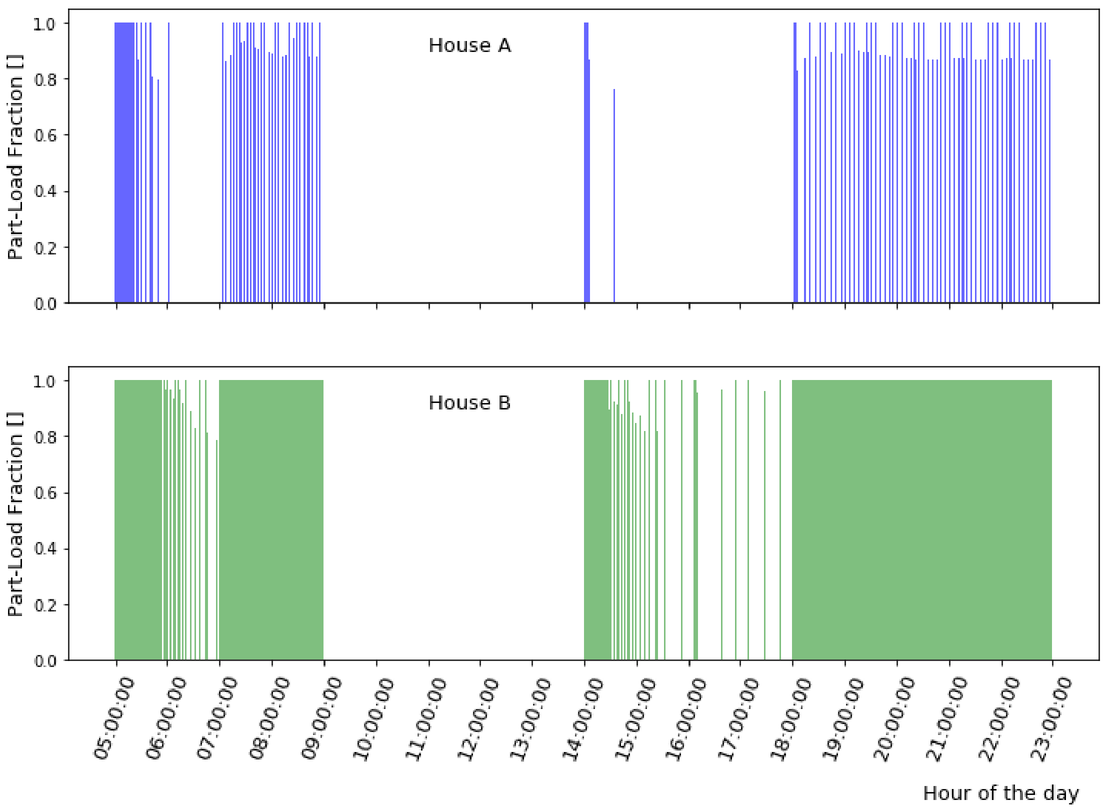



**Figure 4-14: Part Load Fraction (PLF) of the AWHP per simulation timestep (one-minute) on 11 January for House A and House B**

***Conclusions***

The focus of the previous example was to offer an insight into the reasons why the simulated AWHP results in achieving relatively higher SPFs for houses with relatively higher heating demand and mostly, for those houses that are not adequately sized (see *Figure 4.9*). This happens for two reasons as follows.

- First, in non-adequately sized houses, the retrofitted AWHP will run closer to its full-load conditions and thus, no significant degradation of COP is expected to occur (due to compressor's cycling).
- Second, in non-adequately sized houses, the differences between DBT and condenser water temperature are expected to be low due to the fact that the retrofitted AWHP does not manage to achieve the water set-point temperature.

The example used demonstrates that part-load operation can have a significant impact on COP, and consequently on SPF of the AWHP. This means that AWHP's size selection (represented by nominal heating capacity) is critical for the system's effectiveness. Although the AWHP should have enough capacity to meet house's heating demand, the designer/installer should ensure that this does not result in a long period, where the AWHP operates under part-load conditions. As a result, although MIS Standard recommends *100.0 % peak space-heating load coverage* by the AWHP itself (BEIS, 2017), this should be always evaluated in combination with the extent to which this strategy increases part-load operation and thus, limits the effectiveness of the installed AWHP. This example highlights the need to revise current guidelines for AWHPs' size selection and suggests the adoption of a more sophisticated sizing method in the future addressing over-sizing issues that might arise from the current recommended heat-pump sizing method.

## 4.4 **Supplementary energy use**

This section investigates the distribution of the supplementary electric heating that is needed to top-up the energy provided by the AWHP itself across the modelled housing stock. Supplementary heating can be provided by either the auxiliary electric heater (which comes as a part of the AWHP retrofit) or DHW immersion heater. The configuration of the modelled heating system is illustrated in *Figure 3-10*.

The retrofitted AWHP unit is linked to a storage water tank, and the tank transfers heat to the radiators and DHW tank. The storage water tank incorporates an auxiliary electric heater, which is scheduled to operate when the AWHP is either OFF due to the application of the frost-protection technique or incapable of meeting the entire heating demand of the house. As it happens for actual AWHP installations, the modelled AWHP system cannot provide hot water and space-heating simultaneously. Thus, a DHW immersion heater is also considered to be located in the DHW tank to maintain water in a temperature range of 54.0 - 55.0 $^{o}$C; this is scheduled to be ON only when the AWHP operates on space-heating mode. The control of the modelled heating system is explicitly described in Section 3.5.5. Both the auxiliary electric heater and DHW immersion heater are modelled to have a maximum heating capacity of 3.0 kW and effectiveness of 0.90.

*Figure 4-15* illustrates the hourly electric input of the AWHP itself, auxiliary electric heater and DHW immersion heater for a semi-detached house with medium levels of wall insulation (0.50 < U-value < 1.50) and volume in the range 180.0 $m^3$- 250 $m^3$. This house is considered to be an “average” house lying in the category, which contains the highest number of house archetypes across the modelled stock. This figure is used as an example to demonstrate the operation and control of the employed heating system over two consecutive working days in January (30-31 January). The vertical dashed lines show the operation mode of the system (OFF, DHW mode, Space-Heating (SH) mode). Further, the horizontal red line shows the limit of DBT below which the AWHP is forced to switch-off in order to avoid the accumulation of frost on its evaporator side. From 5 am to 7 am and from 2 pm to 4 pm, where all occupants are considered to sleep or be away from home, respectively, the space-heating is OFF and the AWHP operates on DHW mode to pre-heat the DHW tank. During these periods, the DHW immersion heater is scheduled to be OFF and heat is provided by the AWHP and auxiliary electric heater. From 7 am to 9 am and from 4 pm to 11 pm, where occupants are considered to be active (at home), the AWHP with the auxiliary electric heater operate to deliver heat only to the radiators. During these periods, the DHW immersion heater is ON to maintain the temperature of DHW tank at desirable levels (54.0 °C - 55.0 °C).

As seen in *Figure 4-15*, the electric input of the auxiliary heater can be significant throughout the day with this resulting from the application of the frost-protection and not from the incapacity of the AWHP to meet house's heating demand. Thus, it should be acknowledged that the selection of the DBT threshold is a critical parameter for the total energy use and overall effectiveness of the modelled heating system and the results presented in this section do significantly depend on that. The threshold of 2.0°C is determined based on actual AWHP systems that are sold by Mitsubishi Electric (Mitsubishi Electric, 2015) (for more details, see Section 3.4.1).

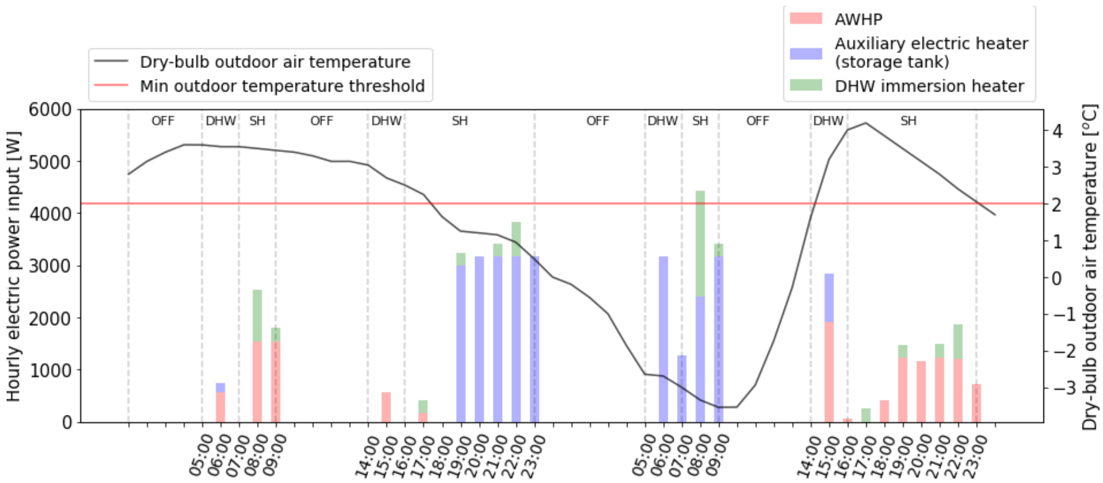



**Figure 4-15: Operation of the modelled AWHP heating system in one house archetype (example)**

*Figure 4-16* illustrates the annual electric input of the auxiliary heater per house category. The value corresponding to each category represents the average of all house archetypes lying in that specific category. As seen, there is need for auxiliary heating even for house archetypes, in which the retrofitted AWHP has enough capacity to meet the entire heating demand of the house. Generally, for house archetypes, where the AWHP is adequately sized, the auxiliary electric heater is forced to operate only due to the application of the frost-protection technique; this happens for almost 10.0% of the annual heating hours (379 out of 3,499 hours), where DBT is lower than 2.0°C. On the other hand, for house archetypes, where the retrofitted AWHP has not enough capacity to meet the entire heating demand of the house, the auxiliary electric heater also operates to top-up the energy provided by the AWHP itself. It is evident from *Figure 4-16* that the auxiliary electric input has a similar pattern with the AWHP's electric input (see *Figure 4-6*) with both increasing as building size, exposed-wall U-value and exposed-wall area increases. However, although the maximum heating capacity of the auxiliary electric heater is fixed for all house archetypes (3.0 kW), the heating capacity of the AWHP varies based on the dwelling's peak heating load and as a result, the AWHP's electric input presents a wider variation between the different house categories compared to auxiliary electric input.

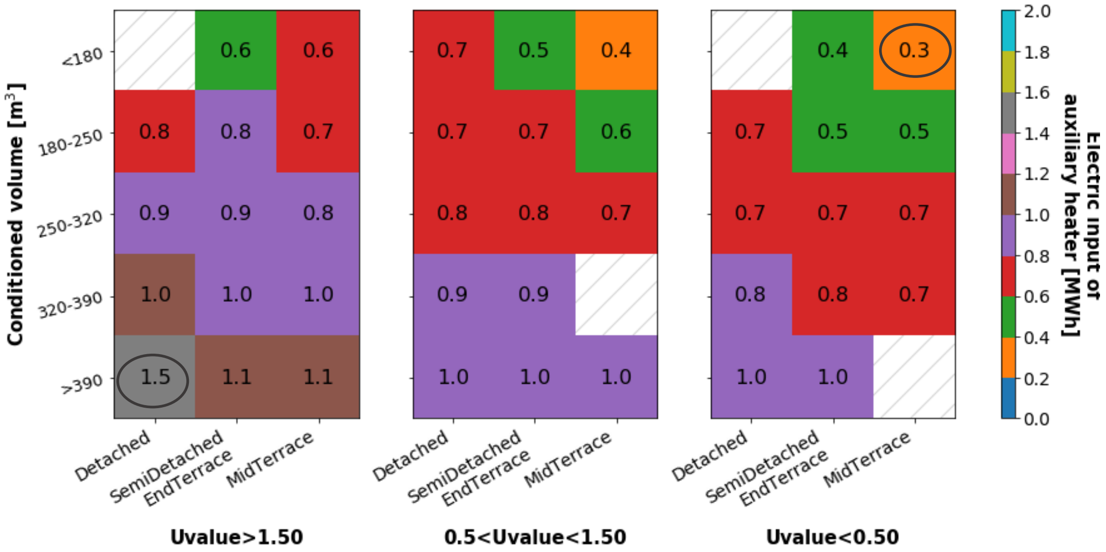



**Figure 4-16: Average annual auxiliary electric input per house category**

*Figure 4-17* illustrates the ratio of the annual electricity consumed by the AWHP itself to the annual electricity consumed by both the AWHP and auxiliary electric heater per house category. For each separate house, this ratio ($R_{Electric}$) is calculated as follows:

$$R_{Electric} = \frac{E_{AWHP}}{E_{AWHP}+E_{Auxiliary}}, \quad \text{(Equation 4-3)}$$

where $E_{AWHP}$ and $E_{Auxiliary}$ is the annual electric input of the AWHP unit and auxiliary heater, respectively. The $R_{Electric}$ corresponding to each category represents the average $R_{Electric}$ of all houses lying in that particular category. $R_{Electric}$ shows the contribution of the AWHP itself to the overall electricity used by the system (excluding DHW tank's immersion heater).

It is evident from *Figure 4-17* that $R_{Electric}$ decreases as the insulation level increases, dwelling's volume decreases, and the house becomes "more terraced". More specifically, $R_{Electric}$ varies from 0.52 for mid-terrace houses with U-value lower than 0.50 and volume lower than 180.0 $m^3$ (house category *A*) to 0.73 for detached houses with no wall insulation and volume higher than 390.0 $m^3$ (house category *B*) (for house categories *A* and *B*, see annotations in *Figure 4.17*). This implies that as the heating demand of the house is expected to decrease, the share of the auxiliary heater to the total electricity consumption becomes more significant. Considering the houses belonging to category A (in which the retrofitted AWHP has enough capacity to meet even the peak heating load of the house), the significant contribution of the auxiliary heater to the total electricity consumption comes as a result of the application of the frost-protection technique.

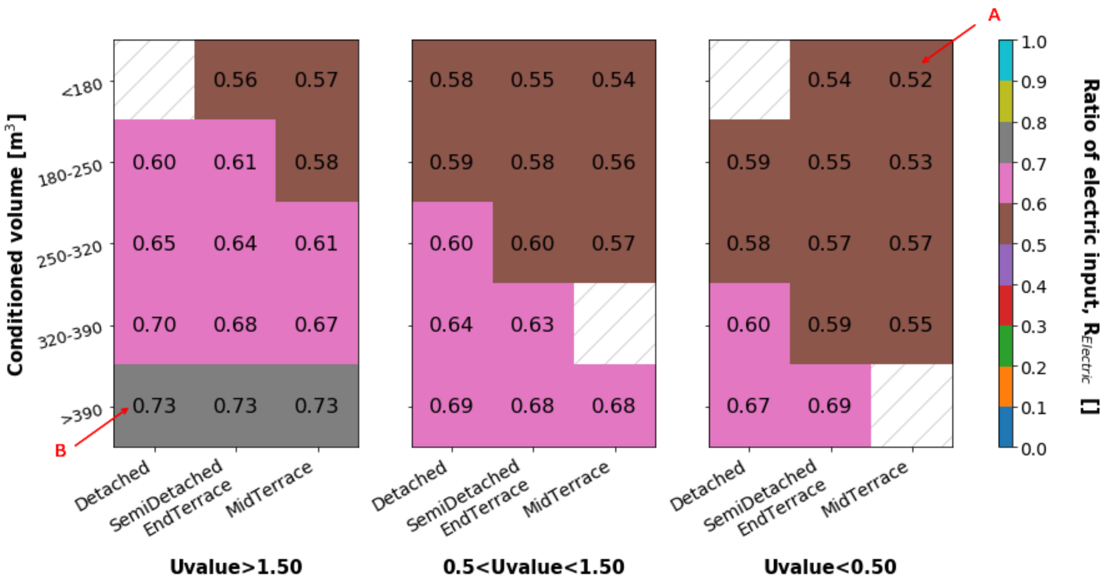



**Figure 4-17: Average ratio of AWHP's to auxiliary heater's electric input per house category**

To more clearly show the contribution of the auxiliary electric heater to the total electricity consumption and how this may vary for different categories, the hourly electricity input of the AWHP and auxiliary heater is plotted for two separate houses belonging to categories A and B; see *Figure 4-18* and *Figure 4-19*, respectively. It is evident that the distribution of the AWHP's electric input does more significantly differ between the two houses compared to the distribution of the auxiliary heater's electric input. First, in the case of the detached house (*Figure 4-19*), which is retrofitted with a 14.0 kW AWHP, the AWHP itself operates for a significantly longer period of time throughout the heating season with an average hourly rate that is significantly higher than in the case of the mid-terrace house, which is retrofitted with a 5.0 kW AWHP (*Figure 4-18*). Second, the hourly electric input of the auxiliary electric heater seems to have a similar pattern between the two houses due to the fact that its operation is mainly controlled by the application of the frost-protection technique. These two facts, however, result in a greater contribution of the auxiliary heater for the case of the mid-terrace house to the total electricity consumed, which as it will be discussed in the following pages, has an important impact on the effectiveness of the retrofitted AWHP system.

It should be acknowledged in this point that the contribution of the auxiliary heater in the case of the modelled system might be more significant if compared with actual AWHP installations, which usually employ reverse cycling to account for defrosting (rather than direct use of electric heating).

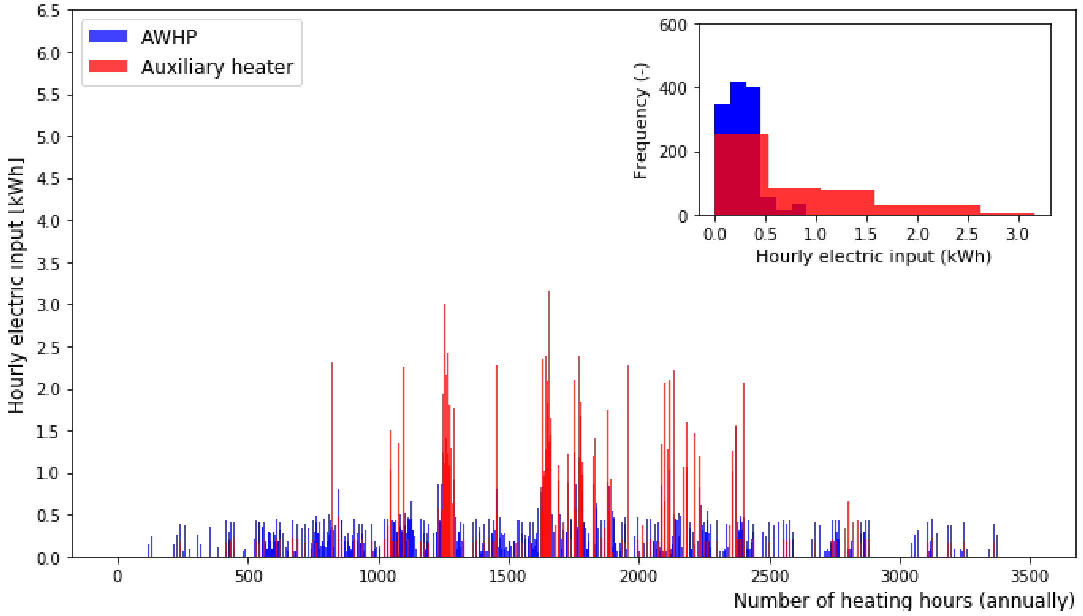



**Figure 4-18: Hourly electric input of the AWHP and auxiliary heater for a mid-terrace house with U-value < 0.50 and volume lower than 180.0 m$^3$ (category A, see *Figure 4-17*)**

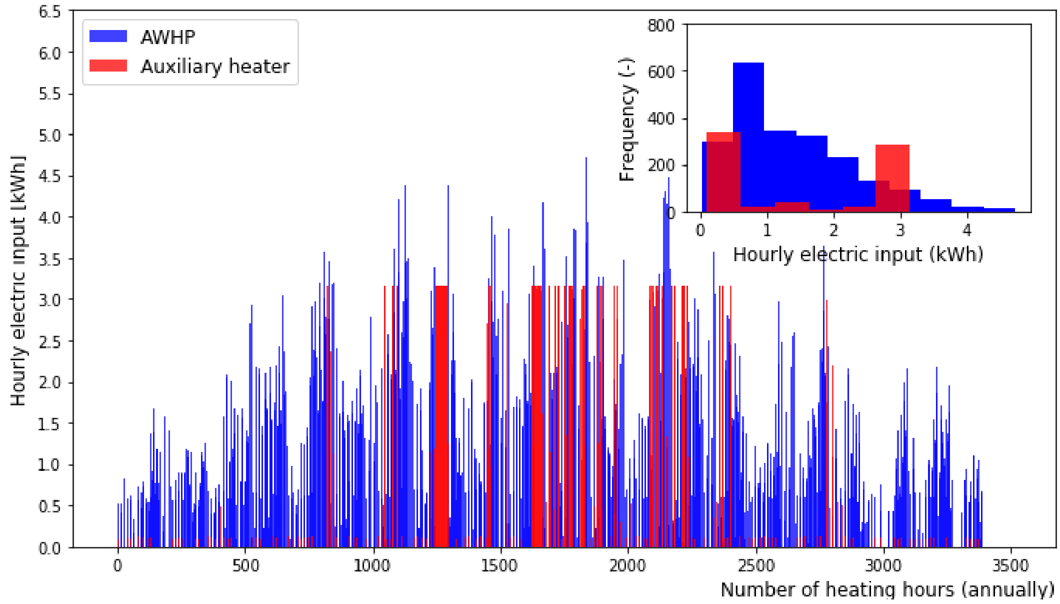



**Figure 4-19: Hourly electric input of the AWHP and auxiliary heater for a detached house with U-value > 1.50 and volume greater than 390.0 m³ (category B, see *Figure 4-17*)**

*Figure 4-20* illustrates the average effectiveness of the AWHP and auxiliary electric heater per various house categories. This is expressed as follows:

$$SPF_{AWHPsystem} = \frac{H_{AWHP}+H_{Auxilary}}{E_{AWHP}+E_{Auxiliary}}, \quad \text{(Equation 4-4)}$$

where $H_{AWHP}$ and $H_{Auxiliary}$ is the heating output of the AWHP and auxiliary electric heater, respectively. As seen, this ranges from 2.0 for mid-terrace houses with high insulation level (Uvalue < 0.5) and volume lower than 180.0 $m^3$ to 2.5 for detached houses with no wall insulation and volume greater than 390.0 $m^3$. Again, the fact that the effectiveness of the AWHP system decreases as the heating demand of the house decreases reflects the impact of the frost-protection technique.

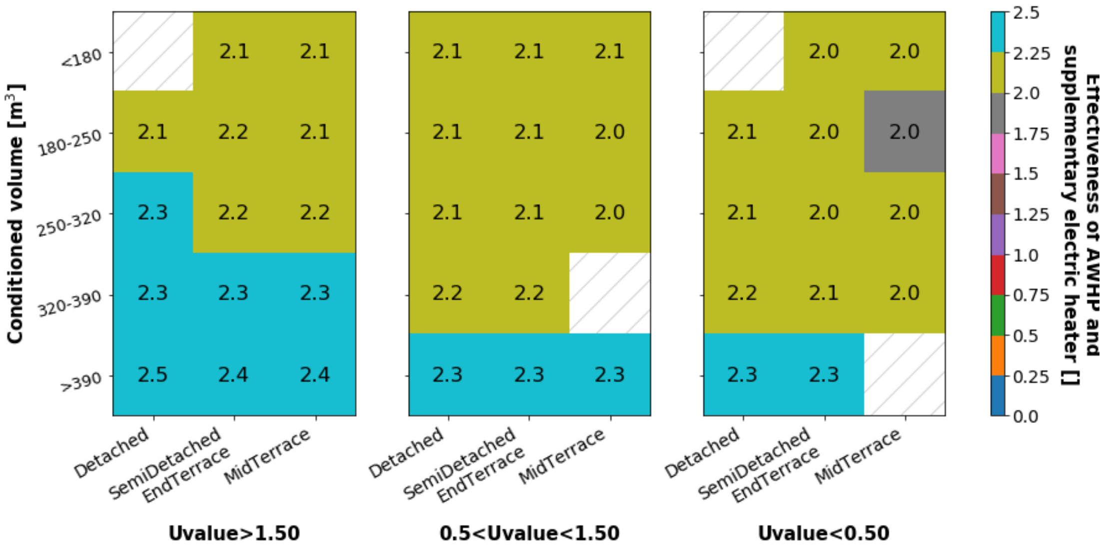



**Figure 4-20: Average effectiveness of AWHP and auxiliary electric heater per house category**

*Figure 4-21* illustrates the effectiveness of the entire modelled heating system per various house categories; this includes the AWHP, auxiliary electric heater and DHW immersion heater and is defined as follows:

$$SPF_{WholeSystem} = \frac{H_{AWHP}+H_{Auxilary} + H_{DHW,Immersion}}{E_{AWHP} + E_{Auxiliary} + E_{DHW,Immersion}}, \quad \text{(Equation 4-5)}$$

where $H_{DHW,\ Immersion}$ and $E_{DHW,\ Immersion}$ is the heating output and electric input of the DHW immersion heater, respectively. As expected, the effectiveness of the system further decreases when the contribution of the DHW immersion is also considered due to the fact that its effectiveness is lower than 1.0 (as also happens in the case of the auxiliary electric heater). Generally, the effectiveness of the entire heating system in this thesis is found to be lower when compared with previous works. For example, as mentioned in Section 2.2.2, the $SPF_{H4}$ for 15 ASHPs measured during the EST heat-pump field trials is found to be in the range 2.2 - 3.6 with an average of 2.45 (Dunbabin *et al.*, 2013).

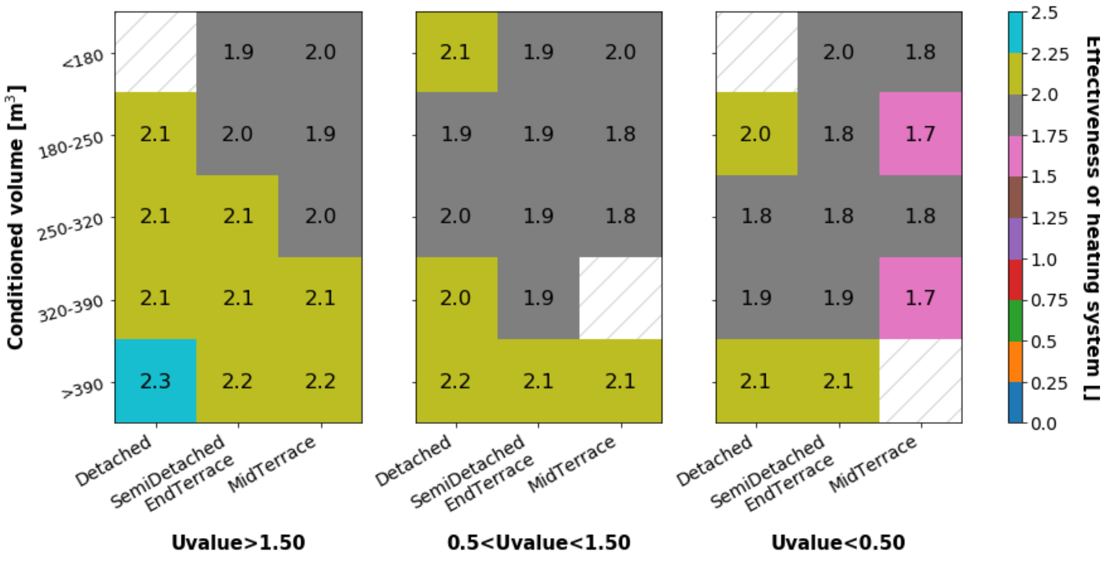



**Figure 4-21: Average effectiveness of the entire heating system per house category**

## 4.5 Level of under-heating

ASHRAE Standard 90.1-2007 - Appendix G introduces the term *unmet load hours*, which are defined as follows: "*any hours of operation when conditioned spaces are outside the throttling range for heating or cooling controls. That is, they are the hours in a year that the HVAC system serving a space cannot maintain space set-point. If unmet load hours for multiple spaces coincide (occur in the same hour), they are counted as only one unmet load hour for the building"* (ASHRAE, 2016). It should be noted that for heating set-points, throttling range is the permitted temperature difference below the set-point temperature before the system switches-on. In the case of this thesis, the throttling range is considered to be equal to 0.50°C, which means that when the set-point temperature of a zone is 21.0°C, the system does not switch-on until the zone temperature falls below 20.5°C. Thus, for each house archetype, the annual unmet load hours are the total number of hours throughout the entire heating season, where mean indoor air temperature is lower than 0.5°C below the selected set-point temperature in at least one thermal zone. In other words, one unmet load hour is considered when mean air temperature is lower than 20.5°C in the living-zone (living-room) or lower than 17. °C in the rest of the conditioned spaces (or both). The annual unmet load hours are calculated in order to investigate the extent of under-heating in the modelled house archetypes.

To identify whether a house archetype is eligible for the AWHP retrofit in terms of under-heating, a maximum acceptable limit should be imposed to the annual unmet load hours. ASHRAE Standard 90.1-2007- Appendix G recommends that when designing a heating and/or cooling system, unmet load hours should not exceed 300 per year. However, this Standard is not applicable to low-rise residential buildings (ASHRAE, 2016). To the extent of the author's knowledge, current standards (that are applicable to domestic buildings) do not impose a maximum number of hours throughout the year that zone air temperature can be lower than the heating set-point temperature. More specifically, existing standards and guidelines (such as the BS EN 15251:2007 Standard, CIBSE Environmental Guide A, WHO, SAP etc.) only include minimum limits for mean air temperature without further specifying the maximum acceptable number of hours that mean air temperature can be lower than recommended values. Therefore, in the absence of a suitable guideline, under-heating will be evaluated (in this thesis) using the limit of 300 hours as recommended by ASHRAE Standard 90.1-2007.

To conclude, the AWHP retrofit is considered to be effective (in terms of under-heating) if unmet load hours are equal to or lower than 300 annually. It should be noted that in the case of this thesis, the selected house archetypes are not considered to have any cooling system and thus, the unmet load hours do not include any over-heated hours.

*Figure 4-22* illustrates the number of unmet load hours per house category. Each value shown in the figure represents the average number of unmet load hours of all houses lying in each particular house category, while the colour of each box indicates the range to which the unmet load hours of each house category belongs (see colour-bar). As seen, the average annual unmet load hours for all house categories is less than 300 and thus, the AWHP retrofit appears to be effective in terms of under-heating performance. However, four detached house archetypes with no wall insulation and conditioned volume greater than 390.0 m$^3$ were found to have more than 300 unmet load hours throughout the year.

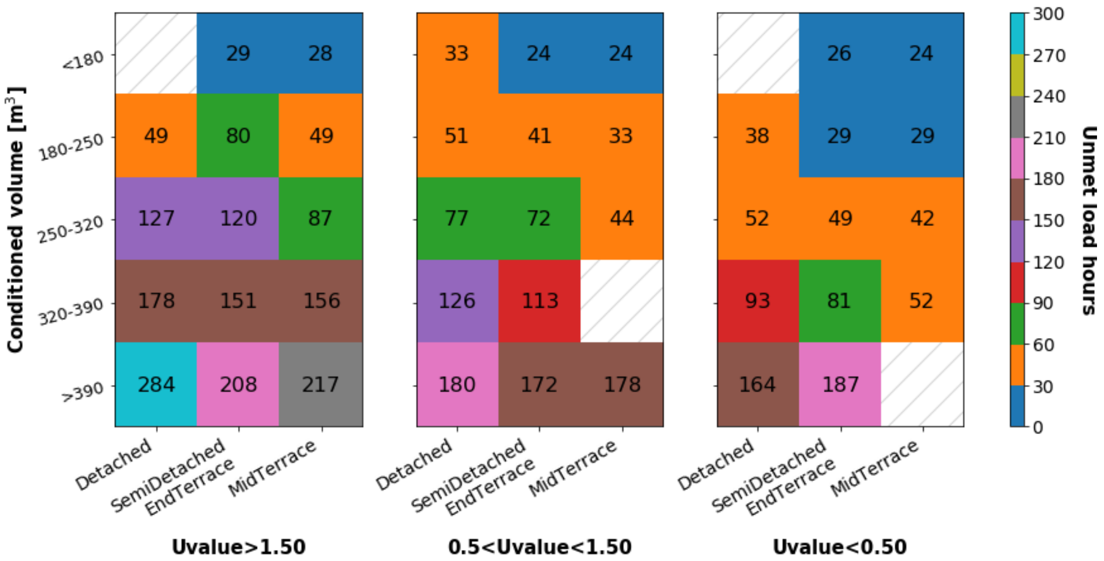



**Figure 4-22: Average number of unmet load hours per house category**

## 4.6 Thermal comfort conditions

This section focuses on assessing the conditions of thermal comfort in the modelled house archetypes. Thermal comfort is evaluated in terms of PMV and operative air temperature for the living-zone of each house archetype, which is considered to accommodate only the living-room (lounge) of the house. The selection of the living-room is based on the assumption that people tend to spend most of their time in there (when they are at home). In addition to that, the conditions of thermal comfort in bedrooms (while sleeping) cannot be determined using the PMV model for two main reasons. First, the ASHRAE 55 - Standard states as follows: "*when a person is sleeping or resting in a reclining posture, the bed and bedding may provide considerable thermal insulation*" and people tend to adjust their bedding according to their personal preferences. Thus, the clothing insulation value (clo) may considerably vary from one person to another while sleeping or resting (ASHRAE, 2004). In addition to that, ISO Standard 7730 recommends using the PMV model when metabolic rate ranges from

0.80 met to 4.0 met (from 46.0 $W/m^2$ to 232.0 $W/m^2$) with this being 0.7 met (around 40.0 $W/m^2$) during sleeping (BS EN ISO 7730:2005, 2006).[1]

For each house archetype, the annual PMV index (and operative air temperature) is calculated as the average hourly PMV index (and operative air temperature) throughout the entire heating season considering only the periods that space-heating is scheduled to be ON in the living-zone (from 07:00 to 09:00 and from 16:00 to 23:00 during the weekdays and from 07:00 to 23:00 during the weekend) (see *Figure 2-10*) and correspond to 2,633 hours annually.

### 4.6.1 Predicted Mean Vote (PMV) index

*Figure 4-23* illustrates the annual PMV index of the living-zone per house category. Each value shown in this figure represents the average annual PMV index of all houses lying in each particular house category. The colour of each box indicates the range to which the PMV index of each house category belongs (see colour-bar). As seen, PMV index generally decreases (becomes "more negative") as the dwelling's volume and U-value increases and the house becomes "more detached". However, for the house archetypes with relatively high insulation levels (U-value < 0.50$W/m^2K$), the PMV index does not vary according to dwelling's size. For example, the lowest PMV (-0.59) is reported for mid-terrace houses with volume in the range of 320.0 $m^3$ to 390.0 $m^3$. This could happen due to the low number of houses being included in some of the categories (see *Figure 3-9*), which does not always allow a strict comparison between them. As seen, the PMV index can be as low as -0.95 for detached houses with no wall insulation (U-value>1.50 $W/m^2K$) and volume higher than 390.0 $m^3$. Based on the PMV thermal sensation scale, the average annual PMV index is in the range *neutral* to *slightly cool* direction for all the examined categories (ASHRAE, 2004).

[1] The metabolic rate of a seated person is considered to be equal to 1.0 corresponding to 58.0 $W/m^2$.

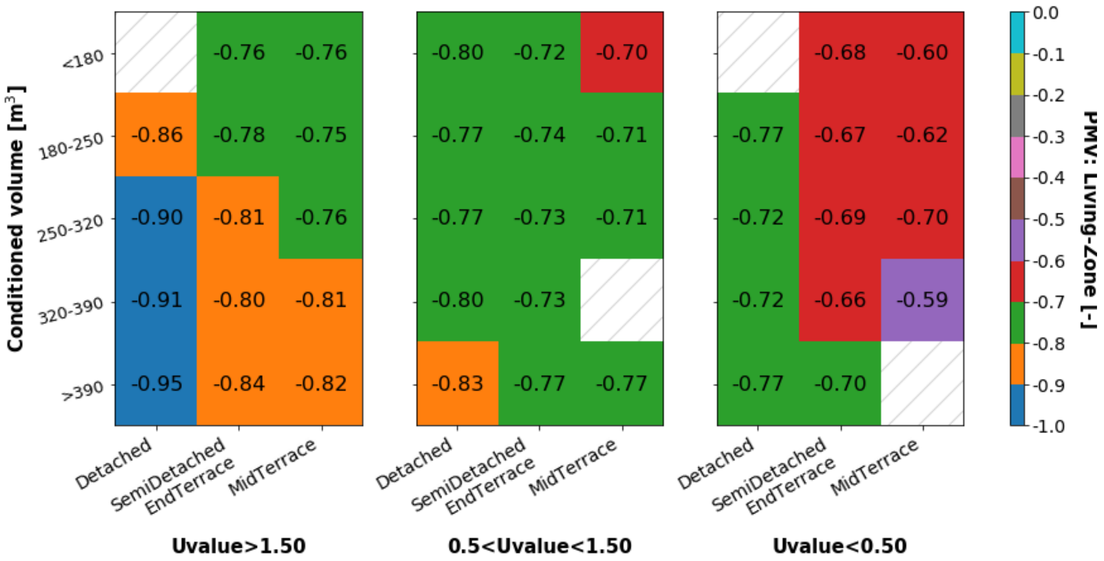



**Figure 4-23: Average annual PMV index of the living-zone (living-room) per house category**

Based on BS EN 15251:2007, which is used in this thesis to evaluate comfort, the PMV index should not be outside the range of -0.70 and +0.70 in existing dwellings; this complies with moderate comfort conditions (Category III-see Table 2-1). Further, BS EN 15251:2007 reports that the PMV index can also be considered acceptable when being outside this range, but this should only occur for limited periods (Category IV). In this work, the houses that are considered to be eligible for the AWHP retrofit in terms of PMV index are those that achieve an average PMV index in the range of -0.7 to +0.7. For the current weather scenario, these houses are as follows:

- **semi-detached and mid-terrace houses with high wall insulation levels (U-value < 0.50) and volume lower than 390.0 m$^3$** (8 categories in total)
- **mid-terrace houses with medium wall insulation levels (0.5 < U-value < 1.5) and volume lower than 180 m$^3$** (only 1 category).

*Figure 4-24* illustrates the average percentage of heating hours (per house category), where the hourly PMV is either lower (more negative) than -0.70 or higher than +0.70 in the living-zone of the modelled house archetypes. As seen, even for those house categories presenting an average PMV index higher than (less negative) or equal to -0.70 (see *Figure 4-23*), the percentage of the annual heating hours that are outside comfort band is generally high. For example, although the average PMV index is reported to be -0.60 for mid-terrace houses with U-value < 0.50 W/m$^2$K and volume lower than 180.0 m$^3$, the hourly PMV index is found to be outside the indicated comfort band for 34.0 % of the annual heating hours.

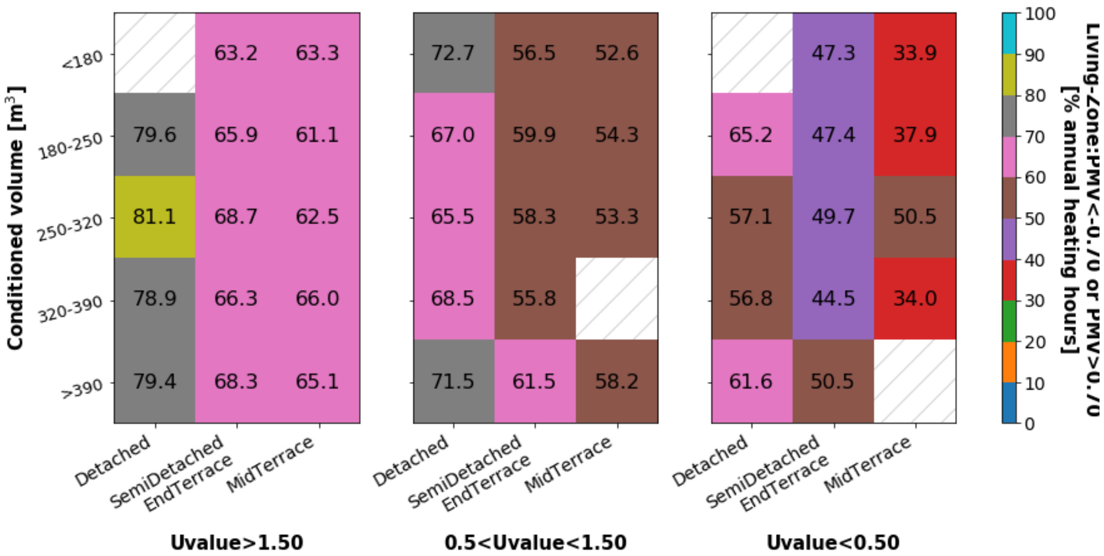



**Figure 4-24: Average annual percentage of heating hours per house category where the PMV index for the living-zone is outside the range of -0.7 to +0.7**

Following that, it would be interesting to investigate whether the deviation of the hourly PMV index from the comfort band is marginal or significant during the hours that PMV is not satisfied and how this may differ between house archetypes belonging to different categories. *Figure 4-25* illustrates the distributions of the hourly PMV index throughout the entire heating season for two different house archetypes (*House A* and *House B*). More specifically, *House A* belongs to the category of mid-terrace houses with volume lower than 180.0 m$^3$ and high insulation levels (U-value < 0.50), whereas *House B* belongs to the category of detached houses with volume greater than 390.0 m$^3$ and without wall insulation. For *House A*, the PMV index is found to be within the indicated comfort band for 1713 hours throughout the year (corresponding to 65.1 % of the total annual heating hours). For the rest of the time (where PMV is more negative than -0.70), this ranges between -0.7 and -1.0 for a total of 825 hours, while this is more negative than -1.0 for only 115 hours (corresponding to just 4.3 % of the annual heating hours). This means that although there is a significant number of hours, where PMV index requirement is not satisfied, its deviation from the threshold of -0.7 is for most of these hours in the range of 0.3 degrees with PMV still ranging from the neutral towards slightly cool direction of the thermal sensation scale. On the other hand, for *House B*, the PMV is found to be less (more negative) than -1.0 for 982 hours throughout the year corresponding to 37.3 % of the total heating hours with this being, in some cases, lower than -2.5.

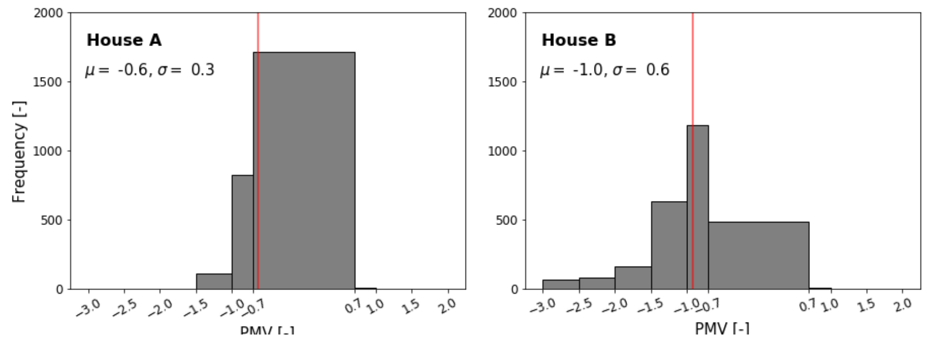



**Figure 4-25: Distribution of the hourly PMV index (throughout the entire heating season) for two selected house archetypes (*House A* and *House B*)**

It is evident from the previous example that the assessment of PMV index using just the constraint of -0.7 (based on BS EN 15251:2007) may not fully capture the thermal comfort conditions of a house. It is suggested that future guidelines should address issues of marginal deviations from the recommended PMV index thresholds.

### 4.6.2 Operative air temperature

The PMV index is calculated for each simulation timestep by $E^+$ using six individual factors as follows: mean air temperature, mean radiant temperature, relative humidity, indoor air velocity, clothing insulation value and metabolic rate. For the living-zone of all the simulated house archetypes, indoor air velocity, clothing value and metabolic rate are user-specified values and were set equal to 0.137 m/s (default value), 1.0 clo (CIBSE, 2006 - Table 1.5) and 1.1 met corresponding to 63.8 $W/m^2$, respectively. The selected metabolic rate, in particular, corresponds to the amount of energy that is considered to be used by a person performing a sedentary activity in the living-room of the house (CIBSE, 2006 - Table 1.5). Mean air temperature, mean radiant temperature and relative humidity are calculated for each simulation timestep by $E^+$ and thus, they vary between the different house archetypes.

*Figure 4-26* illustrates the annual operative air temperature for the living-zone per house category. Each value shown in this figure represents the average annual operative air temperature for all houses lying in each particular house category. Although the operative air temperature itself is not a direct input for estimating PMV index, it combines the mean and radiant air temperature with both these variables being direct inputs for estimating PMV index. More specifically, in the present thesis, the operative air temperature for each simulation timestep is modelled to be the average between mean and radiant air temperature. The comparison between *Figure 4-23* (illustrating the distribution of PMV index across the stock) and *Figure 4-27* reveals that PMV and operative air temperature have an identical variation across the entire modelled housing stock. It can be observed that as operative air temperature increases between the different house categories, PMV index increases (becomes “less negative”) as well.

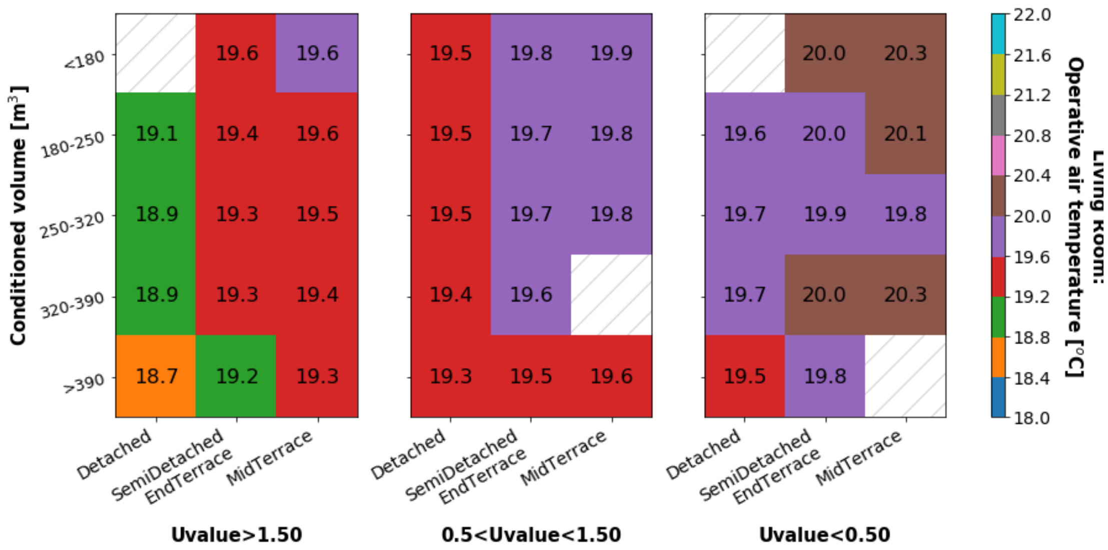



**Figure 4-26: Average annual operative air temperature of the living-zone per house category**

In fact, the variation of operative air temperature appears to be the main reason for the respective variation of PMV across the stock. This is further supported by the strong positive correlation found between the hourly PMV index and hourly operative air temperature throughout the entire heating season for a specific semi-detached house archetype with average characteristics in terms of wall insulation levels and total conditioned volume (see *Figure 4-27*). More specifically, *Spearman rank correlation factor* equals to 0.955 between PMV and operative air temperature, while this equals to 0.410 between PMV and mean air temperature and 0.653 between PMV and relative humidity.

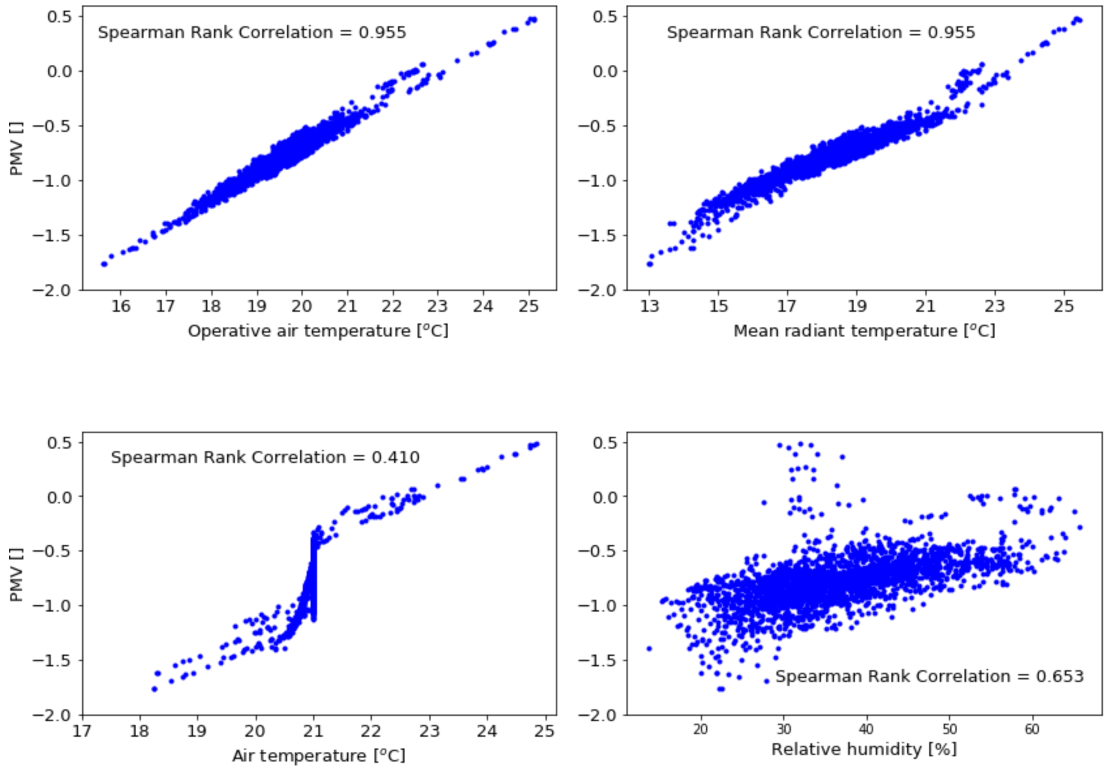



**Figure 4-27: Correlation between PMV and operative air temperature, mean radiant temperature, zone air temperature and relative humidity for an "average" house archetype**

In addition to the recommendations regarding the minimum and maximum acceptable limit for PMV index, the BS EN 15251:2007 Standard also recommends that operative air temperature should be no less than 18.0°C in existing buildings; this also complies with moderate thermal comfort conditions (Category III - see Table 2-1). As seen in *Figure-26*, the average operative temperature is higher than 18.0°C for all the examined house categories and thus, the operative air temperature constraint is found to be satisfied across the modelled stock.

## 4.7 Chapter summary

In Chapter 4, the applicability of the AWHP retrofit was evaluated for 756 house archetypes selected to represent the housing stock of the NE region of England. The heating performance of the selected house archetypes with the integrated AWHP system was studied using the $E^+$ simulation tool for a current weather scenario. The distribution of energy use, level of under-heating and degree of thermal discomfort across the stock was investigated by categorising houses based on their built form, exposed-wall insulation level and size (represented by the range of dwelling's total conditioned volume) (45 house categories in total).

In Section 4.2, the method of selecting AWHP size was presented. Then, the most frequently selected size per house category was found and the discussion focused on the extent to which this can be considered representative and directly used by AWHP installers (and homeowners). First, some of the categories include a very low number of houses and this limits the level of confidence to recommend the AWHP size as representative. Second, the analysis proved that there is a wide variation in AWHP's size within some of the categories proving that the size of the system should be determined by precisely calculating the house's peak heating load.

In Section 4.3, the distribution of the annual energy use and SPF of the AWHP itself was explored. The one-minute variation of COP for two houses belonging to different categories was compared during a typical winter day. One of the key findings is that the COP can be reduced up to 20.0 % when AWHP runs under part-load conditions. The discussion concluded that guidelines about sizing should account for the extent to which the matching of nominal heating capacity with the peak heating demand power of the house results in operating the AWHP under part-load conditions (which, in turn, results in COP degradation).

In Section 4.4, the distribution of the amount of supplementary electric heating (as a result of the AWHP retrofit) was investigated across the modelled stock. The energy consumption of the auxiliary electric heating was found to be significant for all houses. This, however, results from the limitation of the modelled AWHP system to account for defrosting through reverse cycling. The effectiveness of the AWHP and storage tank's auxiliary heater was found to range from 2.0 - 2.5 across the stock, while this range reduces to 1.7 – 2.3 when the contribution of the DHW immersion heating is also considered.

In Section 4.5, the distribution of the under-heating level across the modelled stock was investigated. This was evaluated through the calculation of the unmet load hours throughout the entire heating season. Apart from 4 detached houses with no wall insulation and volume greater than 390.0 $m^3$, the AWHP retrofit was found to be effective to maintain unmet load hours in acceptable levels for the rest housing stock (less than 300 hours annually).

In Section 4.6, the effectiveness of the AWHP retrofit to maintain occupants' comfort was evaluated across the modelled stock. The average annual PMV index was found to be outside comfort band for a very significant number of houses. The only houses for which the AWHP retrofit manage to achieve an average PMV in the range of -0.7 to +0.7 are as follows:

- semi-detached and mid-terrace houses with high wall insulation levels (U-value < 0.50) and volume lower than 390.0 $m^3$
- mid-terrace houses with medium wall insulation levels (0.5 < U-value < 1.5) and volume lower than 180 $m^3$.

# Chapter 5

# Results 2: Impact of future weather scenarios on the applicability of AWHPs

## 5.1 Introduction

Based on the latest and Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), global temperature has risen 0.85$^{o}$C over the period 1880 to 2012, while the difference between the average temperature of the 1850-1900 period and 2003-2012 period is estimated at 0.78$^{o}$C (IPCC, 2014). Especially in the UK, temperature is reported to be on average 0.3$^{o}$C warmer over the 2009-2018 period compared to 1981-2010 period (Met Office, 2019). The study of various emission scenarios led to the conclusion that global warming is more likely to be in the range of 1.5 $^{o}$C to 2.0 $^{o}$C by the end of the 21$^{st}$ century. The dominant cause of the observed warming over the last few decades is associated with the increased concentration of greenhouse gas emissions in the atmosphere arising mainly due to the economic and population growth. The most significant changes in weather conditions are associated with reductions in cold temperature extremes, increases in warm temperature extremes, increases in sea level and appearance of more intense precipitation events (IPCC, 2014). The biggest challenge over the following years is to limit warming to below 2.0$^{o}$C (relatively to pre-industrial levels) and to do so, governments should aim at tremendous emissions reductions and urgently move towards the adoption of the net-zero $CO_2$ emission concept. The definition of robust and up-to-date future weather scenarios is considered to be a key factor by the UK Government to mitigate climate change (Street *et al.*, 2009). In the context of BPS, future weather scenarios are recently used to inform decision-making for climate change adaptation (Herrera *et al.*, 2017).

Chapter 5 investigates the heating performance of AWHPs under future weather scenarios. The existing housing stock of the NE region of England (consisting of 756 house archetypes) with the integrated AWHP model has been simulated with the $E^+$ simulation tool using various future weather files including probabilistic climate change projections for 2050 and 2080. First, the different future weather scenarios that are used in this thesis are presented (Section 5.2). Then, the implications of using future weather scenarios for the existing building stock are discussed and the impact of future weather scenarios on the heating performance of the AWHP system is evaluated in terms of energy use, level of under-heating and thermal discomfort through the comparison with the current weather scenario (Section 5.3).

## 5.2 Definition of future weather scenarios

In this thesis, the evaluation of the heating performance of the AWHP retrofit under future weather scenarios is carried out using CIBSE's 2016 TRY future weather files (see section 3-6). More specifically, in 2016, CIBSE released weather files incorporating future probabilistic projections of climate change based on the UK's national climate scenario projections of 2009 (UKCP09) (CIBSE, 2019). However, it should be noted that since then, the Meteorological Office (Met Office) supported by BEIS and the Department for Environment, Food and Rural Affairs (Defra) published new climate projections (November 2018 – UKCP18) (Met Office, 2018). As a result, the weather files used in this thesis are based on the previous and not the latest projections of climate change (CIBSE has not yet updated the 2016 weather files based on the latest climate change projections) (Eames and Mylona, 2018; CIBSE, 2019).

### 5.2.1 CIBSE weather files

The future weather files created by CIBSE contain a set of hourly weather variables representing climatic projections for 2020 (covering the period 2011-2040), 2050 (covering the period 2041-2070) and 2080 (covering the period 2071-2100) under different emissions scenarios, which are defined as *low*, *medium* and *high*. More specifically, there is only a high emissions scenario for 2020, a medium and high emissions scenario for 2050 and a low, medium and high emissions scenario for 2080. In addition to that, for each different emissions scenario, the UKCP09 defines three different cumulative distribution function percentiles as follows: *$10^{th}$ percentile*, *$50^{th}$ percentile* and *$90^{th}$ percentile* (CIBSE, 2019). In statistics, the values representing the $10^{th}$ and $90^{th}$ percentile of a dataset are those specific values below which is the 10.0 % and 90.0% of all values included in that dataset, respectively. In this case, using the $10^{th}$ percentile (regarding e.g. a temperature value) implies that there is a 10.0% chance that actual (future) temperature will be less than this value. In a similar way, using a value representing the $90^{th}$ percentile implies that there is a 90.0% chance that actual (future) temperature will be less than this value. In other words, using a weather file representing the $10^{th}$ percentile implies that actual (future) weather data are unlikely to be less than the values included in it. Likewise, using a weather file representing the $90^{th}$ percentile implies that actual (future) weather data are unlikely to be greater than the values included in it. Finally, the $50^{th}$ percentile weather files represent the median or central estimation. The transition from weather files that are based on a fixed (standard) weather scenario to probabilistic climate projections was a key step to increase the level of confidence with which future weather files can be used for BPS. The use of probabilistic climate change projections enables the quantification of the uncertainty associated with natural variability and future emissions levels.

In this thesis, the weather scenarios for 2050 and 2080 are used. They are represented by five different weather files including a medium and a high emissions scenario for 2050 as well as a low, a medium and a high emissions scenario for 2080. For *each* of these five future weather scenarios, three separate weather files are provided by CIBSE with each file corresponding to the $10^{th}$, $50^{th}$ and $90^{th}$ percentile (10%, 50% and 90% probability level). Thus, in total 5x3 (=15) future weather files are used. The main effects of climate change that can have an impact on buildings' performance are connected with changes in air temperature, wind speed (and direction), solar radiation and relative humidity. It should be noted at this point that the 2020 weather scenario is not studied in this thesis. In fact, weather for 2020 comes at a time when there has been limited heat-pump roll-out up to now. Hence, future scenarios are more informative for deciding future roll-out policies for heat-pumps.

### 5.2.2 Weather variables

The generation of future weather files suitable to be used for BPS is conducted using weather generators or following a so-called 'morphing' procedure, which is the method applied to construct the CIBSE weather files. Morphing involves the utilization of suitable *scaling factors* to modify current to future weather variables based on climate projections derived from either global or regional climate models. In the case of the CIBSE weather files, UKCP09 climate projections were used; these refer to changes in the monthly mean values of selected weather variables. Morphing is based on the following operations: a) shifting, b) stretching *or* c) combination of shifting and stretching. Shifting is used when the change of a specific variable for the future is reported as an absolute change to the mean. Stretching is used when a change of a specific variable for the future is reported as a percentage or fraction concerning either the mean or variance of the average monthly variable. Stretching is also used when a specific variable has to be off at specific periods (e.g. solar radiation should always be 0 at night). A combination of shifting and stretching is used when both the mean and variance of a variable are reported to be changed (Belcher *et al.*, 2005).

The following pages focus on presenting and discussing the distributions of the dry-bulb outdoor air temperature (DBT) for the different weather scenarios throughout an entire year. DBT is considered to play a very important role in the operation and thermal performance of the modelled AWHP system as amongst others, it determines the ON/OFF periods of the AWHP unit and influences its COP and consequently the amount of electricity input.

*Figure 5-1* illustrates the histograms of the hourly DBT for the current and 15 future weather scenarios. The above histograms are constructed to depict the distribution of the hourly DBT only for those hours that the modelled AWHP is scheduled to be ON (5:00 am-9:00 am/2:00 pm-11:00 pm during weekdays and 5:00 am-11:00 pm during weekends). For the future weather scenarios, in particular, different emission scenarios are presented, while each emission scenario includes three probabilities of climate change. For each histogram, the mean ($\mu$) and standard deviation ($\sigma$) of the distribution are displayed, while the red vertical line indicates the median (central estimation) of the distribution. As seen, there is no significant difference between the distributions of the medium and high carbon emissions scenario of 2050. This occurs due to the fact that the lifetime of carbon dioxide in the atmosphere is about 100 years and hence, atmospheric concentrations for earlier projections are considerably governed by past emissions (Belcher *et al.*, 2005). The range of the mean DBT rise for the 2050 and 2080 medium emissions scenarios (compared to the current weather conditions) is estimated to be in the range 0.3$^{o}$C - 1.4$^{o}$C and 0.7$^{o}$C – 2.7$^{o}$C, respectively, between the 10% and 90% probability levels. Additionally, the range of the respective mean DBT rise for the 2050 and 2080 high emission scenarios is estimated in the range 0.4$^{o}$C - 1.5$^{o}$C and 1.0$^{o}$C – 3.3$^{o}$C, respectively, between the 10% and 90% probability levels.

It can be observed from the histograms that the *shape of the distributions* of DBT are similar between the different emissions scenarios with the difference that they tend to be more negatively skewed as the future weather conditions move towards a higher carbon emissions scenario and the probability of climate change moves from the 10$^{th}$ to 90$^{th}$ percentile. The negative skewness indicates that the frequency of higher temperatures increases, whereas the frequency of lower temperatures decreases. However, although the frequency of lower temperatures decreases for all the studied future weather scenarios, it can be observed from the above histograms that there are still similar ‘cold snaps’ as those observed in the current weather conditions. More specifically, for all the examined future weather scenarios, there are periods where DBT ranges between -2.5$^{o}$C and 0.0$^{o}$C, whereas for few of them, there are periods, where DBT can be as low as -5.0$^{o}$C. This fact indicates that although the heating demand is expected to decrease as the mean DBT is expected to increase within the following decades, the peak heating load is not expected to significantly reduce. As a result, the installed capacity of the selected heating plant, which in the case of this study is the AWHP, will not be significantly influenced. (It should be recalled at this point that the selection of the size of the AWHP that is considered to be retrofitted in each house archetype was carried out based on the peak heating load of the house, see Section 3.5.2) Nevertheless, it should be acknowledged the fact that the composition of the building stock will most probably change within the next decades due to the progressive introduction of new-built houses and the application of refurbishments to the old stock. As a result, the heating demand of houses is expected to further decrease and therefore, the installed capacity of the heating plant will probably be influenced (Levermore *et al.*, 2012); this is further discussed in the following section of this thesis.

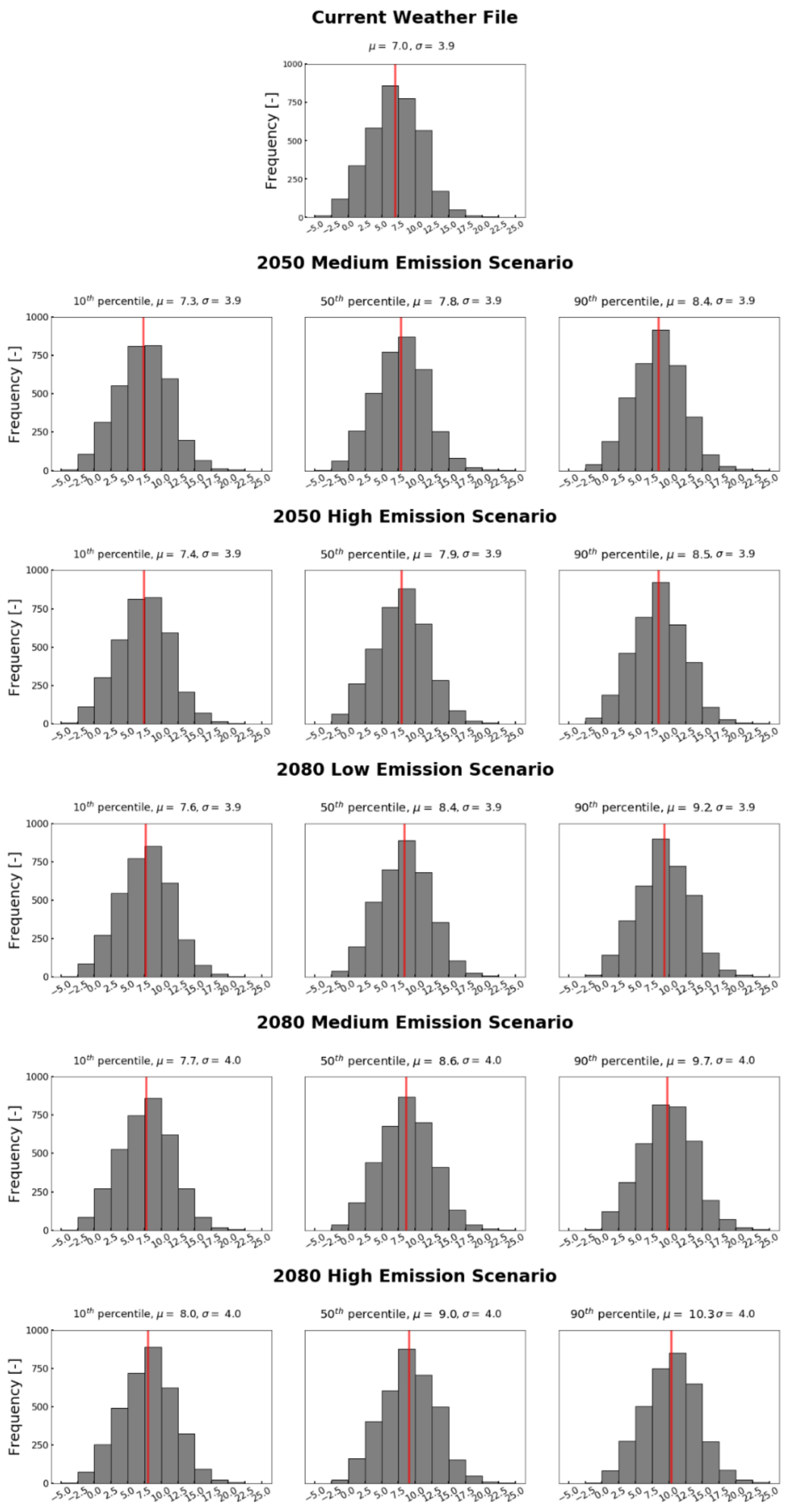



**Figure 5-1: Distributions of DBT under various weather scenarios**

*Table 5-1* shows the annual number (and percentage) of heating hours, where DBT is lower than 2.0$^{o}$C for the various weather scenarios; the limit of 2.0$^{o}$C is selected as the minimum DBT below which the modelled AWHP is controlled to switch-off in order to avoid the accumulation of frost on its evaporator (frost-protection technique, see Section 3.5.1). As seen in the above table, the number of hours with DBT below 2.0$^{o}$C presents negligible differences between the 2050 medium and 2050 high emissions scenarios that correspond to the same probability level. However, compared to the current weather conditions, the number of hours with DBT lower than 2.0$^{o}$C presents an apparent decrease even for the scenarios corresponding to the 10% probability level. Regarding the various future weather scenarios for 2080, the number of hours with DBT below 2.0$^{o}$C is significantly influenced by the amount of carbon emissions. For example, the 2080 low emission scenario that corresponds to the 50% probability level is reported to present 50.8% less hours with DBT below 2.0$^{o}$C compared to the current weather scenario and 11.3% and 25.3% more hours with DBT below 2.0$^{o}$C compared to the 2080 medium and 2080 high emissions scenario, respectively. The reduction of the annual number of hours with DBT below 2.0$^{o}$C is expected to significantly reduce the total energy use of the retrofitted AWHP system for two reasons. First, the AWHP itself is expected to operate more effectively due to the milder outdoor air temperatures and more importantly, the operation of the auxiliary electric heater is expected to be limited as the DBT will not force the AWHP to switch off.

**Table 5-1: Annual number and percentage of heating hours, where DBT is below 2.0 ºC under current and future weather scenarios**

| Weather scenario | Number of heating hours below 2.0ºC [-] | Percentage of heating hours below 2.0ºC [%] |
|---|---|---|
| Current | 378 | 10.8 |
| 2050 Medium emission scenario, 10th percentile | 331 | 9.4 |
| 2050 Medium emission scenario, 50th percentile | 240 | 6.9 |
| 2050 Medium emission scenario, 90th percentile | 176 | 5.0 |
| 2050 High emission scenario, 10th percentile | 330 | 9.4 |
| 2050 High emission scenario, 50th percentile | 239 | 6.8 |
| 2050 High emission scenario, 90th percentile | 173 | 5.0 |
| 2080 Low emission scenario, 10th percentile | 288 | 8.2 |
| 2080 Low emission scenario, 50th percentile | 186 | 5.3 |
| 2080 Low emission scenario, 90th percentile | 121 | 3.5 |
| 2080 Medium emission scenario, 10th percentile | 275 | 7.9 |
| 2080 Medium emission scenario, 50th percentile | 165 | 4.7 |
| 2080 Medium emission scenario, 90th percentile | 91 | 2.6 |
| 2080 High emission scenario, 10th percentile | 255 | 7.3 |
| 2080 High emission scenario, 50th percentile | 139 | 4.0 |
| 2080 High emission scenario, 90th percentile | 46 | 1.3 |

## 5.3 Heating performance of AWHP under future weather scenarios

Having discussed the distribution of energy use, under-heating and thermal discomfort (resulting from the AWHP retrofit) across the housing stock for a current weather scenario (Chapter 4), this section now focuses on evaluating the impact of various future weather conditions resulting from 15 different future weather scenarios on the heating performance of the AWHP retrofit. More specifically, the housing stock of the NE region of England *at its current state* (without considering the application of any refurbishment measure) with the integrated AWHP system is dynamically simulated using $E^+$ simulation engine under various future weather scenarios and the "sensitivity" of AWHP's thermal performance on these weather conditions is discussed.

It is acknowledged that the building stock is not expected to remain 'static' within the following few decades. Various changes are expected to occur concerning the adoption of energy efficiency strategies aiming to reduce buildings' energy use; the replacement of some of the existing stock by new; the construction of more thermally efficient buildings; and the overall increase of the building stock. The latter, in particular, arises due to the expected population growth (Levermore *et al.*, 2012). However, any provision associated with the composition of the future housing stock is outside the scope of this thesis and it involves many sources of uncertainty mainly arising from the unknown number of new-built houses and the fact that any assumed change of the existing houses would be based on current and not future building regulations.

Thus, the estimates included in this present section aim to assess the impact of weather conditions on the operation and effectiveness of the AWHP irrespectively of any changes in the condition of the building stock. The energy use of the AWHP and auxiliary electric heating as well as the degree of under-heating and level of thermal discomfort resulting from the simulation of the housing stock of the NE region of England is estimated for future weather scenarios and is compared with the current weather scenario. However, since the energy demand of the housing stock is expected to decrease within the following few decades, the utilization of the AWHPs is expected to be even more favourable than presented in this chapter. In other words, the combination of the existing housing stock with future weather scenarios can be considered as a conservative or even a worst-case scenario for the applicability of AWHPs in the future.  Studying the applicability of AWHPs for the existing stock, this work will attempt to identify those houses that need further retrofit in order to benefit from the AWHP retrofit. As a result of the analysis, this thesis aims to indicate those houses that should be on the focus of upcoming retrofit policies in order for the AWHPs to be smoothly and widely accepted as a heating solution for the UK residential sector in the near future.

In the following pages, the percentage difference of *AWHP's electric input*, *auxiliary heater's electric input* and *unmet load hours* between the current and those future weather scenarios referring to 50 % probability level are shown as average values per house category. Further, the average value of PMV index per house category is also shown for those future weather scenarios referring to 50 % probability level. (For the categorisation of the examined house archetypes, see Section 3.4.2.) Due to the very large amount of simulation data, for the rest future weather scenarios referring to 10 % and 90 % probability level, the distributions of the electric input of the AWHP and auxiliary heater as well as the distributions of unmet load hours and PMV index across the entire housing stock of the NE region of England are shown in the Appendix A (from Figure A-3 to Figure A-7).

### 5.3.1 AWHP energy use

Section 5.3.1 discusses the distribution of the percentage difference of the AWHP's electric input across the modelled housing stock between the current and various 2050 and 2080 weather projections incorporating different carbon emissions scenarios.

*Figure 5-2* illustrates the average percentage difference of the annual AWHP's electric input per house category between the current and selected future weather scenarios. The electricity input of the AWHP for the current weather conditions has been shown in *Figure 4-5*. In *Figure 5-2*, five different weather scenarios are included (medium and high emissions scenario for 2050 and low, medium and high emissions scenario for 2080), all referring to 50% probability level. Negative percentages mean that the AWHP's electric input is expected to decrease in relationship with that estimated for the current weather scenario. For example, the average reduction of the amount of AWHP's electric input between the current and 2050 medium emissions scenario for semi-detached houses with no wall insulation and volume lower than 180.0 $m^3$ is estimated at 7.2 %.

As seen in *Figure 5.2*, the amount of the annual AWHP's electric input is expected to reduce in relationship with that corresponding to the current weather scenario for all the examined house categories and under all the selected future weather scenarios. More specifically, under both the 2050 medium and high emissions scenarios, the reduction of the AWHP's electric input varies from 6.0 % to 9.0 % for most house categories, while for the 2080 weather scenarios, this reduction can be from 11.0 % to 26.0 % per house category depending on the assumed carbon emissions levels. This shows that the utilization of AWHPs is expected to become more favourable in terms of AWHP's electricity use over the century resulting from the continuously rising trend of the ambient temperature (this is shown in *Figure 5-1*). Further, it is evident from *Figure 5-2* that under a specific weather scenario, the percentage reduction of the

AWHP's electricity input does not present significant differences between the various house archetypes. For example, considering the 2080 medium emission scenario, the percentage reduction of AWHP's energy use ranges between 14.0 % and 20.9 % for all the house categories, while this range is even more limited for the 2050 high emission scenario with the percentage reduction of AWHP's electricity input fluctuating between 5.9 % and 9.9 % for all the examined house categories.

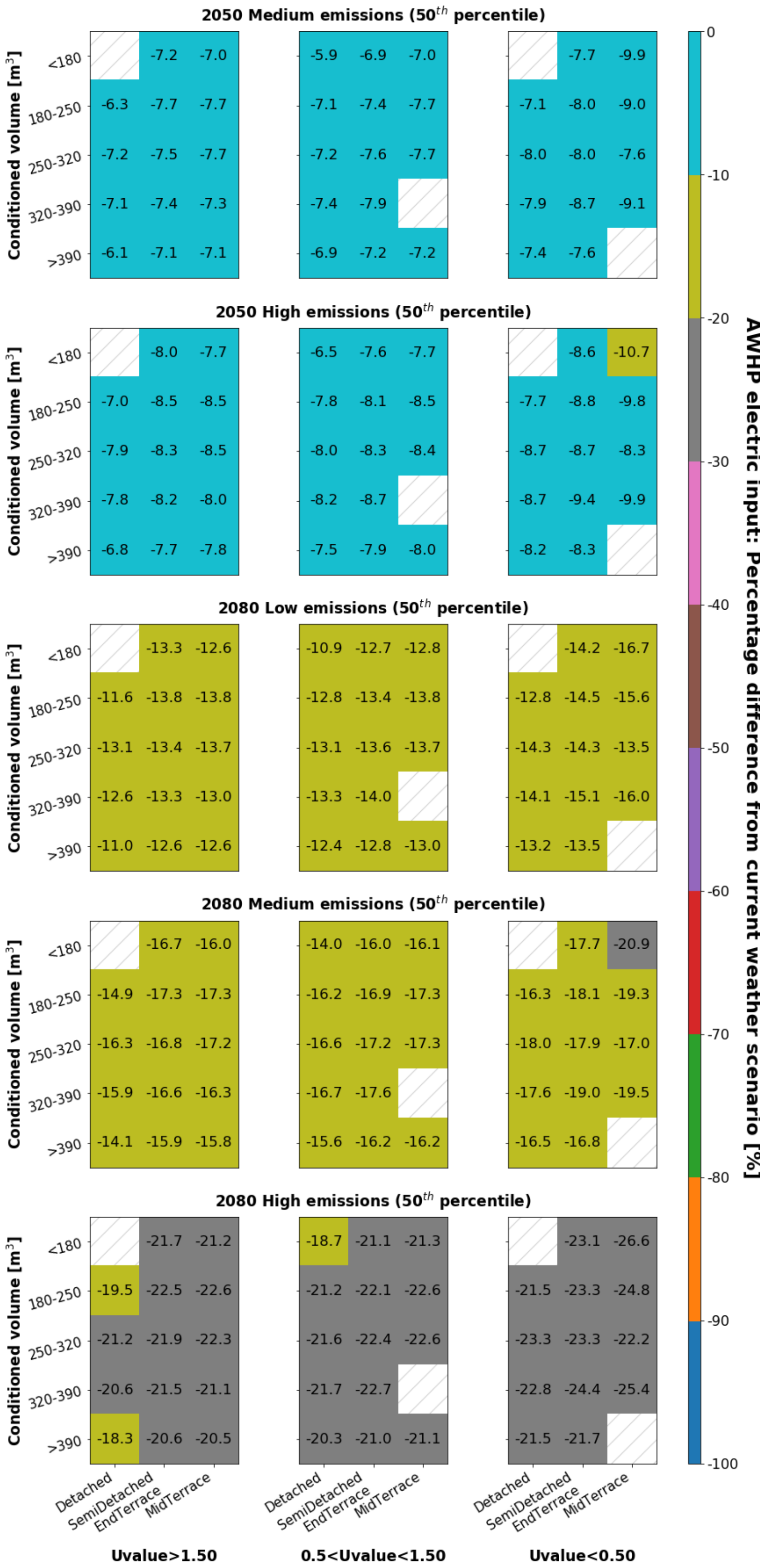



**Figure 5-2: Percentage difference of AWHP's electric input between the current and future weather scenarios (only the scenarios corresponding to 50% probability level are included here)**

Generally speaking, the reduction of AWHP's electric input is more limited compared to the reduction of auxiliary electric input (see *Figure 5-3*, in the following pages). This is due to the fact that the expected ambient temperature rise in the future is inevitably accompanied by a reduction in the number of hours, where DBT is below 2.0$^{o}$C (see *Table 5-1*). Therefore, the number of hours, where the operation of the AWHP is restricted due to the application of the frost-protection technique reduces compared to the current weather scenario. In other words, even if the amount of AWHP's electric input reduces for the future weather scenarios due to the milder winter conditions, this reduction is limited (compared to the reduction of auxiliary electric input) due to the fact that the AWHP itself is forced to be OFF for a shorter period of time throughout the heating season as DBT is predicted to drop below 2.0 $^{o}$C for a shorter period of time throughout the heating season as well.

*Table 5-2* presents the average electric input of the AWHP for the entire housing stock of the NE region of England under the various future weather scenarios (for each weather scenario, three probability levels of climate change are included in this table). As seen, the average AWHP's electricity input presents very limited differences between almost all the future weather scenarios (this further supports the limited percentage differences across the stock discussed previously). A relatively significant difference is only observed for the 2080 medium and high emissions scenarios corresponding to 90 % probability level. The distributions of the AWHP's electric input are illustrated for each different weather scenario in *Figure A-3* in the Appendix.

**Table 5-2: Average electric input of the AWHP for the entire housing stock of the NE region of England under current and future weather scenarios**

| Weather scenario | Average annual AWHP's electric input [MWh] |
|---|---|
| Current | 1.3 |
| 2050 Medium emission scenario, 10th percentile | 1.2 |
| 2050 Medium emission scenario, 50th percentile | 1.2 |
| 2050 Medium emission scenario, 90th percentile | 1.1 |
| 2050 High emission scenario, 10th percentile | 1.2 |
| 2050 High emission scenario, 50th percentile | 1.2 |
| 2050 High emission scenario, 90th percentile | 1.1 |
| 2080 Low emission scenario, 10th percentile | 1.2 |
| 2080 Low emission scenario, 50th percentile | 1.1 |
| 2080 Low emission scenario, 90th percentile | 1.0 |
| 2080 Medium emission scenario, 10th percentile | 1.2 |
| 2080 Medium emission scenario, 50th percentile | 1.1 |
| 2080 Medium emission scenario, 90th percentile | 0.9 |
| 2080 High emission scenario, 10th percentile | 1.1 |
| 2080 High emission scenario, 50th percentile | 1.0 |
| 2080 High emission scenario, 90th percentile | 0.8 |

### 5.3.2 Need for auxiliary electric heating

Section 5.3.2 discusses how the need to provide auxiliary electric heating (to top up the heating supplied by the AWHP itself) varies across the modelled housing stock as a result of various future weather scenarios and, in comparison with the current weather scenario.

*Figure 5-3* illustrates the average percentage difference of auxiliary heater's electric input between the current and selected future weather scenarios per house category (all the future weather scenarios included in this Figure refer to 50% probability level). For the current weather scenario, the average annual amount of auxiliary electric input is illustrated per house category in *Figure 4-16*. It is evident from *Figure 5-3* that the amount of the auxiliary electricity input significantly reduces for all the future weather scenarios and for all the examined house categories. More specifically, its percentage reduction (from the current weather scenario) ranges from (around) 40.0 % for the 2050 weather scenarios to (around) 66.0% for the 2080 high emissions scenario.

In addition to that, it can be observed that for each specific future weather scenario, the amount of the auxiliary electric input reduces at the same percentage for most house categories. For example, the reduction of the auxiliary electric input between the current and 2050 weather scenarios is found to be in the range of 40.0 % to 42.0 % for almost all the different house categories. The limited range of the percentage difference of the auxiliary electric input between the different house categories can be justified considering the applied control strategy of the auxiliary electric heater. More specifically, for those AWHP units that have enough capacity to meet even the peak heating demand of the house, the modelled auxiliary electric heater does only operate when the DBT is below 2.0$^{o}$C (application of the frost-protection technique). As a result, since the modelled AWHP system operates under the same heating pattern for all the selected house archetypes (same heating periods and set-point temperatures), it is fairly reasonable that any change in the number of hours during which DBT is lower than 2.0$^{o}$C will have the same impact on the electricity use of the auxiliary heater. On the other hand, for the category including detached houses with no wall insulation and volume higher than 390.0 $m^3$, the percentage difference of the auxiliary electric input between the current and 2050 medium emissions scenario is estimated at 35.5 %; this is outside the range 40.0% - 42.0 % in which most house categories are found. This is due to the fact that this particular house category does contain a large number of houses with under-sized AWHPs. In this case, the auxiliary electric heater does not only operate when the DBT is below 2.0$^{o}$C, but also when the energy provided by the AWHP is insufficient to meet heating demand of the house. This shows that for this particular category the heating demand of the included houses is too high even when the 2050 future weather scenarios are considered. In this case, the auxiliary electric heater operates at its maximum heating capacity (as this is the case for the current weather scenario as well) to meet houses' heating demand and thus, the "benefit" from future weather scenarios is more limited compared to the other categories.

*Figure 5-4* illustrates the ratio of AWHP's to auxiliary heater's electric input for the various weather scenario. Comparing its distribution with *Figure 4-17* (referring to the current weather scenario), it can be seen that it increases in the range of 0.10-0.15 depending on the weather and emissions scenario.

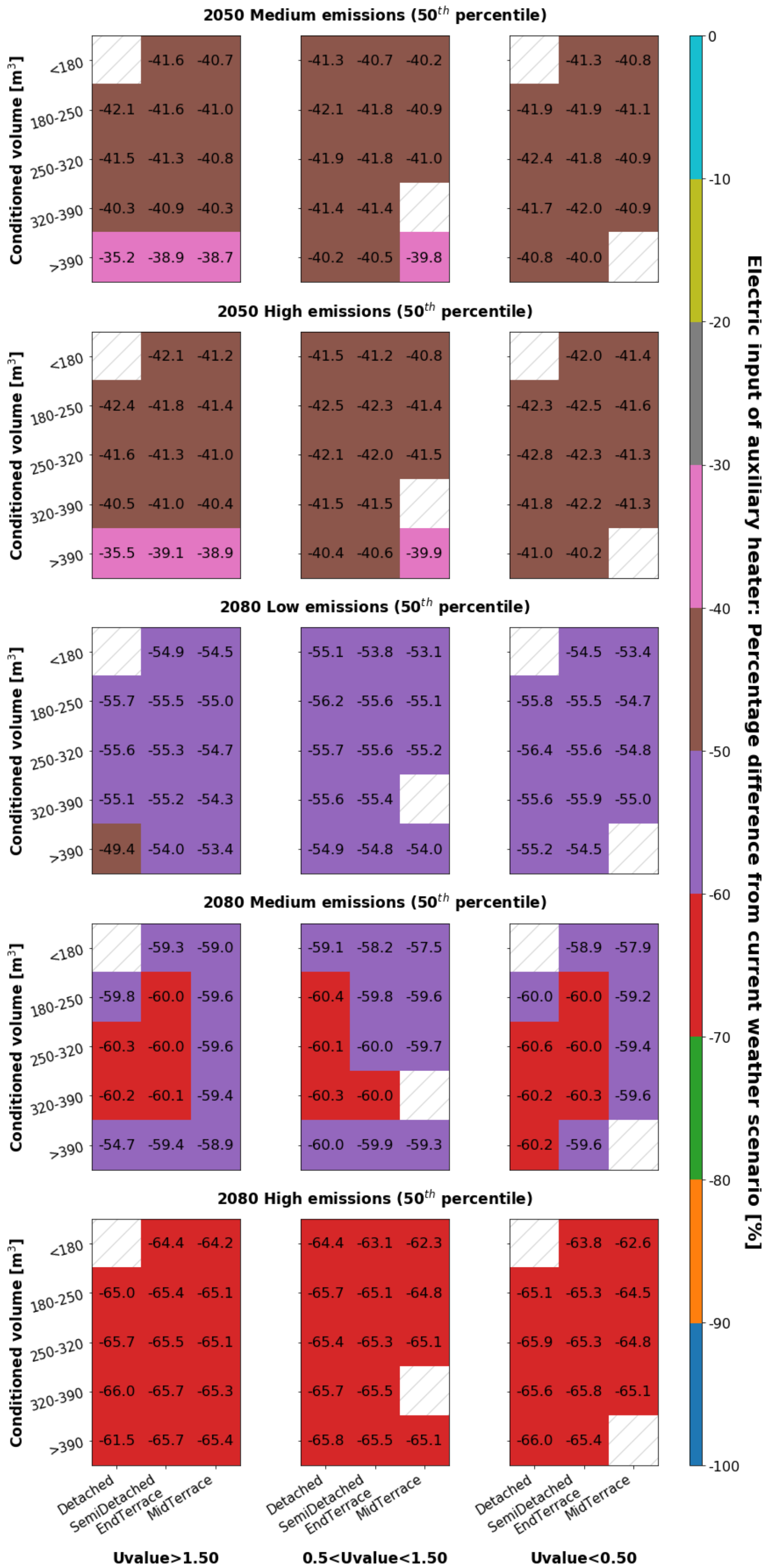



**Figure 5-3: Percentage difference of auxiliary electricity input between the current and future weather scenarios (only the scenarios corresponding to 50% probability level are included)**

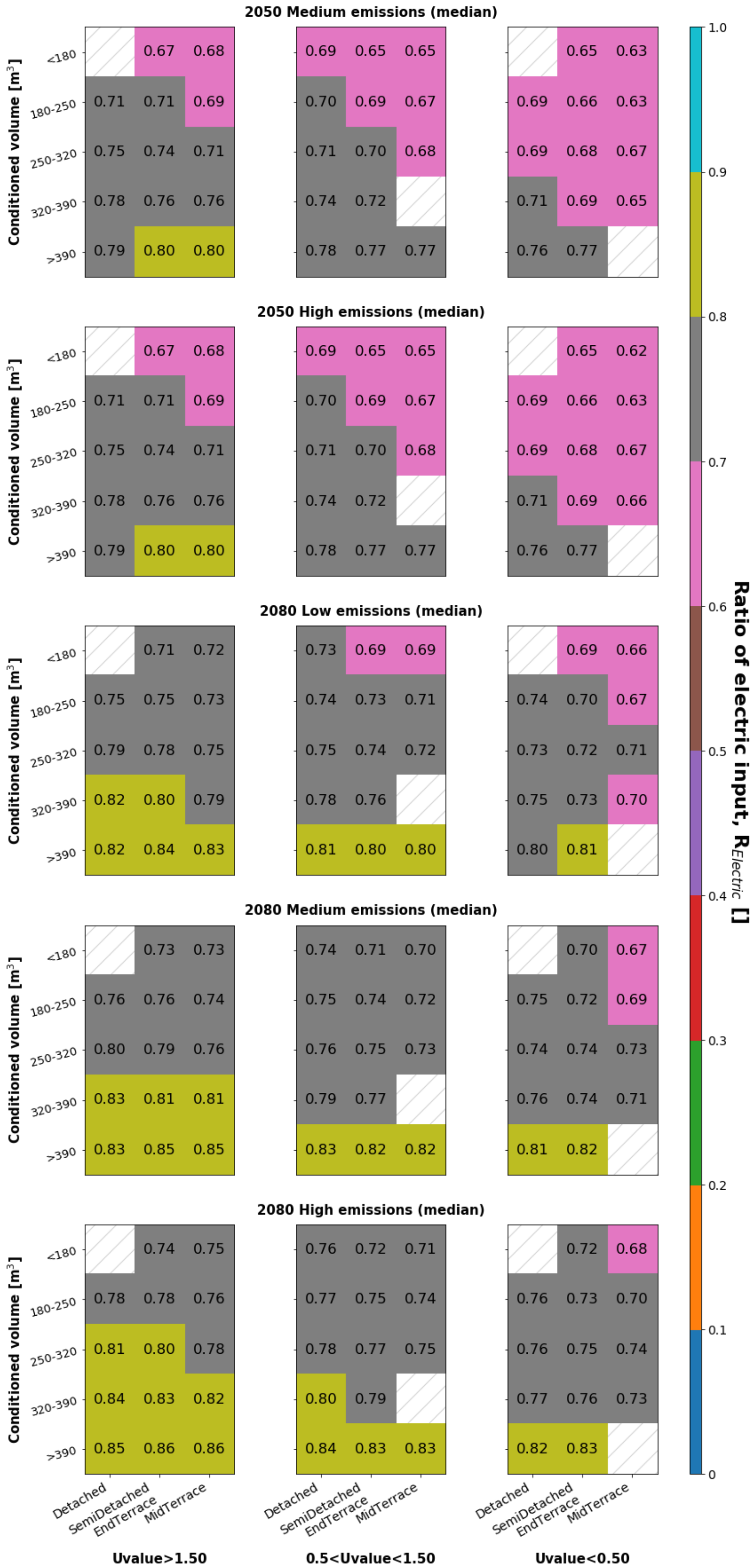



**Figure 5-4 Average ratio of AWHP's to auxiliary heater's electric input various future weather scenarios (only the scenarios corresponding to 50% probability level are included).**

*Table 5-3* presents the average electric input of the auxiliary electric heater for the entire housing stock of the NE region of England under the various future weather scenarios (for each weather scenario, three probability levels of climate change are included). The distributions of the auxiliary electric input are illustrated for each different weather scenario in *Figure A-4* in the Appendix.

**Table 5-3: Average electric input of the auxiliary heater for the entire housing stock of the NE region of England under current and future weather scenarios**

| **Weather scenario** | **Average annual auxiliary electric input [MWh]** |
|---|---|
| Current | 0.8 |
| 2050 Medium emission scenario, 10$^{th}$ percentile | 0.7 |
| 2050 Medium emission scenario, 50$^{th}$ percentile | 0.4 |
| 2050 Medium emission scenario, 90$^{th}$ percentile | 0.3 |
| 2050 High emission scenario, 10$^{th}$ percentile | 0.6 |
| 2050 High emission scenario, 50$^{th}$ percentile | 0.4 |
| 2050 High emission scenario, 90$^{th}$ percentile | 0.3 |
| 2080 Low emission scenario, 10$^{th}$ percentile | 0.6 |
| 2080 Low emission scenario, 50$^{th}$ percentile | 0.3 |
| 2080 Low emission scenario, 90$^{th}$ percentile | 0.2 |
| 2080 Medium emission scenario, 10$^{th}$ percentile | 0.5 |
| 2080 Medium emission scenario, 50$^{th}$ percentile | 0.3 |
| 2080 Medium emission scenario, 90$^{th}$ percentile | 0.2 |
| 2080 High emission scenario, 10$^{th}$ percentile | 0.5 |
| 2080 High emission scenario, 50$^{th}$ percentile | 0.3 |
| 2080 High emission scenario, 90$^{th}$ percentile | 0.1 |

### 5.3.3 Level of under-heating

Section 5.3.3 discusses the impact of various future weather scenarios on the level of under-heating; under-heating is evaluated using unmet load hours.

*Figure 5-5*illustrates the average percentage difference of the annual unmet load hours per house category between the current and selected future weather scenarios (all the future weather scenarios that are included in this Figure refer to 50% probability level). For the current weather scenario, the average number of the annual unmet load hours has been illustrated per house category in *Figure 4-22.* (The unmet load hours are the total number of hours (throughout the year) during which the mean indoor temperature is less than 0.5$^{o}$C below the selected set-point temperature in at least one thermal zone of the house; for the definition, see Section 4.5).

It is evident from *Figure 5-5* that the number of the unmet load hours is predicted to be considerably lower for 2080s than 2050s and it further decreases as the amount of carbon emissions moves toward the “high” emissions scenario. Further, it can be seen that for a particular weather scenario, the magnitude of the reduction of the annual unmet load hours may significantly differ from one house category to another. For example, the percentage difference of the annual unmet load hours between the current and 2080 high emissions scenarios varies from -31.0 % to as high as -68.0%. Comparing *Figure 4.22* and *Figure 5-5*, it can be observed that as the absolute number of the unmet load hours increases between the various house categories for the current weather scenario, the percentage difference of the unmet load hours between the current and each particular future weather scenario increases as well. In other words, those house categories that were found to have a comparatively high number of unmet load hours for the current weather scenario present a comparatively high percentage reduction of unmet load hours between the current and any future weather scenario.

However, it should be note at this point, that the unmet load hours has been found to be less than 300 hours for all the examined house categories even when the current weather scenario is considered, which, as discussed in Section 4.5, means that the AWHP retrofit is viable in terms of under-heating for the entire stock. More specifically, only 4 houses were reported as not being suitable for the AWHP under the current weather scenario and without any fabric interventions, whereas all houses were found to be suitable for an AWHP under all the future weather scenarios included in *Figure 5-5*.

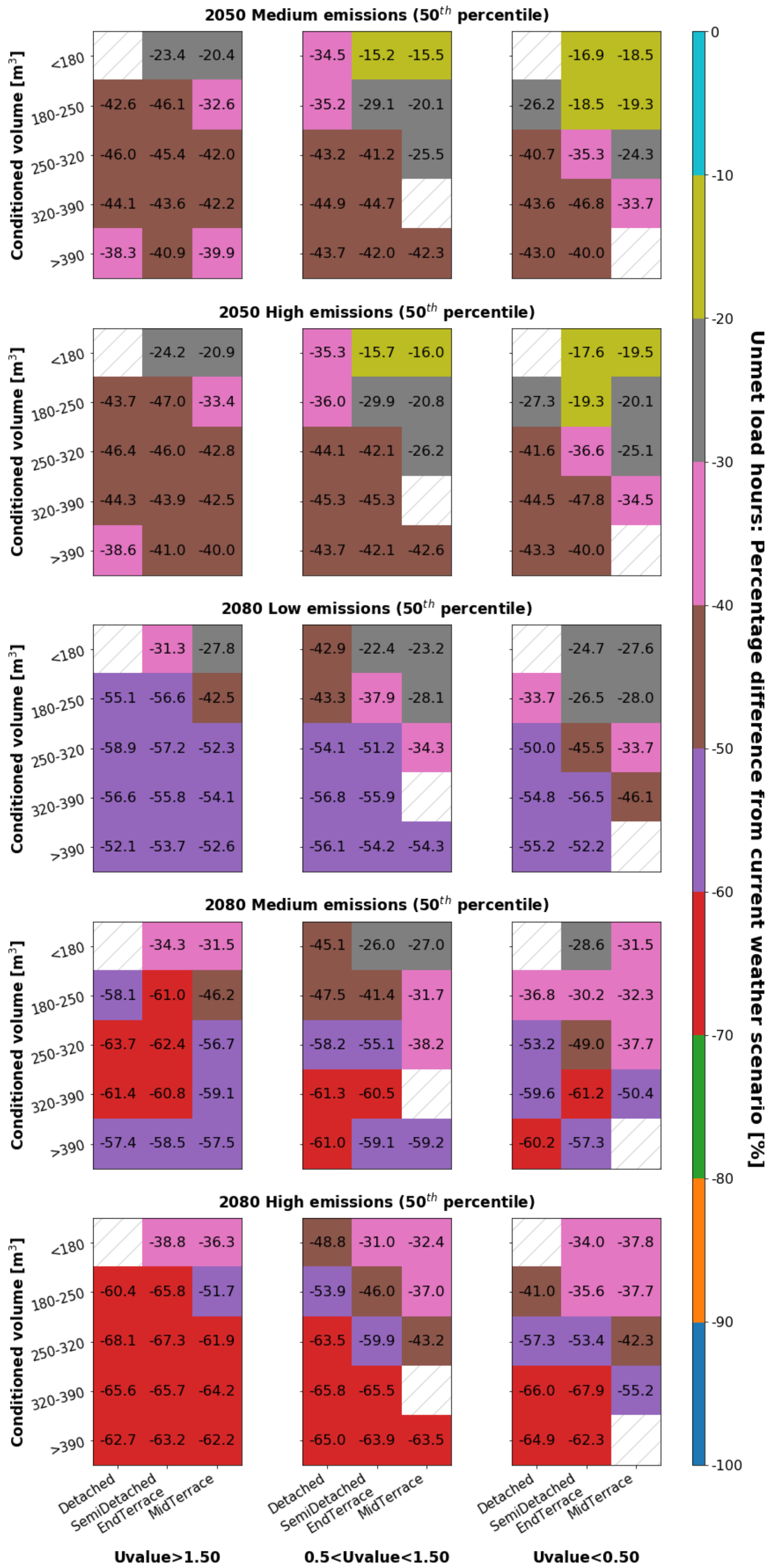



**Figure 5-5: Percentage difference of unmet load hours between the current and future weather scenarios (only the scenarios corresponding to 50% probability level are included)**

*Table 5-4* presents the average number of unmet load hours for the entire housing stock of the NE region of England under the various future weather scenarios (for each weather scenario, three probability levels of climate change are included). The distributions of the annual unmet load hours are illustrated for each different weather scenario in *Figure A-5* in the Appendix.

**Table 5-4: Average number of unmet load hours for the entire housing stock of the NE region of England under current and future weather scenarios**

| Weather scenario | Average annual unmet load hours [hours] |
|---|---|
| Current | 79 |
| 2050 Medium emission scenario, 10th percentile | 68 |
| 2050 Medium emission scenario, 50th percentile | 48 |
| 2050 Medium emission scenario, 90th percentile | 37 |
| 2050 High emission scenario, 10th percentile | 67 |
| 2050 High emission scenario, 50th percentile | 47 |
| 2050 High emission scenario, 90th percentile | 33 |
| 2080 Low emission scenario, 10th percentile | 59 |
| 2080 Low emission scenario, 50th percentile | 39 |
| 2080 Low emission scenario, 90th percentile | 28 |
| 2080 Medium emission scenario, 10th percentile | 56 |
| 2080 Medium emission scenario, 50th percentile | 35 |
| 2080 Medium emission scenario, 90th percentile | 23 |
| 2080 High emission scenario, 10th percentile | 52 |
| 2080 High emission scenario, 50th percentile | 31 |
| 2080 High emission scenario, 90th percentile | 18 |

### 5.3.4 Thermal comfort conditions

Section 5.3.4 discusses the distribution of the PMV index (for the living-zone) across the modelled housing stock for various future weather scenarios.

*Figure 5-6* illustrates the average PMV index of the living-zone per house category and for selected future weather scenarios. The colour of each box indicates the range to which the average PMV index of each separate house category belongs based on the colour-bar. As discussed in Section 2.7.2, the PMV index should not be lower than -0.70 and greater than 0.70 in existing houses (Category III-see Table 2-1) (BS EN ISO 7730:2005, 2006). In *Figure 5-6*, those house categories that fail to achieve an average PMV index between -0.70 and 0.70 for each separate future weather scenario are shown with a black circle. For the current weather scenario, the average PMV index per house category has been illustrated in *Figure 4-23*.

Under the current weather conditions, only few house categories achieve an average PMV in the range of -0.7 to +0.70, all of which include only house archetypes with relatively high wall insulation levels (U-value < 0.50 W/m$^2$K). However, as seen in *Figure 5-6*, the milder future weather scenarios appear to have a positive impact on the thermal comfort conditions by significantly increasing the number of house categories, the PMV index of which is higher (less negative) than or equal to -0.70. More specifically, it can be observed that almost all the house categories including houses with relatively high wall insulation levels as well as a significant number of the house categories with medium wall insulation levels (0.50 W/m$^2$K < U-value < 1.50 W/m$^2$K) have an average PMV higher than or equal to -0.70 when both the 2050 medium and high emissions scenarios are considered. When the 2080 high emissions scenario is considered, thermal comfort conditions appear to become acceptable in terms of average PMV index in all house categories apart from those categories including detached houses with no external-wall insulation (U-value > 1.50 W/m$^2$K).

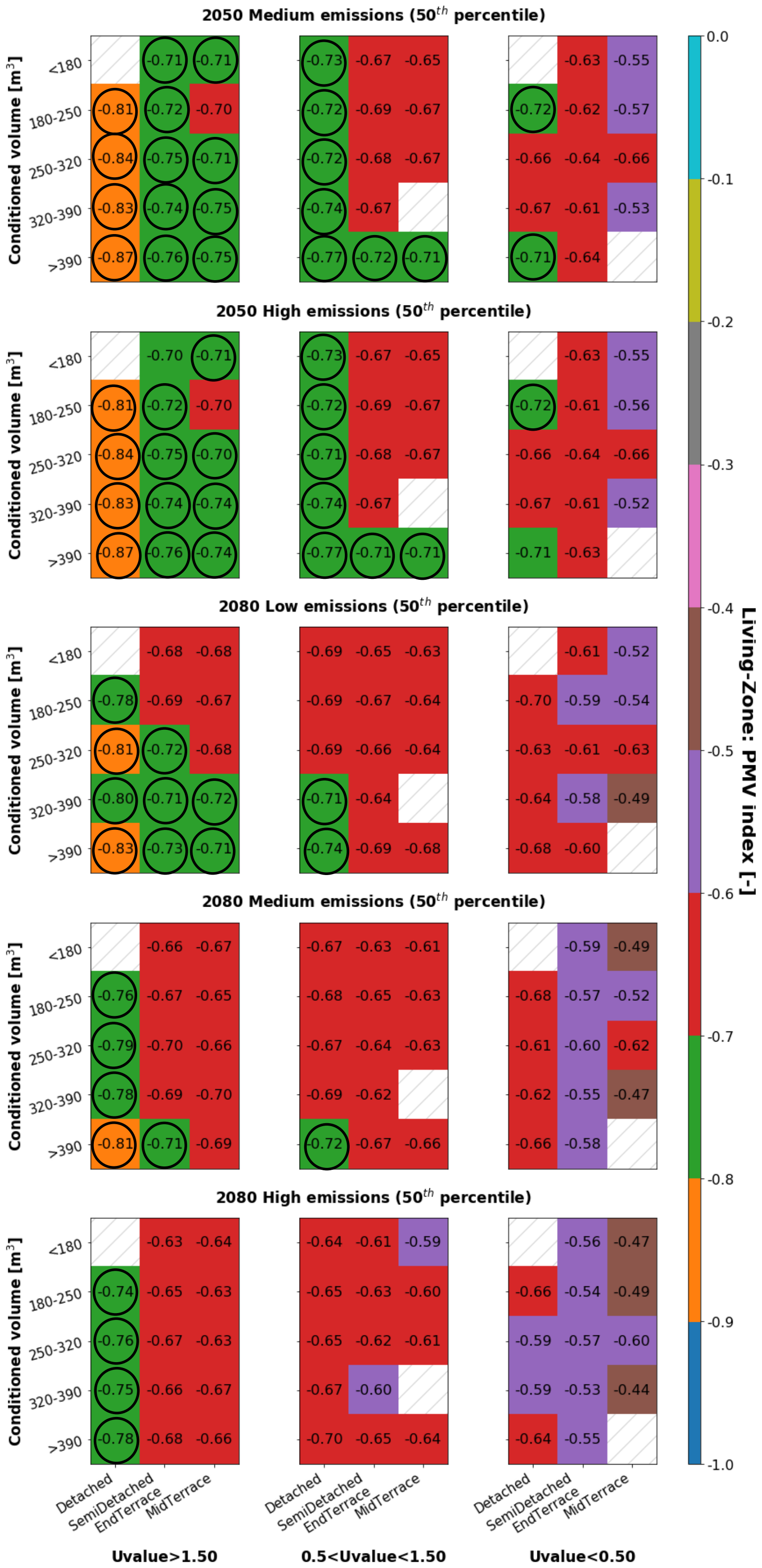



**Figure 5-6: Average PMV index of the living-zone for various future weather scenarios (only the scenarios corresponding to 50% probability level are included). Circles correspond to house categories with average PMV below 0.7**

*Table 5-5* presents the average PMV index for the entire housing stock of the NE region of England under the various future weather scenarios (for each weather scenario, three probability levels of climate change are included). The distributions of the average PMV index and percentage of discomfort in terms of PMV are illustrated in the form of histograms for each different weather scenario in *Figure A-6* and *Figure A-7*, respectively (see Appendix A).

**Table 5-5: Average living-zone's PMV index for the entire housing stock of the NE region of England under current and future weather scenarios**

| Weather scenario | Average PMV index [-] |
|---|---|
| Current | -0.75 |
| 2050 Medium emission scenario, 10$^{th}$ perc. | -0.73 |
| 2050 Medium emission scenario, 50$^{th}$ perc. | -0.70 |
| 2050 Medium emission scenario, 90$^{th}$ perc. | -0.67 |
| 2050 High emission scenario, 10$^{th}$ perc. | -0.73 |
| 2050 High emission scenario, 50$^{th}$ perc. | -0.70 |
| 2050 High emission scenario, 90$^{th}$ perc. | -0.66 |
| 2080 Low emission scenario, 10$^{th}$ perc. | -0.71 |
| 2080 Low emission scenario, 50$^{th}$ perc. | -0.67 |
| 2080 Low emission scenario, 90$^{th}$ perc. | -0.62 |
| 2080 Medium emission scenario, 10$^{th}$ perc. | -0.70 |
| 2080 Medium emission scenario, 50$^{th}$ perc. | -0.65 |
| 2080 Medium emission scenario, 90$^{th}$ perc. | -0.59 |
| 2080 High emission scenario, 10$^{th}$ perc. | -0.69 |
| 2080 High emission scenario, 50$^{th}$ perc. | -0.63 |
| 2080 High emission scenario, 90$^{th}$ perc. | -0.55 |

## 5.4 Chapter summary

This chapter investigated the impact of future weather scenarios on the simulated performance of AWHPs. The selected future weather scenarios incorporated probabilistic climate change projections for 2050 and 2080 under different carbon emissions scenarios (low, medium and high emissions scenario). The characteristics of these future weather scenarios were described in Section 5.2 with the discussion focusing on the implications of DBT rise for the operation and sizing of the modelled AWHP retrofit. In Section 5.3, the simulated performance of AWHPs was evaluated for the housing stock of the NE region of England in terms of energy use, need for supplementary electric heating, level of under-heating and degree of thermal discomfort. The modelled housing stock is considered to be *at its current condition* with the assumption of a "static" housing stock constituting a conservative scenario for the applicability of AWHPs in the future. Considering this conservative scenario for the future condition of the modelled building stock, the results showed that the applicability of AWHPs is expected to be more favourable in the future. More specifically, considering the 2050 weather scenarios, both the AWHP's and auxiliary heater's energy use were found to decrease on average 7.5 % and 40.0 % across the stock compared to the current weather scenario, respectively. Moreover, considering the 2080 scenarios, the AWHP's and auxiliary heater's energy use were found to further decrease in the range 13.0 % - 20.0 % and 53.0 % - 66.0 % compared to the current weather scenario, respectively. The range of reduction corresponds to the different carbon emissions levels with the energy use decreasing as the emissions level moves for the low towards the high emissions scenario.

However, even if energy use reduces (mostly for supplementary electric heating) across the entire stock, thermal discomfort still persists for a significant number of houses. Considering that houses should achieve at least an average PMV index of -0.70, the results showed that almost all categories including houses with no wall insulation (independently of building's size and built-form) do not satisfy this PMV threshold for the 2050 weather scenarios. Apart from the houses with completely uninsulated walls, the results also showed that thermal comfort conditions fail to be achieved for detached houses with medium wall insulation levels (0.50 < U-value < 1.50). The conditions of thermal comfort were found to significantly improve across the stock under the 2080 weather scenarios. However, if for AWHPs are to be widely deployed across the stock and become a major part of the UK's decarbonisation pathway, action should be urgently taken to "prepare" the existing stock for this transition. Hence, the "predictions" of AWHP's applicability for the 2050 weather scenarios should be considered in order to identify those house types that should be targeted by future policies within the next few years; this will be further discussed in the following chapter (see Section 6.3.2).

# Chapter 6

# Discussion

## 6.1 Introduction

Chapter 6 presents a summary of the work undertaken for the purposes of this thesis with a focus on highlighting its achievements and how these addressed its aim and objectives. The discussion provides an overview of the employed housing stock modelling approach (Section 6.2), describes the proposed AWHP system model, its implications to be widely deployed in domestic retrofit applications as well as the wider implications of using AWHPs within the UK context (Section 6.3), explains how the results of the thesis can be used to assess the applicability of AWHPs at the stock level and how the analysis undertaken can further reveal paths for fabric retrofit targets combined with the AWHP retrofit (Section 6.4), presents general implications of retrofit (Section 6.5), makes clear the contribution to knowledge (Section 6.6) and summarizes the limitations of the research (Section 6.7).

## 6.2 The housing stock modelling approach

This section discusses how the research addressed the first of objective of the thesis as presented in Section 1.2. The discussion focuses on justifying the selection of the

HSEM used (Section 6.2.1) and evaluating the approach that was followed to verify the housing stock modelling approach (Section 6.2.2).

### 6.2.1 The selected HSEM

Retrofitting the existing housing stock is a key infrastructure priority in order for the UK to achieve its long-term carbon emissions commitment (net zero emissions by 2050). In recent years, a variety of HSEMs have been developed, these being widely used to assess the applicability of various retrofit scenarios at the local, regional or national level and provide some connection to the development of relevant policy.

In Section 2.6, HSEMs were reviewed and categorised with the focus being on data sources and models developed and used within the UK context. The review concluded that although HSEMs exist for the UK, most are based on steady-state calculation methods and as such, they do not allow for the transient response of building structures to be captured. Thus, although a steady-state model can be used to estimate the annual of even monthly energy use of buildings, it cannot provide insights into the extent to which thermal discomfort and underheating persists with these being of particular importance when studying the performance of heating systems such as heat-pumps. Instead, the adoption of dynamic calculation methods enables the extraction of hourly (or even minutely) patterns of variables such as COP, energy use, internal temperature, thermal sensation index, etc., thus allowing for a holistic investigation of a system's performance. The number of hours that the set-point temperature is not satisfied or the number of hours that thermal sensation is outside comfort bands are all important factors to evaluate the effectiveness of energy efficiency interventions for houses.

Considering the above, the present thesis employed a bottom-up HSEM capable of dynamically modelling the energy demand of large areas of the built environment. The model was used to investigate the applicability of AWHPs for 756 unique house archetypes representing the housing stock of the NE region of England, this being used as the case study area for the purposes of this research. Deriving information from the CHM (which, in turn, derives data relating to geometry and houses' physical properties from the national EHS), the employed HSEM can automatically generate house models that are suitable to be studied using $E^+$. A similar housing stock modelling approach was followed by Swan and Ugursal (2009) with their model being used later by Asaee *et al.* (2017) to assess the applicability of AWHPs to some 17,000 Canadian houses.

It is worth mentioning at this point that in contrast to models accessing data relating to houses' geometry through EPCs or data sets equivalent to the EHS, there is an increasing number of urban stock models using GIS to derive the geometric characteristics of the stock. These might follow either an archetype modelling approach similarly to this thesis (Mastrucci *et al.* (2014), Rosser *et al.* (2019) and McCallum *et al.* (2020)) or a house-by-house modelling approach (Gupta and Gregg (2018) and Steadman *et al.* (2020)). GIS-based models have recently gained ground as decision-making tools offering advantages in the spatial identification of suitable areas for the application of energy efficiency interventions combined with their advanced visualisation capabilities.

### 6.2.2 Model verification

An inter-model comparison technique was applied in order to verify the selected HSEM's suitability to represent the diversity of the energy demand across the housing stock (*Objective 1: to verify the suitability of a dynamic bottom-up HSEM to be used for representing the diversity of the energy demand across the housing stock*). The annual space-heating energy demand of each of the 756 house archetypes as predicted by the dynamic $E^+$ simulation engine was compared against CHM predictions with the latter following the BREDEM calculation methodology.

In the absence of (real) measured data, the application of comparative tests between different models can be used instead as a model verification technique (He *et al.*, 2014; Badiei, 2018). However, it should be clarified at this point that the (potential) agreement between two different models (or modelling approaches) does not imply that both models are correct. Instead, although they do agree, both could be wrong. Hence, any agreement obtained between different models *just increases the level of* *confidence* that models are correct (especially in the case that the compared models are based on completely different calculation approaches e.g. steady-state vs dynamic).

For the case of this thesis, the shape of the distribution of the predicted space-heating energy demand across the stock was found to be almost identical when the 756 house archetypes were modelled by either the dynamic $E^+$ simulation engine or the steady-state CHM (see Section 3.3). This increases the level of confidence that the employed modelling approach is suitable for representing the variations of the heating energy demand across the stock. Again, this conclusion is valid following the definition and principles of the inter-model comparison technique based on which the similarity of the distribution between CHM and $E^+$ increases the possibility that both models are capable of representing the diversity of the heating energy demand across the stock.

In previous works, models employing dynamic BPS tools to predict energy demand were compared against BREDEM-based models such as SAP and CHM. Having matched the boundary conditions between the two, BREDEM-based models were generally found to overpredict space-heating demand in the range of 1.0 % - 17.0 % (Badiei, 2018) to as high as 34.4% (He *et al.*, 2014) compared to the $E^+$ dynamic simulation tool. Contrary to Badiei's and He's work, where the authors processed input data so that both SAP and $E^+$ models have an equivalent representation of boundary conditions (weather and occupancy), construction and thermal mass for the modelled buildings, the present thesis did not focus on matching $E^+$ to CHM input data and $E^+$ was found to under-predict space-heating energy demand by 54.0 %. The following paragraphs discuss possible reasons for this under-prediction and summarise the reasons for the under-prediction of the heating energy demand by $E^+$ even when boundary conditions between the two models are matched using findings from Badiei's work.

The heating demand calculations performed for the purposes of the CHM are based on a monthly balance of heat losses and gains determined in steady-state conditions. On the other hand, $E^+$ is a dynamic simulation engine modelling the heat transfer, air flow and system thermodynamics performance of a building for hourly weather conditions and accounting for thermal mass effects. In Badiei's work, the differences in the treatment of thermal mass, in particular, were found to have the most significant impact on the variations between SAP and $E^+$ (Badiei, 2018).

A preliminary comparison of the results obtained from this thesis for a single semi-detached house showed that annual solar gains from $E^+$ are almost two times greater than predicted by CHM. This could be associated with both the weather data used and the calculations followed by the two different modelling approaches. More specifically, although CHM/SAP requires average monthly values for ambient temperature, wind speed and solar radiation, $E^+$ uses detailed weather files including hourly data for ambient temperature, solar radiation, wind speed/direction, atmospheric pressure and relative humidity throughout an entire year. Badiei (2018) used a simplified method to make the hourly weather data used for the case of $E^+$ simulations to SAP equivalent. As a result of this process, the monthly averages estimated by the $E^+$ weather file could be in the range of 0.35 – 1.17 times different for solar radiation than those used by SAP with this indicating that the amount of the solar radiation can be almost three times lower for SAP compared to $E^+$ weather data (this range for ambient temperature and wind speed was found to be 0.84 - 1.30 and 0.83 – 1.45, respectively). In addition to that, in CHM/SAP, all windows are located on the east/west orientated façades of the dwelling, whereas in the $E^+$ models, the glazed area has been equally distributed across the non-sheltered façades of the house (these being orientated N, S, E, and W). This means that even if the global solar radiation was the same for the two models, the amount of solar gains could significantly vary between the two. Further, in case that the sum of solar and internal heat gains is high relatively to the house's heating load, a utilisation factor is used in CHM/SAP to reduce their contribution. Lastly, CHM/SAP applies a shading factor to all the windows (20-60% obstruction), which further reduces the contribution of solar heat gains (SAP, 2014), while in the $E^+$ models, all the windows were considered to be unshaded (this is the default assumption unless the user provides information for the existence of shading due to vegetation, blinds, etc). All the above factors could justify the disagreement for solar heat gains between CHM and $E^+$, which could, at some extent, justify the significant under-prediction of heating energy demand by $E^+$.

Another factor that could contribute to the differences between the two modelling approaches is the definition of a zone's set-point temperature. For the case of CHM/SAP model, the user has to define the set-point temperature only for the living-room (living-zone). The set-point temperature for the rest of the house is then based on living-room's temperature and heat loss parameter of the building with the latter, in particular, varying on a monthly basis (BRE, 2011).

In conclusion, based on the above discussion and the results obtained from the inter-model comparison, it should be acknowledged that the absolute values of energy use might have been under-predicted in this work (and similarly, comfort indices might have been over-predicted). However, the similarity of the heating loads' distribution between $E^+$ and CHM gives confidence that $E^+$ can give a good (and similar to reality) prediction of the variation of heating loads across the stock.

## 6.3 The AWHP retrofit

Having generated the 756 $E^+$ house models (incorporating geometry, materials, internal heat gains, etc.), the thesis then focused on investigating the effectiveness of a particular retrofit scenario applied to all the selected house archetypes. More specifically, an AWHP coupled with supplementary electric heating was selected to be integrated in each individual house archetype to meet its space-heating and hot water demand throughout the winter heating months. This section presents how the second and third objective of the thesis were addressed (Section 6.3.1) and discusses the wider implications of the modelled AWHP system and heat-pumps (in general) to be adopted within the UK context (Section 6.3.2).

### 6.3.1 The selected AWHP system

A review of actual AWHP systems (provided by various manufacturers across the UK) led to the identification of representative AWHP systems (in terms of system's configuration, capacity and COP range, control regime, etc.) that are suitable for UK domestic applications. These were applied to construct an AWHP system model in $E^+$, which was then integrated in each of the 756 house archetypes (Objective 2: *to model an AWHP coupled with thermal energy storage using a previously established dynamic BPS engine; the configuration and control of the AWHP model will be representative of actual AWHP systems that are available and sold in the UK market*). The model comprised an AWHP unit and a capacity-limited electric heater with the AWHP being the primary heat source and the electric heater operating as a secondary heat source to top-up the energy provided by the AWHP. Both the AWHP unit and auxiliary electric heater were linked to a storage water tank through which the heat is transferred to the radiators and DHW tank of each house (see *Figure 3-10*). The architecture of the AWHP system modelled for the purpose of this thesis is similar to that used in previous works (Kelly *et al.*, 2014; Asaee *et al.*, 2017).

The modelled AWHP unit was controlled to switch-OFF when ambient temperature is lower than 2.0$^{o}$C and in this case, heating was solely provided by the auxiliary electric heater. This was selected as a frost-protection technique as the adopted $E^{+}$ AWHP model does not support reverse-cycling operation with the latter being the common practice for defrosting in actual installations (Madonna and Bazzocchi, 2013; Di Perna *et al.,* 2015; Kelly *et al.,* 2014; Asaee *et al.,* 2017). The adopted frost-protection technique was found to significantly increase the use of supplementary energy use and consequently, reduce the effectiveness of the entire system.

Following the recommendations of the MIS 3005, the heating capacity of the retrofitted AWHP unit was selected separately for each house archetype so that the AWHP itself (without the contribution of the auxiliary electric heater) is capable of meeting 100% of the house's peak space-heating power demand (*Objective 3: to investigate the size (represented by nominal heating capacity) of the AWHP that should be retrofitted in various houses covering a wide range in physical characteristics*). The results revealed that matching heat-pump's heating capacity with the house's peak heating load results, in many cases, in operating the system under part-load conditions for a significant amount of time throughout the heating season, thus resulting in COP degradation. This was also shown in other studies proving that the maximum system's SPF is achieved when the heat-pump is sized in the range of 59%-72% of the house's peak heating load (Bagarella *et al.*, 2016). Based on the above, the MIS 3005 (being the official UK's guidance for the design and installation of heat-pumps) should revise sizing recommendations by accounting for the extent to which 100% peak load coverage by the AWHP itself results in reducing system's overall performance.

### 6.3.2 Implications of AWHPs within the UK context

**Space**:

The fact that the proposed heat-pump system includes two different tanks (TES and DHW tank) might be a limiting factor for its large-scale deployment due to the space required for such an installation. A significant number of the existing UK houses have very limited free space, this being even more crucial for the case of flats. The presence of a basement or alternatively, a mechanical room might be necessary for considering the proposed heating system. The CHM does provide the floor area of basement for the included houses (if present), but there is no further information regarding the presence of a mechanical room (this usually exists for houses that were previously heated by oil boilers). The space required for installing a heat-pump (both air and ground source) combined with its increased upfront cost and high electricity rate (compared to gas) constitute significant barriers for the roll-out of the technology. Contrary to heat-pumps, combi-boilers can heat water directly from the water mains and therefore, they do not require a hot water cylinder. Generally speaking, heat-pumps lose ground to combi-boilers in both new-built houses and dwelling refurbishment applications with UK gas boiler sales reaching 1.67 million in 2019 (an increase of 1.8% compared to 2018) (Foster, 2020) and leaving heat-pump market with some 20-30 thousand installations per year far behind.

**Role of policy**:

In Section 2.5 of the present thesis, best practice regarding the large-scale deployment of heat-pumps has been identified across Europe and discussed within the UK context. The role that policy can play in the transition from gas boilers to heat-pumps is very challenging in countries such as the UK, where not only gas is the dominant fuel (85% of houses are connected to the gas grid), but also consumers are generally satisfied with gas central heating and thus, reluctant to consider alternatives (Kozarcanin *et al.*, 2020). Lessons from other European countries that already have a developed heat-pump market have shown that the concerted effort of government, utilities, industry, research institutes, manufacturers and installers network is a necessity in order for AWHPs to widely penetrate domestic heating and be a key contributor to the UK's decarbonization path (Hanna *et al.*, 2016).

Current UK Government's financial incentives such as the RHI have failed to meet the UK Government's expectations on the deployment of low-carbon heating. More specifically, the government's initial ambitions has recently reduced by 65.0% for renewable heat production and 44.0% for carbon emissions savings through the RHI (National Audit Office, 2018). Uncertainty regarding the stability and continuity of the RHI augmented by the repeated delays on its implementation have been identified as important factors for both consumers' and industry's inertia to accept heat-pumps (and other low carbon heating systems) as alternatives to the conventional fossil-fuel-based systems (Hanna *et al.*, 2016). In addition to that, the lack of a trained and certified installers network has led to common failures during the design and installation stage (failure to select the right heating capacity, defective pipework and wiring connections etc.) with these resulting in increased running costs and further deteriorating heat-pumps' publicity (Gleeson and Lowe, 2013). Finally, the very limited evidence from in-situ performance of heat-pumps combined with very few information campaigns about low-carbon heating do significantly contribute to consumers' lack of awareness for heat-pumps and the associated benefits of the low-carbon living concept.

**Demand flexibility**:

A potentially large-scale electrification of the heat and transport sector should be planned alongside with the expansion and reinforcement of the existing electricity grid infrastructure in order to ensure stability and limit events of RES curtailment. In this direction, increasing demand flexibility might be a means to address current grid constraints and ensure reliability for consumers. Previous studies have shown that coupling heat-pumps with TES is a powerful strategy to increase demand flexibility through the shifting of heating loads from high-demand to low-demand periods of the day. Load-shifting has a three-fold purpose: maintain grid's stability; address the intermittent nature of RES; and reduce consumers' electricity bills if combined with suitable pricing programs.

The required storage volume to achieve an effective load-shifting was found to be in the range of 800L to 1200 L (Arteconi *et al.*, 2013; Kelly *et al.*, 2014; Le *et al.*, 2020) or in some cases, this might exceed the 2500 L (Eames *et al.*, 2014) depending on both the storage capacity of the building itself as well as the adopted electricity tariff. Nevertheless, the utilisation of such high-volume tanks might be impractical for the case of UK domestic buildings. In addition to that, as also mentioned in Section 2.3.2, the traditional E7 and E10 electricity tariffs (offering low electricity rates mainly during the night) were found to be ineffective for the case of heat-pumps. More specifically, operating the heat-pump during off-peak periods as defined by the E10 tariff was found to increase electricity bills by 30.0% (Kelly *et al.*, 2014). In this context, the adoption of dynamic Time of Use (ToU) tariffs might be a means to address the drawbacks of conventional UK electricity tariffs. Dynamic ToU tariffs are usually updated on a daily basis and provide hourly or even sub-hourly electricity prices reflecting on the real-time cost of energy on the grid. A dynamic ToU tariff might charge up to 2x higher than conventional electricity tariffs during typical peak consumption periods (usually between 4-7 pm in the UK), while for the rest of the day, rates are significantly lower or they might even be negative implying that consumers are paid for using electricity (Octopus Energy, 2020). The AWHP system developed for the purposes of this thesis employs a storage water tank and can be further extended to study the load-shifting potential of AWHPs and the impact of this on the system's annual running costs (Vatougiou *et al.*, 2020).

Considering all the above, the large-scale deployment of heat-pumps is subject to various techno-economic factors. Alongside with the ban of fossil fuel for new built houses, the UK should focus on creating a mature and competitive heat-pump market with this being expected to not only provide high-standard services and support to consumers but also reduce capital costs (as a result of the greater competition). These are significant steps in order for heat-pumps to be able to compete the well-established gas and oil-fired boilers in the UK.

## 6.4 Applications

Significant effort was made in this thesis in order for the simulation outputs to be communicable to multiple reader groups including consumers, stakeholders and policy makers. This resulted in a novel visualisation way, where results were mainly presented in simplistic (informative though) graphs illustrating data for all the modelled dwellings simultaneously (these graphs resemble the traditional heat maps, where values are presented in a colourful matrix with each colour corresponding to a certain range of the illustrated values).

Each graph refers to a specific simulation output (e.g. annual energy use, annual underheating hours, etc.) and consists of three individual plots with each plot including those house archetypes with uninsulated, medium-insulated and highly-insulated external walls, respectively. The house archetypes included in each of the three plots are further categorized in 15 smaller categories based on their total conditioned volume (5 categories) and built form (3 categories). The selected simulation output is then illustrated as the average value for all those house archetypes belonging to each smaller category. In other words, each graph contains information for 45 different house categories (3 wall U-value ranges x 5 conditioned volume ranges x 3 built forms). Section 3.4.2 provided a detailed description and justification for the implemented categorization of the studied house archetypes. With the houses being separated in different categories using typical physical properties (insulation level, built form and conditioned volume), homeowners can very easily and quickly identify what is the estimated annual energy use or thermal comfort perspective resulted for a particular retrofit measure. In a similar way, policy makers can identify which house types should be targeted first or for which house types a particular energy efficient intervention is eligible.

The developed methodology including this novel graphical representation of the simulation results can be applied to create a tool that will be used to evaluate the applicability of various energy efficiency measures at the stock level. Section 6.4.1 presents how the results obtained from this work can be used to assess the applicability of AWHPs at the stock level (thus addressing the fourth and fifth objective of the thesis). Section 6.4.2 then focuses on presenting how the results can be further exploited to assess AWHP retrofit linked with fabric retrofit targets for the modelled houses.

### 6.4.1 Applicability of AWHPs at the stock level

Using the visualization way explained above, the distribution of the simulated system's energy use, level of under-heating and degree of thermal comfort discomfort were explored at the stock level for both current and future weather scenarios in Chapter 4 and Chapter 5, respectively (***Objective 4****: to investigate the distribution of the energy use, level of under-heating and degree of thermal discomfort across the housing stock as a result of the AWHP retrofit* & ***Objective 5****: to investigate the impact of future weather scenarios on the distribution of the energy use, level of under-heating and degree of thermal discomfort across the housing stock (as a result of the AWHP retrofit) and to discuss implications for future retrofit policy design; the future weather scenarios result from detailed weather files incorporating data for various climate change projections*). The $E^+$ models were simulated for the current and future weather scenarios throughout an entire year using one-minute timestep. The simulations carried out result in a large volume of outputs containing numerous temperature and energy time-series for the modelled houses and integrated heating system.

**Current weather scenario**:

Under the current weather scenario, only few house archetypes were found to achieve an average PMV index in the range of -0.7 to +0.7 after the application of the AWHP retrofit (PMV refers to the dwellings' living-room only and not to the whole house). The indicated PMV range of -0.7 to +0.7 was determined based on the BS EN 15251:2007 Standard and corresponds to moderate comfort conditions, which are considered to be acceptable for the case of existing dwellings. The thermostat of the modelled houses was controlled to be at 21.0$^{o}$C for the living-room with this temperature referring to the *air temperature*. An alternative modelling approach could be based on controlling thermostat based on operative temperature or PMV index, this being an option provided by $E^+$ and a recommended future application of the methodology developed for the purposes of this thesis. Preliminary tests showed that if thermostat was modelled so that the heating system switches ON and OFF based on a PMV set-point equal to 0 (corresponding to neutral comfort conditions), air temperature would be in the order of 25.0$^{o}$C for the modelled houses. In this case, the conditions of thermal comfort would have been significantly improved for most of houses, but the system's required heating capacity and total energy use would have been increased.

Based on the above, several different modelling approaches would be reasonable and justifiable with all these having a profound effect on the results and consequently, the applicability of AWHPs at stock level. It should then be clarified that the results obtained in this thesis are subject to the control of the modelled system including the selected water and air temperature setpoints with the latter being based on SAP recommendations. However, previous works proved that models using the recommended temperatures and heating patterns provided by standards such as SAP, CIBSE or the WHO do not necessarily reflect the living-room temperature of actual English dwellings (Huebner *et al.*, 2013). The same authors also showed that weekday and weekend heating patterns do not differ (contrary to what is suggested by SAP) and indicated that there might be significant variability in the applied heating regimes between different dwellings. Factors such as dwelling's age of construction, built form, energy efficiency as well as household's income were all found to be important determinants of indoor temperature variations (Wilkinson *et al.*, 2001; Oreszczyn *et al.*, 2006; Hamilton *et al.*, 2017).

**Future weather scenarios:**

The selected house archetypes at their current condition (without considering any energy efficiency intervention) were also simulated with the integrated AWHP system using 15 different weather files corresponding to probabilistic climate change projections for 2050 and 2080 under three emissions scenarios (low, medium and high). However, as the housing stock is expected to become more energy efficient in the future with a percentage of the old houses being replaced with new or retrofitted to higher energy standards, studying the impact of future weather scenarios for the *existing* housing stock constitutes a conservative scenario for the applicability of AWHPs in the future. The aim of this exercise can be then summarised as identifying the sensitivity of AWHPs' heating performance on climatic conditions and not attempting to predict what will be the future performance of AWHPs across the stock. The results showed that although the system's energy use decreased, thermal discomfort still persists for a significant number of houses with this further supporting that fabric upgrade needs to be planned alongside with the large-scale deployment of heat-pumps.

### 6.4.2 Assessing AWHPs linked with fabric retrofit

The way that the results were presented offers the advantage for readers to assess different fabric retrofit options in conjunction with the application of an AWHP. By just moving horizontally across graphs, readers can determine for a specific dwelling (e.g. a detached uninsulated house with conditioned volume of less than 180 $m^3$) what is the expected reduction of annual energy use or under-heated hours resulting from the upgrade of wall insulation to either a medium or a high level combined with the AWHP retrofit. In a similar way, readers can get an estimation of how the size of the retrofitted AWHP (represented by the nominal heating capacity) can change for a specific dwelling by upgrading its wall insulation (see *Figure 4.3*). For example, there are specific house categories that were found to need a 14.0 kW AWHP, when they have no wall insulation, while they need an 11.2 kW when their wall insulation is upgraded to medium levels (0.50 < U-value < 1.50) or even an 8.5 kW unit when their wall insulation is upgraded to a high level (U-value < 0.50). This might have several implications on retrofit cost. More specifically, the capital cost of heat-pumps increases as the installed heating capacity increases (the increase per kWh, though, is usually lower as moving from small to larger heating capacities). Based on this and considering also running costs, homeowners might decide that it is more cost-effective to upgrade wall insulation and as a result, select a lower capacity AWHP rather than make no fabric interventions and select a higher capacity unit. This might be the case for cavity walls, where the upgrade of insulation is a relatively low cost fabric intervention.

Future applications of the employed graphical representation strategy can focus on the effect of other fabric energy efficient measures in conjunction with AWHPs (or other heating systems). More specifically, instead of categorizing houses based on the condition of their exposed-walls, categorization can be based on loft insulation thickness, ground-floor insulation level, infiltration rate, type of glazed-area (single, double, mix-glazed). The reader can then determine the impact of investing on loft/ground insulation upgrade, draught proofing measures or glazing upgrade.

All the above applications can lead to the development of a simple online tool to support retrofit decision-making. An important aspect is to include capital and running costs in order for consumers to determine the real benefit of energy efficiency interventions and for policy to target those houses that need further attention.

## 6.5 Further implications of retrofit

The applicability of energy efficiency measures to existing dwellings has been proved to be less cost-effective for occupants than expected. This could be explained by two distinct concepts known as the *rebound* and *prebound* effect, both dealing with the same phenomenon but examining it from a different perspective.

The rebound effect is a well-established issue recognized by policy and mainly associated with the fact that consumers were actually found to have increased comfort expectations following a thermal upgrade (comfort-taking) with this resulting in increased internal temperatures and therefore, lower actual savings than predicted (Barker *et al.*, 2007; Galvin and Sunikka-Blank, 2016). This is even more evident for houses with low SAP ratings (Kelly, 2011) or low-income and fuel poor households, where occupants might see no cost benefit from retrofit interventions as they usually end up spending cost savings to increase comfort (Milne and Boardman, 2000).

On the other hand, the prebound effect was firstly introduced by Sunikka-Blank and Galvin (2012) and involves the over-estimation of energy-saving potential during the design stage (before the application of an energy efficiency intervention) due to the fact that the dwellings' estimated energy consumption is far less than the actual. In their attempt to explain prebound effect, these authors mentioned as follows: "*As retrofits cannot save energy that is not actually being consumed, this has implications for the economic viability of thermal retrofits*" highlighting that the estimated pre-retrofit energy consumption of dwellings is usually less than the actual pre-retrofit consumption and therefore, the economic feasibility of a retrofit measure (often expressed by the payback period) is over-estimated. This was the case with the Green Deal policy, which provided income to households for the implementation of energy efficiency interventions. The analysis carried out by Galvin and Sunikka-Blank (2016) showed that there were cases, where although the consumption of the house was estimated to reduce from 200.0 kW/$m^2$ to 100.0 kW/$m^2$ after the application of retrofit, pre-retrofit actual consumption of the house was even lower than 100.0 kW/$m^2$.

The above discussion confirms again that Standards' recommendations used to estimate energy consumption of buildings do often fail to reflect the reality. This is more apparent for the case of houses, where occupants interact with the environment in a more complicated and unpredictable way than, for example, in office buildings. Thus, the utilisation of standardized temperature recommendations might have several implications on the simulation results. In this direction and based on all the above, it is worth mentioning that the absolute values of the simulated output variables provided in the thesis (e.g. energy use) might (significantly or not) differ from the reality. However, in respect with the purpose of this thesis, the use of typical temperature recommendations provided by national or international standards does still allow for a reasonable and fair comparison between the houses even if the considered and modelled internal temperatures are different from the actual ones.

## 6.6 Contribution to knowledge

This work has contributed to knowledge in two different ways. Firstly, the thesis presented a methodological approach that was developed to enable the evaluation of AWHPs linked with fabric retrofit options at the stock level; to the author's knowledge, such an approach has not been explicitly studied for the UK housing stock to date. Furthermore, the results presented can be easily exploited by both stakeholders and homeowners, thus contributing to a better understanding of AWHPs' applicability for houses covering a wide range in physical characteristics (size, built form, insulation level). These two aspects are expanded upon as follows.

### 6.6.1 A stock-based approach

A number of previous studies have already proved that electrically-driven AWHPs is a high potential retrofit heating solution for UK residential buildings with most of them investigating their applicability from a single-building perspective. However, this work recognises the necessity to adopt a stock-based methodological approach in order to establish a better understanding of the extent to which UK Government policy can rely on AWHPs' viability for the refurbishment of the UK housing stock.

The originality of the methodology presented in the thesis lies in the *number* of houses considered, the fact that these houses represent *real UK houses* and the fact that these houses are studied using a *dynamic simulation* engine. The methodology presented consists of an inter-linked modelling and analysis framework, which is suitable to be applied to all housing stocks across the UK. The data of the houses used for the purposes of this thesis (all of which are included in a simple csv file) can be easily updated and enriched without a restriction on the number of houses included. This means that although the present thesis focuses on the applicability of AWHPs to the housing stock of the NE region of England, future work can follow this approach as presented, to study the entire or even, other parts of the UK housing stock. This is a straight-forward procedure as the data required to construct UK house archetypes models are available by the EHS and updated on an annual basis. However, this might not be the case for housing stocks outside the UK. For example, other countries have different building regulations standards and thus, the approach that this thesis followed to assign U-values might be no be valid to be extrapolated. In this case, alterations need to be made in the original C# code for constructing the required house models. In addition to that, the way that this thesis models the geometry of houses might need to change in the absence of equivalent to EHS data sets.

Pursuing a housing stock-based approach for studying the effectiveness of AWHPs within the UK context and establishing a communicable results visualisation framework is an additional innovation. The results obtained from this thesis allow for the development of a simple tool that can be used in the future as an indication of AWHP's applicability based on house characteristics. In this tool, the user (homeowner, stakeholder, policy maker) could input a detailed set of house characteristics (e.g. age of construction, construction of external-wall, roof, and floor, glazing type, infiltration rate, number of occupants, etc.) and obtain the required size (nominal heating capacity) of the AWHP that should be installed for that particular house, identify the predicted energy consumption of this installed heating system, etc. The tool could be also used to assess fabric retrofit in conjunction with the application of an AWHP as explained in Section 6.4.2. This opportunity given by the adopted dynamic stock-based approach is of particular interest for AWHP installers, who currently rely on a high-level inspection of a house in order to select the size of the installed AWHP. In contrast, the results included in this thesis have been obtained using a well-established and validated dynamic simulation engine and follow national Standards and guidelines.

### 6.6.2 Recommendations to stakeholders; driving future policy

**Housing stock**

The study of AWHP's applicability under future weather scenarios in this thesis has clearly shown that the expected milder winter temperatures are an additional and significant driver to establish AWHPs as the main heating system of the future UK housing stock. However, one of the key messages for future policy is that the planning of a large-scale deployment of AWHPs needs to be alongside with upgrading building fabric in order for thermal comfort conditions to be maintained. This thesis comes to highlight that the effective integration of AWHPs in a house is significantly associated with the condition of the house itself. The results showed that thermal comfort appears to be an issue for a large number of houses across the examined stock even when the 2050 weather scenarios were considered. Therefore, if AWHPs are to be widely deployed in the domestic building stock up until 2050, the "preparation" of the stock for this transition needs to be the main focus of upcoming policies. The large number of houses studied in this thesis with these covering a wide range in physical properties enables the identification of certain house types that need to be thermally upgraded in order to be eligible for the AWHP retrofit until 2050. Based on the 2050 future weather scenarios, the house types that do not achieve an average PMV in the range of -0.7 to +0.7 when being retrofitted with an AWHP system are categorised as follows:

- **All houses with no exposed-wall insulation (independently of house size and built form)**
  (These houses were also found to contain the lowest level of loft insulation across the stock). Based on the characteristics and composition of the housing stock of the NE region of England, around 38.0 % of these uninsulated houses belong to these "hard to treat" houses consisting of solid walls and have been built before 1966. It is true that this part of the stock is challenging when it comes to improve its energy efficiency due to the higher upfront costs associated with insulating solid walls. As such, policymakers should work towards the issue of sophisticated schemes and financially effective incentives that especially target "hard to treat" houses and provide extra benefits in order to persuade consumers to invest in energy efficiency measures
  The remainder 62.0 % of these uninsulated houses have cavity-walls and have been built before 1982. The installation of wall insulation in this case is an easier and less expensive task. However, the current rate of upgrading wall and loft insulation in the existing UK houses is very low with this being in 2017 at 5.0 % of the peak market delivery in 2012 (CCC, 2019c). The existing policy seems to fail in driving even cost-effective and "easy-to-apply" retrofits such as the installation of loft and cavity-wall insulation.

- **Detached houses with either uninsulated or medium-insulated (independently of house size)**
  Among those house categories including detached houses, only these having highly insulated exposed-walls (U-value < 0.50) were found to maintain thermal comfort conditions. In fact, due to the higher heat losses through their fabric (compared to other built forms), detached houses need to be insulated at

high standards. Future building standards are encouraged to target detached houses separately so that a higher level of thermal insulation is required.

- **Uninsulated or medium-insulated houses with volume higher than 390.0 $m^3$ (independently of built form)**
  Assuming an average storey height of 2.5 m, these houses correspond to floor areas of more than 156.0 $m^2$. In this case as well, fabric heat losses are higher than usual and thus, high insulation levels are required in order to ensure energy efficiency.

**Technical**

As a result of this thesis, gaps were identified in current policies regarding the provision of a clear guideline for selecting the "right" heat-pump size. These gaps may, unfortunately, lead to increased running (and probably installation) costs and reduced reliability of this technology in the eyes of consumers. Current guidelines for AWHP's sizing recommend that AWHP's heating capacity should be selected so that the AWHP itself is capable of meeting the peak space-heating demand of the house; this is the strategy followed in the present thesis. However, the results revealed that such an approach might lead to a considerable deterioration of the system's effectiveness due to the fact that the AWHP operates far from its full-load conditions for a significant amount of time. This introduces a significant and unwanted cycling of the system, which reduces COP and consequently, results in high energy costs. This thesis highlights the need for the formulation of a more nuanced guideline aiming to inform heat-pump manufacturers and designers for the "right" installation of heat-pumps with a particular focus on overcoming sizing issues.

## 6.7 Limitations of the research

This section discusses the limitations of the research presented in this thesis; these can be broadly distinguished in two separate categories concerning the representation of the modelled housing stock and the characteristics of the retrofitted AWHP system.

### 6.7.1 The housing stock

- **Data**

One important limitation is associated with the data set that has been used in this thesis; this represents the housing stock of the NE region of England and thus, any findings should not be directly extrapolated for the entire UK housing stock. Although the composition of the housing stock of the NE region of England was found to be representative of the UK housing stock (in terms of the distribution of houses' age band, level of insulation, size and built form), the location and climatic conditions of Newcastle (which has been used to represent the climatic conditions of this region) are considered to be important factors that could have a significant impact on a building's heating demand and consequently, on the applicability of AWHPs across the different UK regions. However, the methodology presented offers the means to carry out evaluations for housing stocks in other parts of the UK.

- **Geometric representation**

Further, the geometric representation of the modelled house archetypes is associated with some assumptions (discussed in Section 3.2.2), which could have an impact on the results. Firstly, the data set used does not include any information for the orientation of the house archetypes and thus, an east/west orientation is considered for all the modelled houses. In addition to that, no information is included about the location of windows on the facades of the house. It has been considered that windows are distributed equally in the exposed facades of the building envelope. However, this assumption could result in misrepresentation of the amount of solar heat gains.

- **Categorization**

The categorisation of the examined stock in 45 groups (with each group including houses of the same built form, range of total conditioned volume and range of insulation) has enabled a more comprehensive communication of the thesis' results. Nevertheless, the disaggregation of the modelled stock at this level has resulted in having a very limited number of house archetypes in some of the categories and this fact implies that a strictly statistical comparison of the results is not possible. The low number of houses included in some of the examined categories does not permit to implement suitable statistical tests to identify the statistical significance of the results for those categories (e.g. one-sample t-test).

- **Occupancy-related factors**

Heating patterns (including selection of set-point temperature, duration of heating and start/end time of daily heating periods) were considered to be the same for all the modelled house archetypes. Therefore, this thesis does not account for the impact of occupants' behaviour, which is amongst the most significant factors of a house's heating energy demand.

### 6.7.2 The AWHP system model

- **Frost protection method**

The adopted ($E^+$) model of the AWHP system does not account for reverse cycling under low ambient temperatures, which was identified in the literature as the common practice in actual AWHP systems in order to avoid frost accumulation on the evaporator side of the AWHP. To account for this, a "frost-protection technique" has been employed; AWHP switches-OFF when DBT is below 2.0$^o$C and the auxiliary electric heater becomes automatically available to meet the entire house's heating demand. However, it was shown that this resulted in operating the auxiliary heater for longer periods than in actual AWHP installations, which, in turn, resulted in increased energy use and reduced overall effectiveness of the retrofitted heating system.

- **Distribution heating system**

The distribution heating system of each house was modelled as a set of convective baseboard heaters with each individual heater serving on thermal zone of the house. In addition to that, the heat emission capacity of each heater was auto-sized by $E^+$ so that the heater was capable of delivering the maximum heat output of the retrofitted AWHP. This, obviously, implies that this thesis considers that the distribution heating system of the houses will be retrofitted in order to be suitable for serving a low-inertia heating system such as heat-pumps. Nevertheless, this is not always the case in actual AWHP retrofit applications, where the common practice is to install the new AWHP system whilst maintaining the current distribution heating system, which consists of high temperature radiators in most UK houses. Previous studies proved that this practice is not effective for the applicability of AWHPs and this is the reason why this thesis recommends that AWHPs should be coupled with a suitable distribution heating system in order to provide their maximum potential. However, in order to evaluate the viability of replacing the current distribution heating system, a detailed analysis of capital and operational costs should be implemented (estimation of pay-back periods, etc.) and this needs to be studied in a future work. Occupants' disturbance should be also considered in this case.

## 6.8 Chapter summary

This chapter provided a discussion on five main aspects of the thesis: the developed modelling approach; its applications; retrofit implications; contribution to knowledge; and research limitations.

In Section 6.2, the justification of the housing stock modelling method was recapped alongside with the applied model verification technique. The possible reasons for the under-prediction of heating energy demand resulted from the employed modelling approach were discussed in relationship with previous works in the field. In Section 6.3, the main characteristics of the modelled AWHP system were pointed out with a particular focus on discussing its implications to be widely adopted in UK dwelling refurbishment applications. The discussion, then, focused on summarizing the wider implications of heat-pumps' deployment within the UK context. The more and more increasing penetration of combi-boilers in domestic heating was identified to pose a significant barrier to the development of the UK heat-pump market. The discussion also referred to the need of increasing demand flexibility through the combination of load-shifting with suitable electricity tariffs as a strategy to make electrified heating systems a viable solution from a technical and economic perspective. Section 6.4 discussed the applications of the developed methodology as presented in this thesis. The discussion was also expanded to highlight possible future applications including the development of an online tool to support retrofit decision making. In Section 6.5, the impact of rebound and pre-bound effects on the simulation results was assessed. Finally, Section 6.6 and Section 6.7 focused on summarizing the contribution to knowledge and the research limitations, respectively.

# Chapter 7

# Conclusions

## 7.1 Introduction

This thesis has described the development of a methodology for using stock-level dynamic building energy modelling to assess heating system retrofit linked with fabric upgrade targets for UK dwellings. The developed methodology has been applied to investigate the effectiveness of AWHPs to be used as a retrofit heating solution across the range of 756 unique house archetypes selected to represent the housing stock of the NE region of England. The houses with the integrated AWHP system have been simulated and studied throughout the winter heating months considering both current and future weather scenarios. The analysis then, including a novel graphical representation of the simulation results, has revealed paths for evaluating fabric retrofit and showed how this can contribute to enhancing the applicability of AWHPs in terms of the system's energy use, extent of underheating and level of thermal discomfort. This final chapter focuses on summarizing the main conclusions of this thesis (Section 7.2) and providing extensions of the present work and recommendations for future research in the field (Section 7.3).

## 7.2 Main conclusions

The review of academic papers including simulation works and field trial studies revealed that there is limited evidence regarding the applicability of heat-pumps at the stock level within the UK context. Although several works focused on investigating the heating performance of common and advanced heat-pumps systems for existing UK residential buildings, most studied that from a single-building perspective. However, as the ability of heat-pumps to maintain comfort conditions is highly dependent on the condition of the house itself, research should focus on exploring which houses need further retrofit in order for heat-pumps to be a viable solution across the range of the UK housing stock. This thesis contributes to addressing this need by developing a suitable methodology and presenting its application to the housing stock of the NE region of England. The following sections summarize the main methodological conclusions (Section 7.2.1) as well as the conclusions made with respect to the results obtained from this work (Section 7.2.2).

### 7.2.1 Methodological conclusions

The developed methodology is based on the employment of a bottom-up HSEM used to study the simulated performance of houses within a dynamic simulation environment. The core of the methodology is the approach followed to represent houses covering a wide range in physical properties and the construction of an AWHP system capable of meeting the houses' space-heating and DHW demand. The main conclusions of this process are summarised upon as follows.

- The employed HSEM was found to be in good agreement with the steady-state CHM with both models resulting in a very similar distribution of the heating energy demand across the stock. The Spearman Rank Correlation coefficient for the two predicted space-heating energy demands is 0.94 with this revealing a very close positive correlation between the results obtained by the CHM and $E^+$.

- The employed HSEM was found to under-predict the absolute value of space-heating energy demand at an average of 54.0.% compared to CHM predictions. However, this significant under-prediction might be subject to variations in the input data (such as weather data) between the two models (the thesis did not focus on matching boundary conditions between the two).

- Selecting the nominal heating capacity of the AWHP to match 100% of the house's peak heating load results in COP degradation in the order of 20%. More sophisticated sizing approaches should be developed and adopted in the future to account for the extent of the heat-pumps' part-load operation.

- The developed methodology benefits from the fact that:
  - models real UK houses, the geometry and physical properties of which were derived from the national EHS
  - presents no restrictions on the number of houses studied
  - uses dynamic simulations, thus allowing for the identification of the hourly or even minutely patterns of variables such as system's effectiveness, comfort-related factors (such as PMV), internal temperatures, etc. with this being impossible for the commonly adopted steady-state-based approaches
  - is generic and directly applicable to either the entire or any part of the UK housing stock
  - employs a novel visualisation way of the simulation results allowing for the identification of energy use/under-heating/thermal discomfort patterns across the stock as a result of heating system retrofit solutions (in this case applied to AWHPs) linked with fabric retrofit targets for dwellings

### 7.2.2 AWHPs' applicability

This section provides the main conclusions regarding the applicability of AWHPs across the modelled stock considering current and future weather scenarios. It should be clarified that the conclusions presented below are subject to the selected housing stock, house modelling choices as well as architecture and control of the modelled AWHP system.

*Considering a current weather scenario*

- The SPF of the AWHP itself (without the contribution of fan and supplementary electric heaters) was found to be in the order of 3.0 across the modelled stock; this being comparable with previous field trials carried out within the UK context.

- The energy use of the auxiliary electric heater was found to be significant for the modelled AWHP due to the adoption of the frost-protection technique (AWHP was modelled to be OFF under low ambient temperatures and heat was solely provided through the auxiliary electric heater). The overall effectiveness of the system ranges from 2.0 to 2.3 across the modelled stock.

- The level of under-heating was found to be within acceptable limits (less than 300 unmet load hours) for 752 out of the 756 house archetypes.

- The evaluation of thermal comfort conditions revealed that only few houses managed to achieve an average annual PMV index within the range of -0.7 to +0.7. These are either:
  **semi-detached and mid-terrace houses with external-wall U-value < 0.50 and conditioned volume < 390.0 m$^3$** (~160.0 m$^2$); *or*
  **mid-terrace houses with external-wall U-value < 1.50 and conditioned volume < 180.0 m$^3$** (~72.0 m$^2$).

*Considering future weather scenarios*

- The annual electric input of the AWHP was found to decrease in the range of 6.0 %-9.0 % and 11.0 %-26.0 % across the stock for the 2050 and 2080 weather scenarios, respectively, depending on the carbon emissions level.

- The annual electric input of the auxiliary heater was found to decrease at an average of 40.0 % for the 2050 weather scenarios, while this reduction was found to be in a range 55.0 %-66.0 % for the 2080 weather scenarios, again depending on the emissions level.

- All house archetypes were found to present less than 300 unmet load hours annually for all the examined future weather scenarios.

- Thermal discomfort was identified to still persist for a significant number of houses when the 2050 weather scenario was applied (under a medium emissions scenario). These are:

  **all houses with no exposed-wall insulation (independently of house size and built form);**
  **detached houses with either uninsulated or medium-insulated (independently of house size);** *and*
  **uninsulated or medium-insulated houses with volume higher than 390.0 $m^3$** (~160.0 $m^2$) **(independently of built form)**

## 7.3 Extensions and recommendations for future work

As a result of this work, this final section includes a number of recommendations for future research that can further improve the adopted modelling techniques and analysis and consequently, add further value to the effectiveness of the stock-based approach developed in this thesis to be used to inform policy and industry. The following bullet points highlight some proposed areas for further research.

- For the purposes of this work, the adopted modelling approach was verified against the predictions of the CHM and it was found adequate to represent the distribution of heating demand across the stock. An important area for future work would be to compare predictions with measurements in order to calibrate the developed house models to provide accurate results representing the reality.

- The representation of occupancy-related factors was based on a deterministic approach; occupants' presence in the house, heating periods, duration of heating, selected set-point temperatures as well as patterns for internal heat gains were modelled using recommendations from national guidelines and standards. Future research should focus on accounting for the diversity of occupants' behaviour adopting a stochastic approach for the determination of occupancy-related factors This would overcome (to some extent) the issues of high uncertainty associated with occupancy that have been found in previous works to have a significant impact on the energy use. With the increasing use of smart controls in homes, the employed modelling approach should be further developed to account for temperature variations throughout the day in response with weather data and occupants' profile, presence at home and occupants' preferences.

- An extension of the present work would be to expand the analysis and assess the economic feasibility of the AWHP retrofit across the stock. This would include the consideration of capital, installation, maintenance and running cost as well as the comparison with current heating systems to ensure the viability of investing in such a retrofit solution. In this context, AWHP's modelling should be combined with the application of suitable DSM strategies (such as load-shifting and dynamic ToU tariffs) to ensure that consumers can make the most of heat-pumps from both a technical and economic perspective.

# References

Adhikari, R.S., Aste, N., Manfren, M., Marini, D. (2012) Energy Savings through Variable Speed Compressor Heat Pump Systems. In *2nd International Conference on Advances in Energy Engineering 2011*. Bangkok, Thailand: Energy Procedia, pp. 1337–1342.

Anderson, B., Chapman, P.F., Cutland, N.G., Dickson, C.M., Doran, S.M., Henderson, G., Henderson, J., Kosmina, L., Shorrock, L.D. (2008) *BREDEM-8 Model Description*. Watford: Construction Research Communications Ltd by permissions of BRE.

Arteconi, A., Hewitt, N.J., Polonara, F. (2013) Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering*. **51**(1–2), 155–165.

Arteconi, A., Hewitt, N.J., Polonara, F. (2012) State of the art of thermal storage for demand-side management. *Applied Energy*. **93**, 371–389.

Asaee, S.R., Ugursal, V.I., Beausoleil-Morrison, I. (2017) Techno-economic feasibility evaluation of air to water heat pump retrofit in the Canadian housing stock. *Applied Thermal Engineering*. **111**, 936–949.

ASHRAE (2016) *Energy Standard for Buildings Except Low-Rise Residential Buildings: ASHRAE Standard*. Atlanta, GA: American Society of Heating Refrigerating and Air-Conditioning Engineers.

ASHRAE (2004) *Thermal Environmental Conditions for Human Occupancy: ASHRAE Standard*. Atlanta, GA: American Society of Heating Refrigerating and Air-Conditioning Engineers.

Badiei, A. (2018) *A reduced data dynamic energy model of the UK houses*. Loughborough University.

Bagarella, G., Lazzarin, R., Noro, M. (2016) Sizing strategy of on-off and modulating heat pump systems based on annual energy analysis. *International Journal of Refrigeration*. **65**, 183–193.

Barker, T., Ekins, P., Foxon, T. (2007) The macro-economic rebound effect and the UK economy. *Energy Policy*. **35**(10), 4935–4946.

BEIS (2019a) *2018 UK GREENHOUSE GAS EMISSIONS, PROVISIONAL FIGURES*. London: Department for Business Energy & Industrial Strategy.

BEIS (2010) *2050 Pathways Analysis*. London: Department for Business Energy & Industrial Strategy.

BEIS (2020) *Annual Fuel Poverty Statistics in England, 2020 (2018 Data)*. London.

BEIS (2018a) *Clean Growth - Transforming Heating - Overview of Current Evidence*. London: Department for Business Energy & Industrial Strategy.

BEIS (2018b) *DIGEST OF UNITED KINGDOM ENERGY STATISTICS 2018*. London: Department for Business Energy & Industrial Strategy.

BEIS (2018c) *ENERGY CONSUMPTION IN THE UK*. London: Department for Business Energy & Industrial Strategy.

BEIS (2019b) *Energy Consumption in the UK ( ECUK ) 1970 to 2018*. London: Department for Business Energy & Industrial Strategy.

BEIS (2019c) *Energy efficiency: building towards net zero*. London: Department for Business Energy & Industrial Strategy.

BEIS (2017) *MIS 3005, REQUIREMENTS FOR MCS CONTRACTORS UNDERTAKING THE SUPPLY, DESIGN, INSTALLATION, SET TO WORK, COMMISSIONING AND HANDOVER OF MICROGENERATION HEAT PUMP SYSTEMS, Microgeneration Installation Standard (MIS)*. Issue 5.0. London: Department for Business Energy & Industrial Strategy.

BEIS (2019d) *Statistical Press Release: UK Energy Statistics 2018 and Q4 2018*. London: Department for Business Energy & Industrial Strategy.

Belcher, S.E., Hacker, J.N., Powell, D.S. (2005) Constructing design weather data for future climates. *Building Services Engineering Research and Technology*. **26**(1), 49–61.

Boyano, A., Hernandez, P., Wolf, O. (2013) Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations. *Energy and Buildings*. **65**, 19–28.

BRE (2008) *A study of Hard to Treat Homes using the English House Condition Survey*. Garston, Watford: Building Research Establishment.

BRE (2011) *SAP 2009 The Government ' s Standard Assessment Procedure for Energy Rating of Dwellings*. Garston, Watford: Building Research Establishment.

British Standard Institution (2013) *BS EN 14511-2:2013: Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling*. London: British Standard Institution.

BS EN 15251:2007 *Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics*. Brussels: European Commission.

BS EN ISO 15927-4:2005 (2005) *Hygrothermal performance of buildings - Calculation and presentation of climatic data - part 5: Data for designg heat load for space heating*. London: British Standard Institution.

BS EN ISO 7730:2005 (2006) *ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*. London: British Standard Institution.

Buckley, J., King-Hele, S. (2014) *What is weighting ?* UK Data Service, University of Essex and University of Manchester.

Cabrol, L., Rowley, P. (2012) Towards low carbon homes – A simulation analysis of building-integrated air-source heat pump systems. *Energy and Buildings*. **48**, 127–136.

CCC (2019a) *Accelerated electrification and the GB electricity system*. London.

CCC (2018) *Biomass in a low-carbon economy*. London: Committee on Climate Change.

CCC (2019b) *Reducing UK emissions - 2019 Progress Report to Parliament*. London: Committee on Climate Change.

CCC (2019c) *UK housing : Fit for the future ?* London: Committee on Climate Change.

Changqing, T., Liang, N. (2006) State of the Art of Air-source Heat Pump for Cold Regions. In *Sixth International Conference for Enhanced Building Operations, Shenzhen, China, 6-9 November 2006*. Renewable Energy Resources and a Greener Future Vol.VIII-12-5.

Chapman, J. (1991) Data accuracy and model reliability. In *Building environmental performance assessment criteria*. Canterbury, pp. 10–19.

Cheng, V., Steemers, K. (2011) Modelling domestic energy consumption at district scale: A tool to support national and local energy policies. *Environmental Modelling and Software*. **26**(10), 1186–1198.

CIBSE (2019) CIBSE - Weather Data Sets. [online]. Available from: https://www.cibse.org/weatherdata#1 [Accessed September 1, 2019].

CIBSE (2006) *CIBSE Guide A: Environmental design*. 7th editio. London: Chartered Institution of Building Services Engineers.

Crawley, D.B., Lawrie, L.K., Winkelmann, F.C., Buhl, W.F., Huang, Y.J., Pedersen, C.O., Strand, R.K., Liesen, R.J., Fisher, D.E., Witte, M.J., Glazer, J. (2001) EnergyPlus : Creating a New-Generation Building Energy Simulation Program EnergyPlus : creating a new-generation building energy simulation program. *Energy and Buildings*. **33**, 319–331.

De Dear, R., Brager, G.S. (2001) The adaptive model of thermal comfort and energy conservation in the built environment. *International Journal of Biometeorology*. **45**(2), 100–108.

De Dear, R., Brager, G.S. (1998) Thermal adaptation in the built environment: a literature review. *Energy and Buildings*. **27**, 83–96.

Dincer, I. (2002) On thermal energy storage systems and applications in buildings. *Energy and Buildings*. **34**(4), 377–388.

Dodds, P.E. (2014) Integrating housing stock and energy system models as a strategy to improve heat decarbonisation assessments. *Applied Energy*. **132**, 358–369.

Dunbabin, P., Charlick, H., Green, R. (2013) *Detailed analysis from the second phase of the Energy Saving Trust's heat pump field trial*. London: Department of Energy & Climate Change, Energy Saving Trust.

Dunbabin, P., Wickins, C. (2012) *Detailed analysis from the first phase of the Energy Saving Trust's heat pump field trial*. London: Department of Energy and Climate Change, Energy Saving Trust.

Eames, M., Mylona, A. (2018) Thermal performance of buildings Find out more Exploiting UKCP18 data.

Eames, M.E., Ramallo-gonzalez, A.P., Wood, M.J. (2016) An update of the UK ' s test reference year : The implications of a revised climate on building design. *Building Services Engineering Research and Technology*. **37**(3), 316–333.

Eames, P., Loveday, D., Haines, V., Romanos, P. (2014) *The Future Role of Thermal Energy Storage in the UK Energy System: An assessment of the Technical Feasibility and Factors Influencing Adoption, Research Report*. London: UKERC UK Energy Research Centre.

EnergyPlus (2020) EnergyPlus. [online]. Available from: https://energyplus.net/ [Accessed August 10, 2020].

EnergyPlus (2016a) *Getting Started*. US Department of Energy.

EnergyPlus (2016b) *Input Output Reference*. US Department of Energy.

EST (2013) The heat is on: heat pump field trials phase 2. , 40.

Etude (2018) Low Carbon Heat: Heat pumps in London. *Greater London Authority (GLA*. [online]. Available from: https://www.london.gov.uk/sites/default/files/low_carbon_heat_-_heat_pumps_in_london_.pdf_london_.pdf [Accessed March 1, 2019].

European Commission (2013) *Commission Delegated Regulation No 818/2013 - supplementing Directive 2010/30/EU of the European Parliament and the Council with regard to the energy labelling of water heaters, hot water storage tanks and packages of water heater and solar device*. Brussels: European Commission.

Fanger, P.O. (1970) *Thermal Comfort: Analysis and applications in environmental engineering*. Copenhagen: Danish Technical Press.

Fawcett, T. (2011) The future role of heat pumps in the domestic sector. In *European Council for an Energy Efficient Economy 2011 Summer Study on energy efficiency: Energy efficiency first: The foundation of a low-carbon society*. Belambra Presqu'île de Giens, France: European Council for an Energy Efficient Economy, pp. 1547–1557.

Foster, M. (2020) 2019 Was Record Year for Gas Boiler Sales. [online]. Available from: https://www.installeronline.co.uk/2019-record-year-gas-boiler-sales/ [Accessed September 10, 2020].

Gagneja, A., Pundhir, S. (2016) Heat Pumps and Its Applications. *International Journal of Advances in Chemical Engineering and Biological Sciences*. **3**(1), 117–120.

Gale, I.N. (2005) *Ground source heat pumps: development of GeoReports for potential site characterisation, issue 1.2*. British Geological Survey Commissioned Report.

Galvin, R., Sunikka-Blank, M. (2016) Quantification of (p)rebound effects in retrofit policies - Why does it matter? *Energy*. **95**, 415–424.

Gellings, C.W., Smith, W.M. (1989) Integrating Demand-Side Management into Utility Planning. *Proceedings of the IEEE*. **77**(6), 908–918.

Gleeson, C.P., Lowe, R. (2013) Meta-analysis of European heat pump field trial efficiencies. *Energy and Buildings*. **66**, 637–647.

Griffith, B., Crawley, D. (2006) METHODOLOGY FOR ANALYZING THE TECHNICAL POTENTIAL FOR ENERGY PERFORMANCE IN THE U.S. COMMERCIAL BUILDINGS SECTOR WITH DETAILED ENERGY MODELLING. In *SimBuild 2006 Conference Cambridge, Massachusetts, August 2-4*.

Gupta, R., Gregg, M. (2018) Targeting and modelling urban energy retrofits using a city-scale energy mapping approach. *Journal of Cleaner Production*. **174**, 401–412.

Hamilton, I.G., O'Sullivan, A., Huebner, G., Oreszczyn, T., Shipworth, D., Summerfield, A., Davies, M. (2017) Old and cold? Findings on the determinants of indoor temperatures in English dwellings during cold conditions. *Energy and Buildings*. **141**, 142–157.

Hanna, R., Parrish, B., Gross, R. (2016) *Best practice in heat decarbonisation policy: A review of the international experience of policies to promote the uptake of low-carbon heat supply. UKERC Technology and Policy Assessment working paper*. London, UK.

Hasnain, S.M. (1998) REVIEW ON SUSTAINABLE THERMAL ENERGY STORAGE TECHNOLOGIES , PART I : HEAT STORAGE MATERIALS AND TECHNIQUES. *Energy Conversion and Management*. **39**(11), 1127–1138.

He, M., Lee, T., Taylor, S., Firth, S.K., Lomas, K.J. (2014) Dynamic modelling of a large scale retrofit programme for the housing stock in the North East of England. In *Proceedings of the 2nd International Conference on Urban Sustainability and Resilience, London, UK , 3-5 November 2014*. London: Urban Sustainability and Resilience (USAR) Conference SERIES.

Henninger, R.H., Witte, M.J., Crawley, D.B. (2004) Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100-E200 test suite. *Energy and Buildings*. **36**(8), 855–863.

Herrera, M., Natarajan, S., Coley, D.A., Kershaw, T., Ramallo-González, A.P., Eames, M., Fosas, D., Wood, M. (2017) A review of current and future weather data for building simulation. *Building Services Engineering Research and Technology*. **38**(5), 602–627.

Hesaraki, A., Holmberg, S., Haghighat, F. (2015) Seasonal thermal energy storage with heat pumps and low temperatures in building projects — A comparative review. *Renewable and Sustainable Energy Reviews*. **43**, 1199–1213.

Hewitt, N., Huang, M.J. (2008) Defrost cycle performance for a circular shape evaporator air source heat pump. *International Journal of Refrigeration*. **31**(3), 444–452.

Hong, T., Sun, K., Zhang, R., Hinokuma, R., Kasahara, S., Yura, Y. (2016) Development and validation of a new variable refrigerant flow system model in EnergyPlus. *Energy and Buildings*. **117**, 399–411.

Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., Summerfield, A. (2013) The reality of English living rooms - A comparison of internal temperatures against common model assumptions. *Energy and Buildings*. **66**, 688–696.

Hughes, M., Palmer, J., Cheng, V., Shipworth, D. (2013) Sensitivity and uncertainty analysis of England's housing energy model. *Building Research & Information*. **41**(2), 156–167.

Hughes, M., Palmer, J., Pope, P. (2013) *A Guide to The Cambridge Housing Model*. London: Department of Energy & Climate Change.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]*. Geneva, Switzerland: IPCC.

Jankovic, L. (2017) *Designing Zero Carbon Buildings Using Dynamic Simulation Methods-Second Edition*. London and New York: Routledge.

Johnston, D., Lowe, R., Bell, M. (2005) An exploration of the technical feasibility of achieving CO 2 emission reductions in excess of 60 % within the UK housing stock by the year 2050. *Energy Policy*. **33**(13), 1643–1659.

Judkoff, R., Wortman, D., O'Doherty, B., Burch, J. (2008) *A Methodology for Validating Building Energy Analysis Simulations, Techical Report NREL/TP-550-42059*. Golden, Colorando: National Renewable Energy Laboratory, U.S. Department of Energy Office of Energy Efficiency and Reneable Energy.

Katiyo, S., Dorey, S., Bone, A. (2015) *The Cold Weather Plan for England Protecting health and reducing harm from cold weather About Public Health England*. Lonndon: Public Health England, Department of Health.

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., Djurovic-Petrovic, M. (2010) A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment*. **45**(7), 1683–1697.

Kaygusuz, K. (1999) The Viability of Thermal Energy Storage. *Energy Sources*. **21**(8), 745–755.

Kelly, J.A., Fu, M., Clinch, J.P. (2016) Residential home heating: The potential for air source heat pump technologies as an alternative to solid and liquid fuels. *Energy Policy*. **98**, 431–442.

Kelly, N.J., Cockroft, J. (2011) Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data. *Energy and Buildings*. **43**(1), 239–245.

Kelly, N.J., Tuohy, P.G., Hawkes, A.D. (2014) Performance assessment of tariff-based air source heat pump load shifting in a UK detached dwelling featuring phase change-enhanced buffering. *Applied Thermal Engineering*. **71**(2), 809–820.

Kelly, S. (2011) Do homes that are more energy efficient consume less energy?: A structural equation model of the English residential sector. *Energy*. **36**(9), 5610–5620.

Klein, K., Huchtemann, K., Müller, D. (2014) Numerical study on hybrid heat pump systems in existing buildings. *Energy and Buildings*. **69**, 193–201.

Kozarcanin, S., Hanna, R., Staffell, I., Gross, R., Andresen, G.B. (2020) Impact of climate change on the cost-optimal mix of decentralised heat pump and gas boiler technologies in Europe. *Energy Policy*. **140**(July 2019), 111386.

Krajačić, G., Duić, N., Tsikalakis, A., Zoulias, M., Caralis, G., Panteri, E., Carvalho, M. da G. (2011) Feed-in tariffs for promotion of energy storage technologies. *Energy Policy*. **39**(3), 1410–1425.

Le, K.X., Huang, M.J., Shah, N., Wilson, C., Artain, P. Mac, Byrne, R., Hewitt, N.J. (2019) High temperature air source heat pump coupled with thermal energy storage: Comparative performances and retrofit analysis. *Energy Procedia*. **158**, 3878–3885.

Le, K.X., Huang, M.J., Wilson, C., Shah, N.N., Hewitt, N.J. (2020) Tariff-based load shifting for domestic cascade heat pump with enhanced system energy efficiency and reduced wind power curtailment. *Applied Energy*. **257**(October 2019), 113976.

Levermore, G.J., Courtney, R., Watkins, R., Cheung, H., Parkinson, J.B., Laycock, P., Natarajan, S., Nikolopoulou, M., McGilligan, C., Muneer, T., Tham, Y., Underwood, C.P., Edge, J.S., Du, H., Sharples, S., Kang, J., Barclay, M., Sanderson, M. (2012) *Deriving and using future weather data for building design from UK climate change projections – an overview of the COPSE Project*. Manchester, UK.

Loga, T., Stein, B., Diefenbach, N. (2016) TABULA building typologies in 20 European countries — Making energy-related features of residential building stocks comparable. *Energy & Buildings*. **132**, 4–12.

Madonna, F., Bazzocchi, F. (2013) Annual performances of reversible air-to-water heat pumps in small residential buildings. *Energy and Buildings*. **65**, 299–309.

Makhnatch, P. (2013) Low GWP alternative refrigerants in heat pumps. *KTH*. [online]. Available from: https://www.kth.se/en/itm/inst/energiteknik/forskning/ett/projekt/koldmedier-med-lag-gwp/low-gwp-news/laga-gwp-alternativa-koldmedier-i-varmepumpar-1.426276 [Accessed February 5, 2018].

Mastrucci, A., Baume, O., Stazi, F., Salvucci, S., Leopold, U. (2014) A GIS-based approach to estimate energy savings and indoor thermal comfort for urban housing stock retrofitting. *BauSIM2014 Conference Proceedings and Keynote Lecture Presentations, September 22-24, 2014, RWTH Aachen University, Germany*, 8.

McCallum, P., Jenkins, D.P., Vatougiou, P. (2020) An Urban-scale Residential Stock Model for Grid-constrained Regions. In *BSO2020, Building Simulation and Optimization, IBPSA England*. Loughborough.

McMahon, R., Santos, H., Mourão, Z.S. (2018) Practical considerations in the deployment of ground source heat pumps in older properties—A case study. *Energy and Buildings*. **159**(2018), 54–65.

Met Office (2019) *UK Climate Projections : Headline Findings (Version 2)*. Devon: Met Office.

Met Office (2018) UK Climate Projections (UKCP). [online]. Available from: metoffice.gov.uk/research/approach/collaboration/ukcp/index [Accessed September 1, 2019].

MHCLG (2017) *50 years of the English Housing Survey*. London: Ministry of Housing Communities & Local Government.

MHCLG (2015) *English housing survey: Headline Report 2017-18*. London: Ministry of Housing Communities & Local Government.

MHCLG (2009) *English Housing Survey - Housing Stock Data User Guide*. London: Ministry of Housing Communities and Local Government.

Milne, G., Boardman, B. (2000) Making cold homes warmer: The effect of energy efficiency improvements in low - income homes. *Energy Policy*. **28**, 411–424.

Mitsubishi Electric (2015) *AIR TO WATER HEAT PUMP SYSTEMS, ecodan, Data Book*. Tokyo: Mitsubishi Electric Corporation.

Mitsubishi Electric *OPERATIONAL MANUAL, ecodan*. Tokyo: Mitsubishi Electric Corporation.

Natarajan, S., Levermore, G.J. (2007) Predicting future UK housing stock and carbon emissions. *Energy Policy*. **35**(11), 5719–5727.

National Audit Office (2018) *Low carbon heating of homes and businesses and the Renewable Heat Incentive*. London.

Nicol, S., Roys, M., Ormandy, D., Ezratty, V. (2014a) *The cost of poor housing in the European Union*. BRE.

Nicol, S., Roys, M., Ormandy, D., Ezratty, V. (2014b) *The cost of poor housing in the European Union*. BRE.

Nowak, T. (2018a) *Heat Pumps, Integrating technologies to decarbonise heating and cooling*. Brussels: European Heat Pump Association.

Nowak, T. (2018b) Heat pumps – key technology to achieving Europe ' s energy and climate goals : 2017 Market development and outlook. , 1–25.

Nyers, J., Stuparic, D., Nyers, A. (2015) COP of refrigerants in heat pumps. In *Expres 2015, 7th International Symposium on Exploitation of Renewable Energy Sources and Efficiency, 19-21 March 2015*. Subotica, Serbia, pp. 121–124.

Octopus Energy (2020) Agile Octopus | Octopus Energy. [online]. Available from: https://octopus.energy/agile/ [Accessed September 14, 2020].

Office for National Statistics (2017) *Families and Households: 2017*. London: Office for National Statistics.

Office for National Statistics (2018) Labour Force Survey. [online]. Available from: https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths [Accessed May 8, 2019].

Ofgem (2019) Domestic Renewable Heat Incentive. [online]. Available from: https://www.ofgem.gov.uk/environmental-programmes/domestic-rhi [Accessed May 17, 2019].

Oreszczyn, T., Hong, S.H., Ridley, I., Wilkinson, P. (2006) Determinants of winter indoor temperatures in low income households in England. *Energy and Buildings*. **38**(3), 245–252.

Palmer, J., Cooper, I. (2013) *United Kingdom housing energy fact file*. London: Department of Energy & Climate Change.

Peeters, L., Dear, R. de, Hensen, J., D'haeseleer, W. (2009) Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*. **86**(5), 772–780.

Di Perna, C., Magri, G., Giuliani, G., Serenelli, G. (2015) Experimental assessment and dynamic analysis of a hybrid generator composed of an air source heat pump coupled with a condensing gas boiler in a residential building. *Applied Thermal Engineering*. **76**, 86–97.

Pieterse, R. (2019) UK heat pump market likely to double by 2025. *DELTA-EE*.

Ranson, R.P. (1988) *Guidlines for Healthy Housing*. Copenhagen: World Health Organization.

Renaldi, R., Kiprakis, A., Friedrich, D. (2017) An optimisation framework for thermal energy storage integration in a residential heat pump heating system. *Applied Energy*. **186**, 520–529.

Rony, R.U., Yang, H., Krishnan, S., Song, J. (2019) Recent Advances in Transcritical CO 2 (R744) Heat Pump System: A Review. *Energies*. **12**(3), 457.

Rosser, J.F., Long, G., Zakhary, S., Boyd, D.S., Mao, Y., Robinson, D. (2019) Modelling urban housing stocks for building energy simulation using CityGML energyade. *ISPRS International Journal of Geo-Information*. **8**(4).

Safa, A. a., Fung, A.S., Kumar, R. (2015) Performance of two-stage variable capacity air source heat pump: Field performance results and TRNSYS simulation. *Energy and Buildings*. **94**, 80–90.

SAP (2014) *SAP 2012 The Government ' s Standard Assessment Procedure for Energy*

*Rating of Dwellings*. Garston, Watford: Building Research Establishment.

Shah, N., Hewitt, N. (2015) High temperature heat pump operational experience as a retrofit technology in domestic sector. In *21st International Conference on Engineering, Technology and Innovation/ International Technology Management Conference (ICE/ITMC)*. Belfast.

Shorrock, L.D., Dunster, J.E. (1997) The physically-based model B R E H O M E S and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock. *Energy Policy*. **25**(12), 1027–1037.

Singh, H., Muetze, A., Eames, P.C. (2010) Factors influencing the uptake of heat pump technology by the UK domestic sector. *Renewable Energy*. **35**(4), 873–878.

Sousa, G., Jones, B.M., Mirzaei, P.A., Robinson, D. (2017) A review and critique of UK housing stock energy models, modelling approaches and data sources. *Energy and Buildings*. **151**, 66–80.

Staffell, I., Brett, D., Brandon, N., Hawkes, A. (2012) A review of domestic heat pumps. *Energy & Environmental Science*. **5**(11), 9291–9306.

Steadman, P., Evans, S., Liddiard, R., Godoy-Shimizu, D., Ruyssevelt, P., Humphrey, D. (2020) Building stock energy modelling in the UK: the 3DStock method and the London Building Stock Model. *Buildings and Cities*. **1**(1), 100–119.

Street, R.B., Steynor, A., Bowyer, P., Humphrey, K. (2009) Delivering and using the UK climate projections 2009. *Weather*. **64**(9), 227–231.

Sunikka-Blank, M., Galvin, R. (2012) Introducing the prebound effect: the gap between performance and actual energy consumption. *Building Research & Information*. **40**(3), 260–273.

Swan, L.G., Ugursal, V.I. (2009) Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*. **13**(8), 1819–1835.

Taylor, S., Allinson, D., Firth, S., Lomas, K. (2013) Dynamic Energy Modelling of UK Housing: Evaluation of Alternative Approaches. In *13th Conference of International Building Performance Simulation Association*. pp. 745–752.

Timperley, J. (2018) UK homes need 'deep efficiency retrofit' to meet climate goals.

Vatougiou, P., Jenkins, D.P., McCallum, P. (2020) Techno-economic Feasibility Of Replacing Oil Boilers With Air-To-Water-Heat-Pumps Coupled With Thermal Energy Storage. In *BSO2020, Building Simulation and Optimization, IBPSA England*. Loughborough.

Viessmann (2012) *VITOCAL Air/water heat pumps, Technical guide*. Telford: Viessmann.

Virk, D., Eames, M. (2016) *CIBSE Weather Files 2016 release: Technical Briefing and Testing*.

Welch, T. (2009) Heat pump technology. *CIBSE Journal*. [online]. Available from: http://www.cibsejournal.com/cpd/modules/2009-05/ [Accessed September 28, 2016].

De Wilde, P. (2018) *Building performance analysis*. Hoboken, NJ: Wiley Blackwell.

Wilkinson, P., Landon, M., Armstrong, B., Stevenson, S., Pattenden, S., Mckee, M., Fletcher, T. (2001) *Cold comfort: The social and environmental determinants of excess winter deaths in England , 1986-96*. York, UK.

Witte, M.J., Henninger, R.H., Glazer, J., Analytics, G., Ridge, P. (2001) Testing and Validation of a New Building Energy Simulation Program. *Proceesings of 7th International IBPSA Conference, Rio de Janeiro, Brazil, Augusr 13-15*.

Zhang, Y. (2009) 'Parallel' EnergyPlus and the Development of a Parametric Analysis Tool. In *Eleventh International IBPSA Conference*. Glasgow, Scotland: IBPSA, pp. 1382–1388.

# APPENDIX A

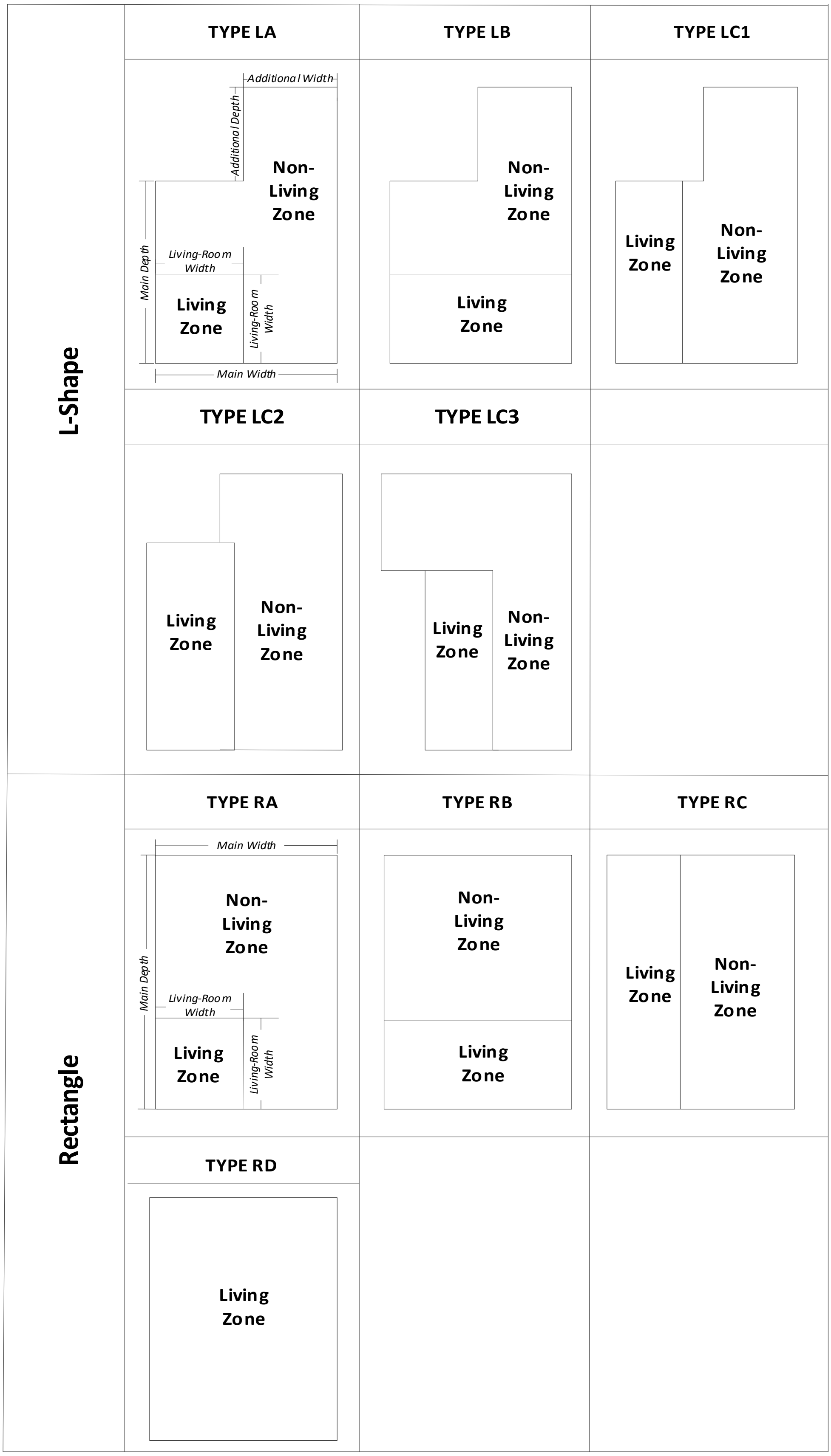



**Figure A- 1: Ground-floor layout variations for rectangle and L-shaped house archetypes**

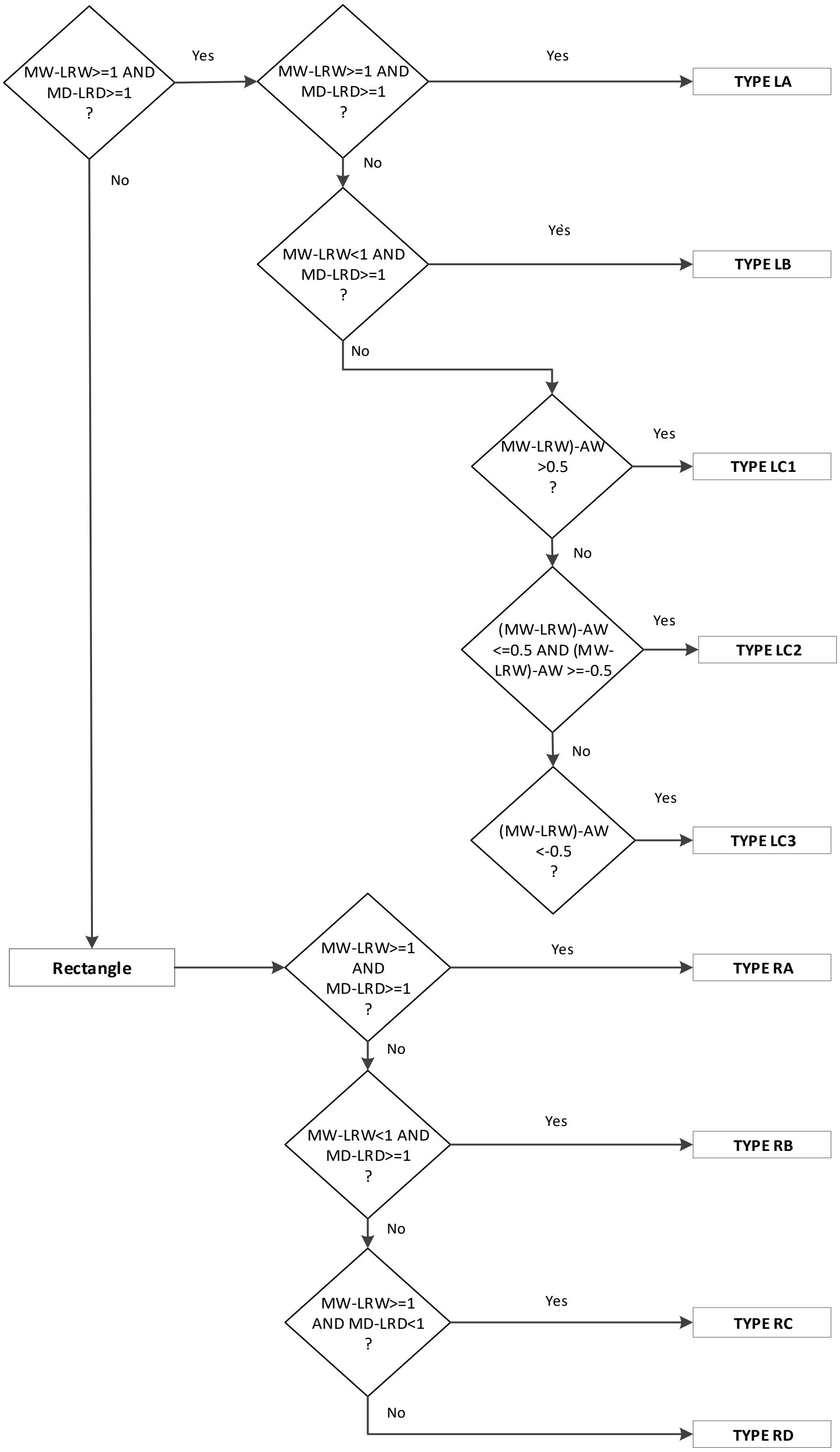



**Figure A- 2: Living-room location in L-shaped and rectangular house archetype**

For the main rectangle: MW: Main Width, MD: Main Depth, For the additional rectangle: AW: Additional Width, AD: Additional Depth, For the living-room: LRW: Living-Room Width, LRD: Living-Room Depth

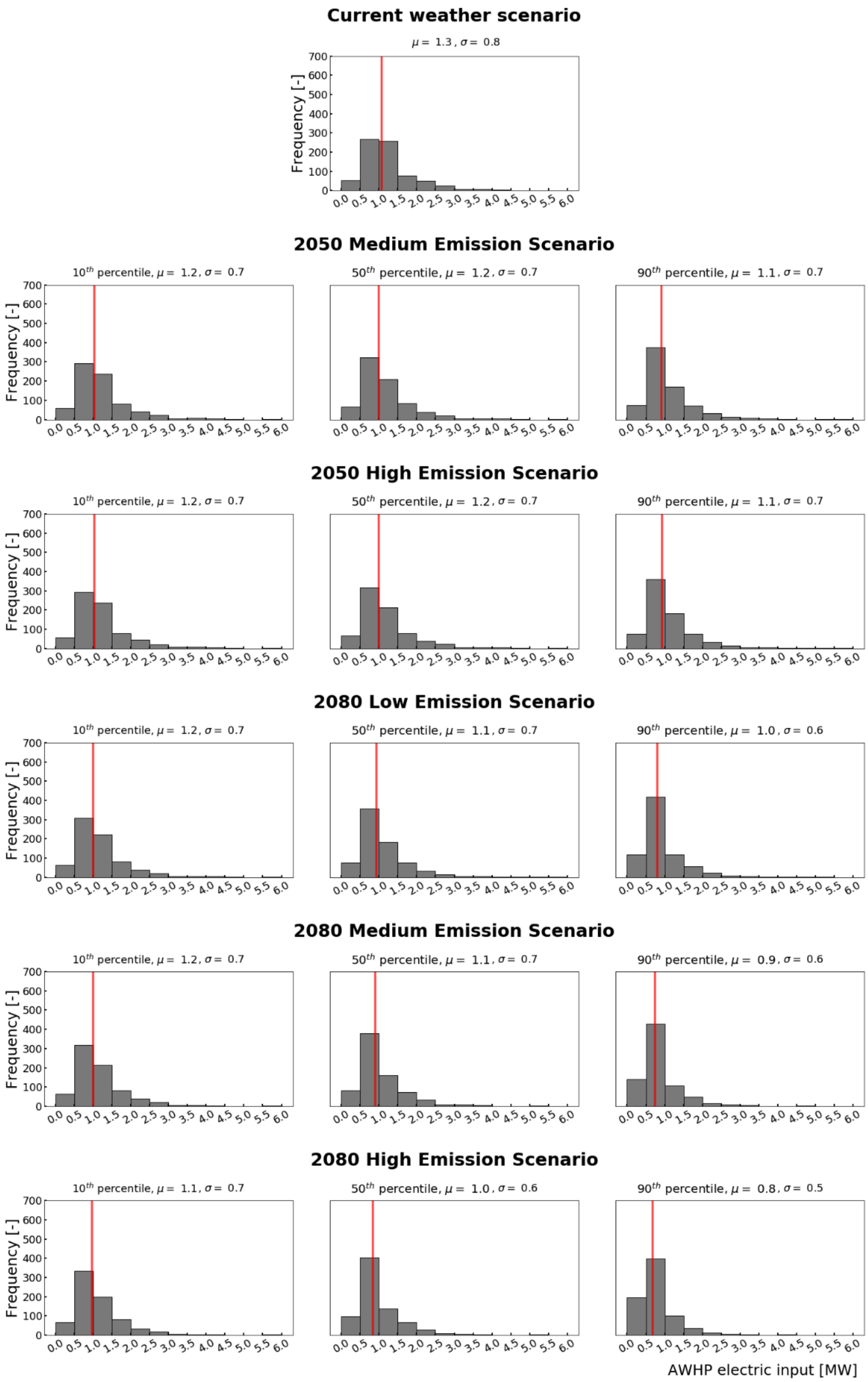



**Figure A- 3: Distribution of AWHP's electric input for the entire housing stock under current and various future weather scenarios (the red line depicts the median of each distribution)**

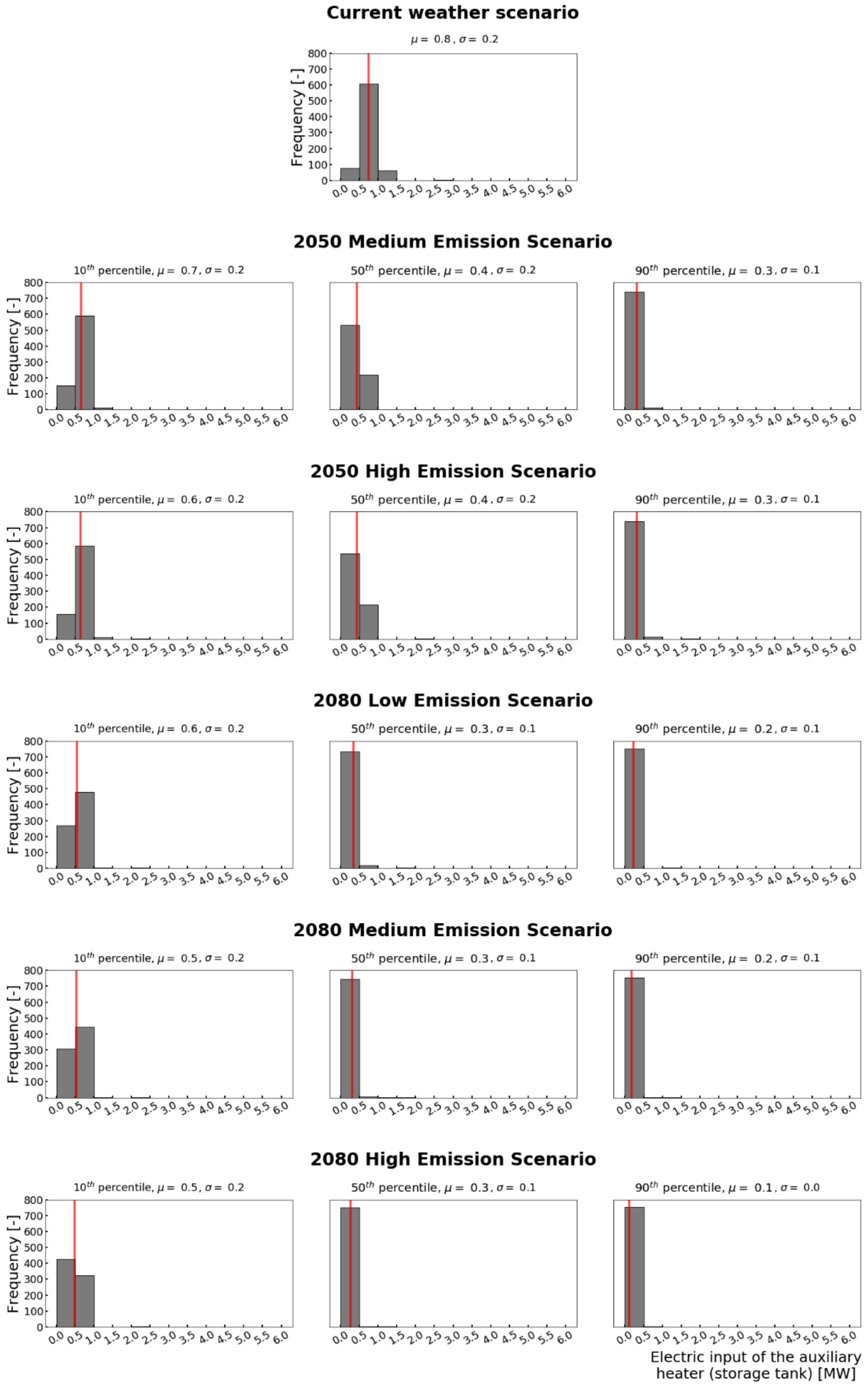



**Figure A- 4: Distribution of auxiliary heater's electric input for the entire housing stock under current and various future weather scenarios (the red line depicts the median of each distribution)**

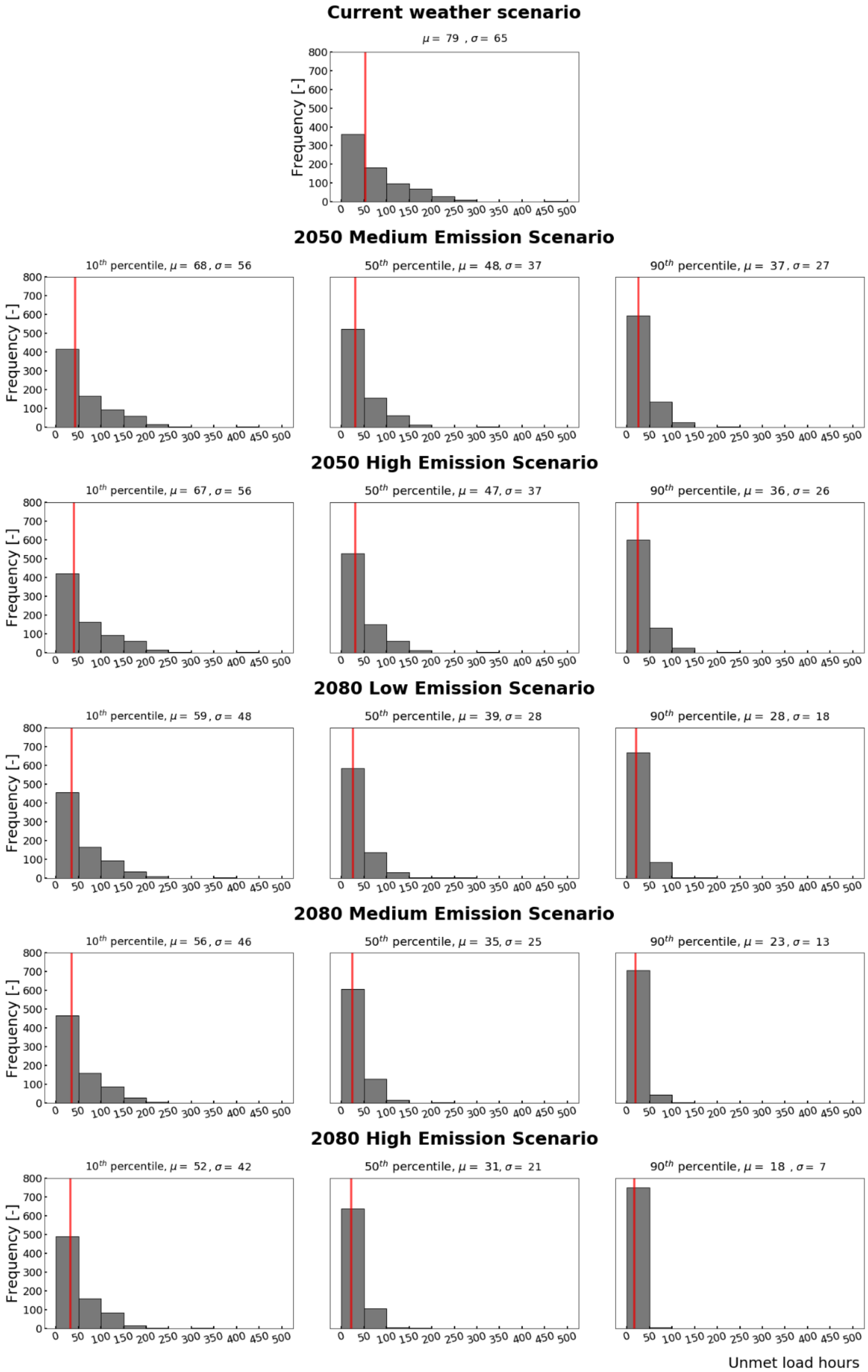



**Figure A- 5: Distribution of unmet load hours for the entire housing stock under current and various future weather scenarios (the red line depicts the median of each distribution)**

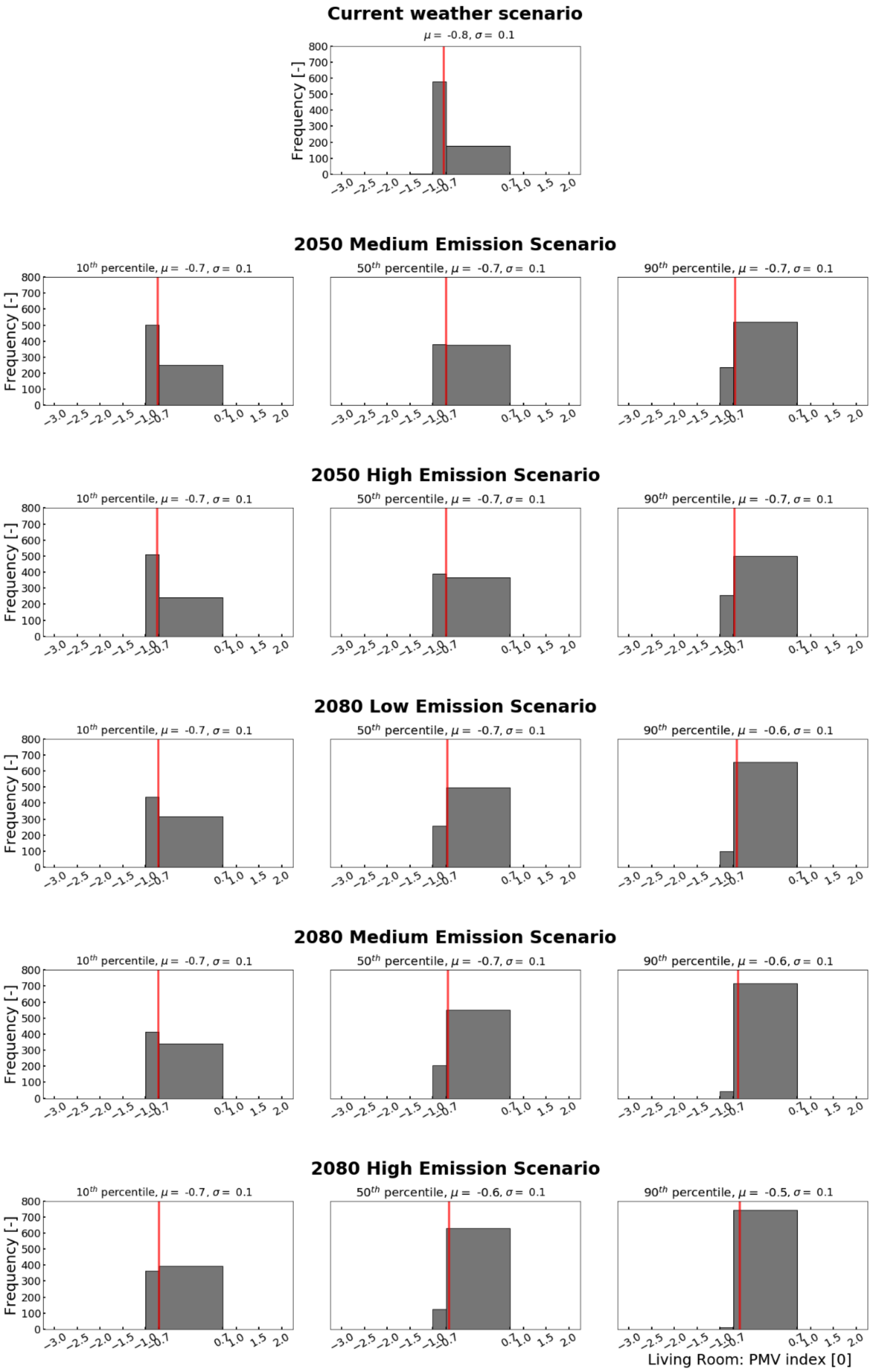



**Figure A- 6: Distribution of PMV index for the entire housing stock under current and various future weather scenarios (the red line depicts the median of each distribution)**

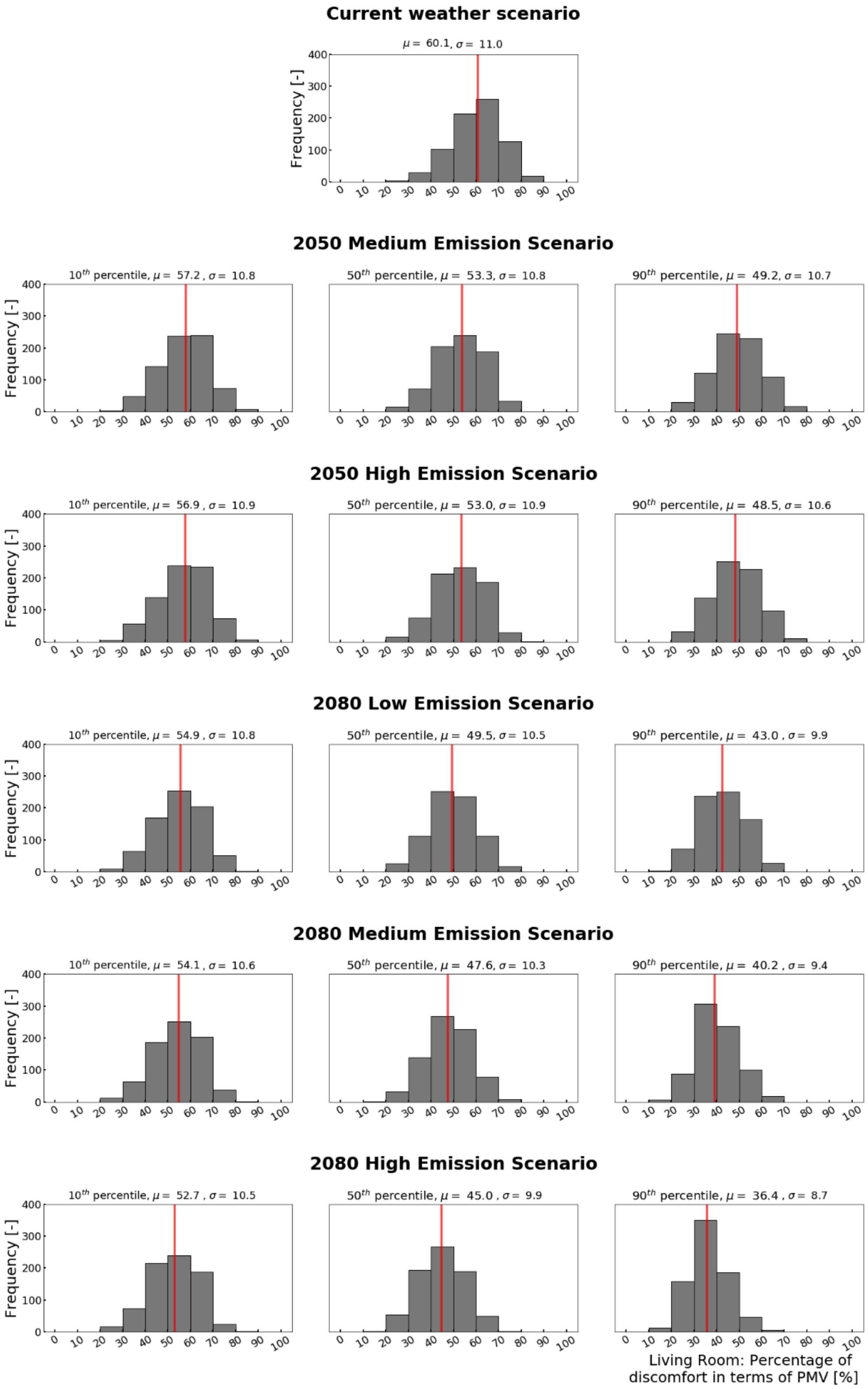



**Figure A- 7: Distribution of percentage of discomfort in terms of living-zone's PMV for the entire housing stock under current and various future weather scenarios (the red line depicts the median of each distribution)**

# APPENDIX B

INTERNATIONAL BUILDING SIMULATION ASSOCIATION ENGLAND

Proceedings of BSO 2018:
4th Building Simulation and Optimization Conference, Cambridge, UK: 11-12 September 2018

# The Heating Performance Of Air-Source-Heat-Pumps In The Retrofit Of Domestic Buildings

Paraskevi Vatougiou, Jonathan Wright, Dennis L. Loveday, Miaomiao He
School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK

## Abstract

The adoption of Air-to-Water Heat Pumps (AWHPs) is a promising retrofit strategy for reducing heating energy consumption and decarbonizing domestic heating in temperate climates. In this paper, an AWHP with supplementary electric heating has been employed as a retrofit heating strategy for 756 house archetypes, which have been selected to represent the housing stock of the North-East region of England. The objective of this study is to investigate the effectiveness of the AWHP system in terms of both the system's energy use and the extent to which the system has sufficient capacity to meet the space heating demand of the buildings. As a result of the study, the paper reveals that only 482 house archetypes (with their current level of thermal insulation) are eligible for the AWHP retrofit.

## Introduction

The exploitation of renewable resources is an imperative need for achieving UK's ambitious target of cutting down carbon emissions by 57% in 2030 and by at least 80% in 2050 (compared to 1990 levels) (Committee on Climate Change, 2017). The domestic sector is of particular interest for the UK Government mainly due to its poor energy performance and low uptake of renewables and thus the deployment of low-carbon heating technologies in residential buildings is being currently promoted by national policies and encouraged by legislative incentives, such as the domestic Renewable Heat Incentive (RHI) scheme, which provides income for the use of renewable technologies (Ofgem, 2018).

UK residential buildings account for 29 % of the total energy use and 36% of the total $CO_2$ emissions, while 80% of the total domestic energy is used for meeting their space and water heating demand. For the last four decades, 66% of heating energy has been provided by natural gas (Department for Business Energy & Industrial Strategy, 2017).

In this context, although the upgrade of building fabric and the integration of renewable technologies to existing residential building have been proved effective retrofit strategies, AWHPs could also contribute to the reduction of energy use and greenhouse gas emissions (Cabrol and Rowley, 2012). AWHPs are expected to be widely deployed in the UK within the next few decades and to play a significant role in the decarbonization of domestic heating. To meet the anticipated carbon budgets, the Committee on Climate Change (2017), suggests that around 2.5 million heat pumps should be installed in UK houses by 2030.

So far, AWHPs have had a limited uptake in the UK market compared to other European countries, mainly due to the severe weather conditions during winter months as their Coefficient of Performance (COP), reduces as the ambient temperature drops. In addition, while AWHPs have been found to be beneficial for new-built houses, the high heat demand of the existing UK dwellings limits the effectiveness of AWHPs and their potential for use in dwelling retrofit applications (Shah and Hewitt, 2015). Nevertheless, the monitored performance of 29 residential air-source-heat-pumps across the UK (installed in both new and existing houses) proved that heat-pumps have the potential to achieve an average COP of 2.45±0.11; this being highly dependent on the correct sizing and operation of the system (Dunbabin *et al.*, 2013).

Several studies have already focused on assessing the simulated performance of AWHPs in UK dwellings. Kelly and Cockroft (2011) employed an AWHP as a retrofit heating option for a domestic building located in Scotland and found that although $CO_2$ emissions reduced up to 12%, operational cost of the AWHP was approximately 10% higher compared to that of a gas boiler. However, the same authors stated that the introduction of the Governments "Renewable Heat Incentive" may balance this difference in energy consumption. Moreover, the coupling of AWHPs with suitable demand-side management strategies (load-shifting and feed-in electricity tariffs) has the potential to further improve the applicability of AWHPs and reduce electricity bills (Arteconi *et al.*, 2013). The assessment of a massive AWHP retrofit in the Canadian housing stock proved that energy consumption can be reduced up to 36%, if all eligible houses meet their space and hot water demand by an AWHP coupled with an auxiliary boiler (Asaee *et al.*, 2017).

The objective of this research is to investigate the extent to which the existing English housing stock can be retrofitted with AWHPs that supply energy for space heating alone (energy use associated with domestic hot water demand is not considered). The paper examines the performance of the heat-pumps without considering the extent to which the energy demand could be reduced by refurbishing the building envelope; this will be considered in future research. The novelty of this study lies in the number of houses studied using a dynamic thermal simulation, the models being automatically generated from a survey of real houses located in the UK.

## Methodology

A bottom-up housing stock energy model has been developed to investigate the extent to which AWHPs can be retrofitted to 756 house archetypes that have been selected to represent the housing stock of the North-East region of England. The same housing stock energy model has been used to evaluate the applicability of various retrofit strategies (upgrade of wall and loft insulation and replacement of single with double-glazed windows) in terms of cost and reduction of energy demand by assuming an *"ideal"* heating system with infinite capacity and 100% efficiency (He *et al.,* 2015). For the current study, an AWHP with a supplementary, capacity-limited, electric heater has been integrated to all the selected house archetypes to meet the space heating demand throughout the heating season. The viability of installing the AWHP heating system is evaluated from the AWHP energy use, the need for supplementary heating and the degree of underheating resulting from systems that have insufficient capacity to meet the heating demand of the buildings.

The main source of data for representing the housing stock is derived from the database of the Cambridge Housing Model (CHM) (2011, version), which is a domestic steady-state energy model for the UK, developed by Cambridge Architectural Research to support the UK Housing Energy Fact File (HEFF) and the Energy Consumption in the UK (ECUK) (Hughes *et al.,* 2013). The CHM dataset is constructed using data from the national English Housing Survey (EHS), which includes detailed information, such as age band, dwelling type, wall type, total floor area, etc., for 16,150 house archetypes selected to describe the entire UK housing stock (each house archetype is assumed to represent a specific number of "real" UK houses) (DCLG, 2013). The EHS data was "cleaned" to remove any inconsistent elements, run through suitable data converters and copied to excel worksheets to form the CHM dataset (Hughes *et al.,* 2013).

The level of detail provided by the CHM dataset offers the possibility to create detailed house models suitable to be studied with a dynamic simulation engine, which in the case of this research is EnergyPlus ($E^+$) (Crawley *et al.,* 2000). $E^+$ input data files (idf) are automatically generated for *each house archetype* located in the North-East region of England by using an in-house Building Generation Tool (BGT). The BGT is a software developed in C# programming language that reads three different text files (the content of which is described below), and directly creates $E^+$ input files. The idf creation is done separately for those house archetypes that have the same number of storeys (the selected house archetypes have up to three storeys). The number of storeys determines the number of thermal zones in each house archetype.

The first text file used by the BGT includes selected data that are copied from the CHM and EHS datasets (each row represents one house archetype), such as the dwelling type, number of storeys, total wall, floor and window area, type of constructions, glazing type, etc. These data are processed through the C# code to mainly generate the geometry of each house archetype, distribute the windows and doors to the building envelope, create constructions for exposed-walls, floors, roof, etc., based on reasonable assumptions (which are explained in the following section of this paper). The second text file is a template, that contains $E^+$ objects, which are common for all the house archetypes (independently of the number of storeys of each house archetype), such as operating and occupancy schedules, simulation parameters, output variables, etc. The third text file contains all the zone-dependent $E^+$ objects, mainly associated with the HVAC system; the number of objects depending on the number of zones. For each house archetype, the $E^+$ objects created by the process of the first text file plus the $E^+$ objects included in the second and third text files are put together by the BGT and form a new text file that includes all the required information and can be simulated through the $E^+$ simulation engine.

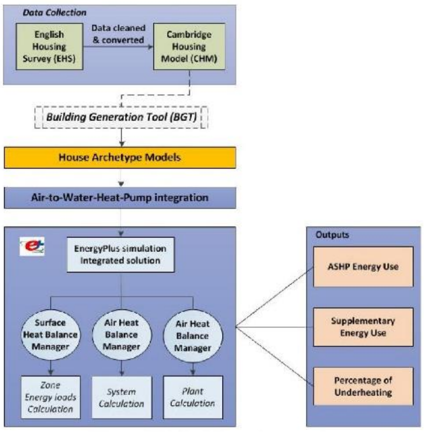



*Figure 1: Methodological approach.*

The following section gives an insight on how the CHM (and EHS) data was used and what further assumptions were required to be made by the BGT to create representative house models.

### Housing stock

The modelled housing stock for this study consists of 756 house archetypes representing 978,490 *real* houses located in the North-East region of England (flats and empty dwellings are excluded from the current research). The housing stock is simulated by using the UK's

Chartered Institution of Building Services Engineers Test Reference Year (CIBSE TRY) weather file for Newcastle, England, this being the closest available location representing the climatic conditions of the North-East region of England (CIBSE, London, UK).

The survey and modelled houses cover a wide variation in size, type (detached, semi-detached, mid or end-terrace), infiltration rate level, age of construction, the age in particular resulting in a wide range of wall and loft constructions and states of repair. However, the CHM database does not include detailed information on the geometry of the houses, which is a required input for performing dynamic E⁻ simulations. For this reason, the dimensions of external walls were extracted from the original EHS datasets and used by the BGT simulation file creator to generate the shape of the selected house archetypes. All houses are assumed to be either rectangular or L-shaped (for simplicity reasons, the additional rectangle of the L-shaped house archetypes was assumed to be attached in the right-back side of the main rectangle) (He *et al.,* 2014). The ground floor of each house archetype has been divided into two different zones, one living and one non-living, while each additional upper floor is assumed as a separate non-living zone (Anderson *et al.,* 2008). This means that all the one, two and three-storey buildings have two, three and four zones, respectively. The *living* ground-floor zone contains only the living-room, the width and depth of which were also extracted from the original EHS datasets.

As mentioned, the wall, floor and roof type as well as the thickness of the loft insulation (if present), are specified for each house archetype in the CHM dataset. However, the particular materials and their thermal properties, are unknown for each construction. This issue was resolved by using recommendations given by the UK government for the U-value of various wall, roof, floor and loft construction types based on the age band of the house (DECC, 2012). Thus, the construction type recorded in the CHM dataset (e.g. "filled-cavity") and the recommended U-values from DECC (2012), were used as indicators to assign the particular material layers and thermal properties for each house archetype based on its age band (He *et al.,* 2014).

Figure 2, illustrates the simulated U-values for exposed-walls based on the age band and the exposed-wall construction type reported in the CHM database. The colour of each box indicates the total number of house archetypes found in each separate category. The term "System Built" shown in Figure 2, refers to non-traditional constructions built through some type of systemized process (not built on construction site) and consists of 200m heavy concrete blocks (BRE, 2014).

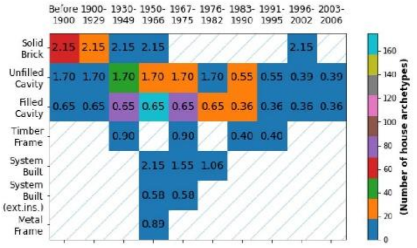



*Figure 2: Exposed-wall U-value (W/m² k) and total number of house archetypes per age band and construction type.*

House archetypes have been categorized based on the U-value of their exposed-walls, total conditioned floor area and dwelling type (Figure 3). Semi-detached and end-terrace houses are treated as one category, as their building envelope is similarly exposed to the outside environment (similar surface-to-volume ratios) and consequently, when built at same standards and have similar sizes, it is expected that they present similar fabric heat losses.

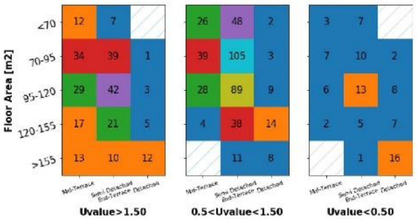



*Figure 3: Total number of house archetypes per dwelling type, range of floor area and exposed-wall U-value. House archetypes with U-value>1.50 W/m² k have no wall insulation.*

It is evident from Figure 3, that there is a significant variation in the number of houses across the sub-categories (ranging from 1 house to a 105 houses). The variation, and in particular, the sub-categories having a low number of houses, suggests that a strictly statistical comparison of the AWHP performance between categories would not be possible. For the purposes of this paper, any comparison of results between different sub-categories is justified through consideration of engineering principles (for instance, as the U-value and floor area increase, it would be expected that the annual heating energy demand would also increase).

### Integration of an AWHP heating system in the housing stock

The heating system modelled for each house archetype is an electrically-driven AWHP with supplementary electric heating, and with both the heat-pump and electric heater being connected to a storage water tank. More specifically, the total water heating energy produced by the AWHP coil is stored to the water tank through which energy is transferred to the heating distribution system of the house, (with the room heaters being modelled as convective baseboard heaters). Although, it is well known that heat pumps are much more effective when serving low inertia distribution heating systems, such as underfloor heating systems or larger low temperature radiators, the common practice in domestic retrofit applications is to integrate the heat pump in the existing distribution heating system, which in the majority of UK houses is high temperature radiators (Singh *et al.*, 2010).

### AWHP characteristics

The modelled AWHP unit contains an evaporator heat exchanger, which is an outdoor coil used to extract heat from ambient air, a condenser water heating coil, a compressor and a water pump, this is modelled to cycle on and off with the compressor. The compressor is controlled to operate only when ambient temperature is above 5°C to prevent the AWHP from operating under severe weather conditions. More specifically, when ambient temperature is lower than 5°C, there is high possibility of frost formation on the evaporator side of the AWHP, this significantly deteriorates the performance of the system (Changqing and Liang, 2006). In real installations, AWHPs perform defrost/reverse cycles when ambient temperature is low. In a defrost cycle, the operation of the evaporator and condenser heat exchangers are reversible, and this means that heat is extracted from the condenser to defrost the evaporator coil (Huang and Hewitt, 2013). However, the defrost operation of the AWHP has not been considered in this study and the lowest limit of the ambient temperature below which the compressor stops operating (5°C) has been established as a "*frost protection*" technique.

Several AWHP systems that are available in the UK market have been reviewed. The characteristics of the *Vitocal 300-A* AWHP system in terms of nominal heating capacity and COP and performance curves have been used in this study (Viessmann, 2012). Models with similar characteristics were also used in previous studies and considered suitable for typical UK domestic applications (Kelly and Cockroft, 2011). The nominal heating capacity and COP of the AWHP are modelled to vary with the dry-bulb temperature of the air entering the evaporator coil and the temperature of the water entering the condenser coil based on 2$^{nd}$-order polynomial performances curves derived from the manufacturer's technical brochure (Viessmann, 2012). As the fan of the system is assumed to be located outdoors, the temperature of the air entering the evaporator coil is modelled to be always equal to the outdoor dry-bulb temperature. The characteristics of the modelled AWHP is presented in the Table 1. It should be noted that this study considers that the retrofitted AWHP system has the same nominal capacity in all the selected house archetypes independently of their design heating load; matching of the heat-pump's capacity to the peak heating load of each house archetype will be considered in a future study.

### Water heater tank

The supplementary heater located in the water heater tank has a maximum capacity of 3.0 kW and operates as a secondary heat source. The tank is modelled as perfectly insulated (no parasitic or on and off-cycle losses were considered).

### Control of the AWHP system

The heat-pump is the main heat source, while the supplementary heater located inside the tank provides additional heat when needed. The heat-pump and electric tank water heater operation are controlled using an ON-OFF control strategy, with the operation of the two devices being separated by their control setpoints and control differentials. In addition, the frost protection strategy prevents the heat-pump being operated when the ambient temperature falls below 5.0°C. Figure 4, illustrates the system controls, with the heat-pump having a setpoint temperature of 65.0°C and the tank electric heater of 60.0°C; both devices operate with a control differential of 2.0°C. This strategy results in three possible system operating modes: heat-pump only operating; heat-pump and electric heater operating; electric heater only operating. Figure 4, illustrates these scenarios.

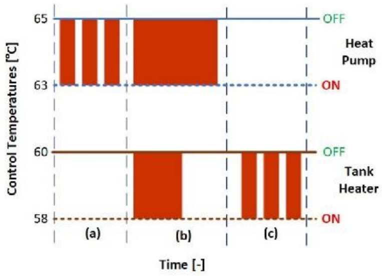



*Figure 4: Representation of system's controls and operational modes.*

During operating period (a) the energy demand is low enough for the tank temperature to be maintained (between 63°C and 65°C), by cycling the heat-pump operation alone. Operating period (b) illustrates the case where the energy demand has resulted in the tank temperature falling below the system "ON" temperature (of 58.0°C) for the electric heater. Provided that the ambient temperature is above the frost limit of 5.0°C, the heat-pump will also be "ON" (since its "ON" temperature is also higher than the tank temperature). Both the electric heater and heat-pump would operate until the tank temperature rises above the 60.0°C setpoint of the electric heater, at which point, the heater would be turned "OFF"; the heat-pump would continue to operate alone until the tank temperature reached its setpoint of 65.0°C. The operating period (c), illustrates the case where the ambient temperature is below 5.0°C, and so the tank temperature is maintained (between 58.0°C and 60.0°C), by the electric heater alone.

Although the electric tank heater has a lower setpoint than the heat-pump, control strategy can result in significant use of the electric heater, particularly when the ambient conditions result in long periods of ambient temperature below the frost protection limit of 5.0°C, or where the energy demand is high and ambient temperature limits the output of the heat pump. Extensive use of the electric heater will reduce annual coefficient of performance (COP) for the whole system (the system COP being a function of not only the heat pump operation, but also the use of the electric heater, and the impact of the energy remaining in the storage tank).

*Table 1: Characteristics of the AWHP system*

| | |
|---|---|
| **Rated heating capacity, $Q_{nominal}$** | 8.6 kW |
| **Rated COP, $COP_{nominal}$** | 3.90 |
| [1] **Heating Capacity Performance Curve** | $Q = Q_{nominal} * (0.75+0.025x-0.00008x^2-0.0034y+0.00005y^2-0.0002xy)$ (1) |
| [1] **COP Performance Curve** | $COP = COP_{nominal} * (2.1+0.05x-0.00014x^2-0.028y+0.0001y^2-0.0007xy)$ (2) |
| [2] **Crankcase heater capacity** | 55 W |
| **Maximum heating capacity of the supplementary heater** | 3 kW |
| **Supplementary heater's efficiency** | 0.95 |

**Heating pattern**

Heating duration and demand temperatures will be applied to all house archetypes based on UK Government calculation recommendations (Henderson and Hart, 2013). This means that living-rooms are heated at 21°C from 7:00 to 9:00 and from 16:00 to 23:00 during weekdays and from 07:00 to 23:00 during weekends, while all other rooms are heated at 18°C from 07:00 to 09:00 and from 18:00 to 23:00 during weekdays and from 7:00 to 9:00 and from 14:00 to 23:00 during weekends.

**Simulations**

Having generated the simulation input files for all house archetypes, the $E^+$ simulations are run using the JEPlus tool (Zhang, 2009). The recent version of JEPlus offers the possibility to call Python scripts for post-processing of the $E^+$ simulation results, this being the approach adopted in this study.

## Results and discussion

The performance of the retrofitted AWHP system is assessed in terms of the number of occupied hours that the room setpoint has not been reached ("underheating"); the water tank temperature; the number of hours that the heat-pump cycles-on throughout the heating season, this is particular used to assess the conditions under which the system operates; the heat-pump's energy use and the need for supplementary heating. The results are presented as average values for various house categories; the categorization is based on exposed-wall insulation levels, total conditioned floor area and dwelling type as illustrated in Figure 3.

**Level of underheating**

The level of underheating for each house archetype is defined as the total number of hours throughout the heating season (from October to April included), where the zone temperature is lower than 0.5°C below the selected heating set-point temperature in one or more zones. Figure 5, indicates that the annual number of underheating hours increases as the floor area increases, the level of insulation in the exposed-walls reduces and the house becomes "more detached". To identify which of these house archetypes are eligible for the AWHP retrofit based on the level of underheating, a limit should be imposed to the acceptable percentage of underheating hours throughout the year.

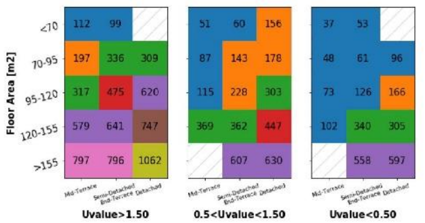



*Figure 5: Average annual number of underheating hours per various house categories.*

[1] x: temperature of the air entering the evaporator coil, y: temperature of the water entering the condenser coil

[2] Crankcase heater is an electric device located in the compressor that operates when the compressor is off, and the ambient temperature is below 10°C (user-defined). It prevents the refrigerant from mixing with the compressor oil (when the compressor is off) and migrating to the coldest parts of the system under low ambient temperatures.

British Standards implies that operative temperature should not be less than 18°C in the living spaces (living-rooms, bedrooms, etc.) of existing buildings (EN15251, 2007). However, to the extent of authors' knowledge, there is no further guideline imposing a maximum acceptable percentage of underheating hours for UK domestic buildings (as this exists for overheating). ASHRAE Standard 90.1-2007 (Appendix G) uses the term *unmet load hours*, which are defined as the hours throughout the year that the HVAC system serving a space cannot maintain the required set-point temperature (heating or cooling) and states that these hours should not exceed 300 out of the total (8760h) when designing an HVAC system (Calm *et al.*, 2007).

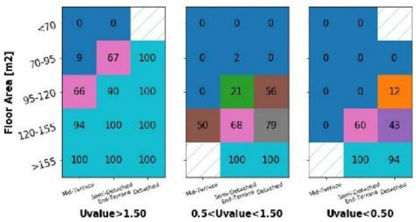



*Figure 6: Percentage of house archetypes with more than 300 hours of underheating per various house categories.*

Results show that 284 out of 756 simulated house archetypes present underheating for more than 300 hours throughout the heating season. More specifically, as shown in figure 5, for almost all the house categories with floor area higher than 155 m$^2$, the underheating hours exceed 300 throughout the heating season, even for those with relatively high levels of exposed-wall insulation (U-value<0.50). It should be noted that the results presented in this paper are restricted to the selection of the specific AWHP system, the heating capacity and control of which is the same for all house archetypes. Those houses for which the current system has insufficient capacity to meet their heating demand, the viability of heat-pump systems with higher nominal capacities will be investigated in future research. Figure 6, also indicates that the performance of the selected house archetypes may vary even for houses lying in the same category.

Figure 7, reports the average annual water tank temperature per various house categories; this has been reported for each house archetype as the average water tank's temperature throughout the heating season only for the periods that the heating system is scheduled to be on.

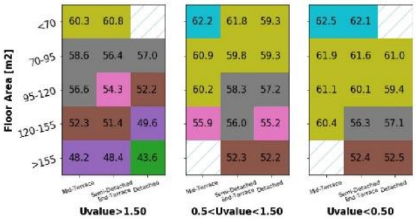



*Figure 7: Average annual water tank temperature per various house categories.*

The main reason for maintaining the hot water tank's temperature around 60°C is to prevent the growth of Legionella bacteria in the bottom of the water tank. The World Health Organisation (WHO) reports that Legionella does not survive in temperatures above 60°C, while it multiplies in temperatures ranging from 20 to 45°C (McDade, 2008). As seen, the water tank's temperature is no lower than 60°C for almost all the house categories that were found to present less than 300h of underheating annually.

**Performance of the AWHP system**

Figures 8 and 9, report the average AWHP and supplementary energy use per various house categories, respectively. It should be noted that the heat-pump's energy use includes the energy consumption of the crankcase heater, which has been simulated to operate when the heat-pump's compressor cycles-off. As shown, the supplementary energy use is higher than the heat-pump's energy use for all house archetypes. For systems with sufficient AWHP capacity to meet the demand of the house, the supplementary heater is mainly operating due to the "frost protection" limit, this switches-off the compressor of the heat-pump when ambient temperature drops below 5°C (the total heating hours with ambient air temperature less than 5°C are equal to 806 for the weather file used in this paper). On the other hand, when the nominal heating capacity of the heat-pump is not sufficient to meet the heating demand, the supplementary heater is on for longer periods to top-up the energy delivered by the heat-pump.

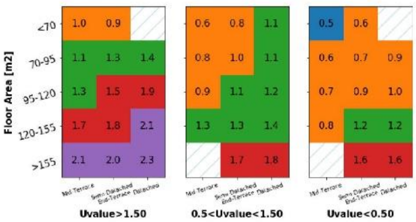



*Figure 8: Average annual AWHP energy use (MW) per various house categories.*

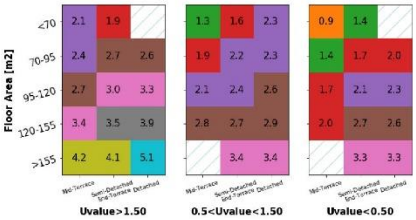



*Figure 9: Average annual supplementary heater's energy use (MW) per various house categories.*

Figure 10, compares the hourly performance of the retrofitted AWHP system in two different house archetypes during three consecutive working days in January. *House 1* is a mid-terrace house with floor area less than 70m² and U-value<0.5, while *House 2* is a detached house with floor area more than 155m² and uninsulated exposed-walls. It should be clarified that this comparison is only presented as an example demonstrating the hourly patterns of the water heating rate delivered by the AWHP and the supplementary heater as well as the relationship between heat-pump's actual and maximum heating capacity when the system is operating under part-load and full-load conditions. Thus, the results shown in Figure 10 cannot be used to draw conclusions regarding the required size of the heat-pump for each house as the water heating rates do not refer to the maximum values throughout the heating season, this will be considered in future research.

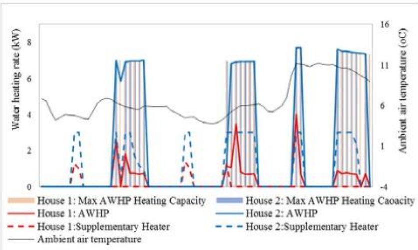



*Figure 10: Example of AWHP's system operation in house archetypes with different characteristics during three working heating days.*

The hourly run-time fraction of the heat-pump is defined as the ratio of the *actual* water heating rate delivered by the heat-pump to the heat-pump's *maximum* heating capacity, the latter is the heat-pump's heating capacity under full load operation and is estimated using Equation 1 presented in Table 1. Thus, when the heat-pump's maximum heating capacity exceeds the hourly heating demand, its run-time fraction is lower than 1.0, meaning that the heat-pump operates under part-load conditions (*House 1*). On the other hand, when the heat-pump's maximum heating capacity is either equal or less than the hourly heating demand, the heat-pump cycles-on continuously and its run-time fraction equals to 1.0 (*House 2*). Generally, to avoid oversizing, the system should operate close to full-load conditions for as long as possible throughout the heating season.

Figure 11, illustrates the average annual number of hours that the AWHP cycles-on per various house categories, this has been reported for each house archetype as the sum of the hourly AWHP run-time fractions throughout the heating season.

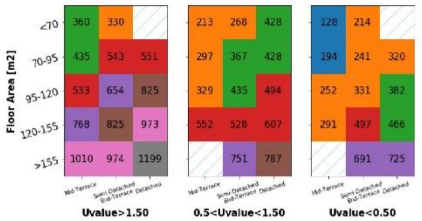



*Figure 11: Annual number of hours that the AWHP cycles-on per various house categories.*

The graph indicates that the total AWHP operation time increases as the floor area and the exposed-wall U-value increase and the house becomes "more detached". The fact that some house categories present a low number of heat-pump's operation hours could imply that the retrofitted AWHP is oversized and runs for most of the heating season under part-load conditions. Generally, oversized AWHPs that perform very short cycling are reported to present increased peak-load demands and reduced overall efficiency (Madonna and Bazzocchi, 2013). On the other hand, undersized heat-pump units increase underheating and could result in an excessive use of the supplementary heater to meet the demand. Thus, even if the retrofitted AWHP system can sufficiently maintain comfort to accepted levels for some house archetypes, the selection of AWHP's size should be revised.

## Conclusions

An air-to-water-heat-pump with supplementary electric heating has been integrated in 756 house archetypes, which have been selected to represent the housing stock of the North-East region of England. The selected houses have been simulated throughout the heating season and results have shown that only 482 are eligible for the AWHP retrofit in terms of underheating. Moreover, results have shown that heat-pump's energy use, supplementary energy use and underheating hours increase as the total floor area and exposed-wall U-value increase and the house becomes more detached. Finally, the annual duration of heat-pump's operation significantly varies between the selected house archetypes. It should be noted that the results presented in this paper are restricted to the selected heating system, the characteristics and controls of which are considered the same for the entire housing stock. Further research and analysis is required to apply a more sophisticated heat-pump sizing method based on the peak heating load of each house archetype. The extent to which heat-pump energy use can be reduced for houses that have been found *eligible* for the AWHP retrofit in this research and the extent to which the integration of heat-pumps with higher nominal heating capacities can reduce underheating in houses that have been found as *ineligible* for the AWHP retrofit, should be further investigated.

## References

Anderson, B., Chapman, P.F., Cutland, N.G., Dickson, C.M., Doran, S.M., Henderson, G., Henderson, J., Kosmina, L., and Shorrock, L.D., 2008. *BREDEM-8 Model Description 2001 update*. London: Watford: DEFRA.

Arteconi, A., Hewitt, N.J., and Polonara, F., 2013. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering*, 51 (1–2), 155–165.

Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I., 2017. Techno-economic feasibility evaluation of air to water heat pump retrofit in the Canadian housing stock. *Applied Thermal Engineering*, 111, 936–949.

BRE, 2014. *SAP 2012 The Government ' s Standard Assessment Procedure for Energy Rating of Dwellings*. Energy.

Cabrol, L. and Rowley, P., 2012. Towards low carbon homes – A simulation analysis of building-integrated air-source heat pump systems. *Energy and Buildings*, 48, 127–136.

Calm, J.M., Hanson, S.S., Marriott, C.E., Amrane, K., Higa, R.T., Hogan, J.F., Baselici, P. a, Beaty, D.L., Conrad, E. a, Lane, M.D., Cottrell, C.C., Crane, R., Lord, R., Deringer, J.J., Luther, K., Emerson, K.I., Majette, R., Fraser, A., Mcbride, M.F., Garrigus, J. a, Montgomery, J., Weitz, D., Wilson, R., and Woodford, M.W., 2007. ASHRAE STANDARD Energy Standard for Buildings Except Low-Rise Residential Buildings. *Society*, 8400, 404–636.

Changqing, T. and Liang, N., 2006. State of the Art of Air-source Heat Pump for Cold Regions. *Renewable Energy Resources and a Greener Future*, VII-12-5, 1–6.

Committee on Climate Change, 2017. *Meeting Carbon Budgets: Closing the policy gap*.

Crawley, D.B., Pedersen, C.O., Lawrie, L.K., and Winkelmann, F.C., 2000. EnergyPlus: Energy Simulation Program. *Ashrae*, (April), 49–56.

DCLG, 2013. *English Housing Survey HOMES 2011*.

DECC, 2012. RdSAP 2009 version 9.91. Appendix S : Reduced Data SAP for existing dwellings. *The Government's Standard Assessment Procedure for Energy Rating of Dwellings*, 91 (January).

Department for Business Energy & Industrial Strategy, 2017. *Energy Consumption in the Uk*.

Dunbabin, P., Charlick, H., and Green, R., 2013. *Detailed analysis from the second phase of the Energy Saving Trust's heat pump field trial*.

EN15251, 2007. *Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics*. European Commission and the European Free Trade Association. Brusells.

He, M., Brownlee, A., Lee, T., Wright, J., and Taylor, S., 2015. Multi-objective optimization for a large scale retrofit program for the housing stock in the North East of England. *Energy Procedia*, 78 (0), 854–859.

He, M., Lee, T., Taylor, S., Firth, S.K., and Lomas, K.J., 2014. Dynamic modelling of a large scale retrofit programme for the housing stock in the North East of England. *In: Proceedings of the 2nd International Conference in Urban Sustainability and Resilience*.

Henderson, J. and Hart, J., 2013. BREDEM 2012 – A technical description of the BRE Domestic Energy Model BREDEM 2012.

Hughes, M., Palmer, J., and Pope, P., 2013. *A Guide to The Cambridge Housing Model*.

Kelly, N.J. and Cockroft, J., 2011. Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data. *Energy and Buildings*, 43 (1), 239–245.

Madonna, F. and Bazzocchi, F., 2013. Annual performances of reversible air-to-water heat pumps in small residential buildings. *Energy and Buildings*, 65, 299–309.

McDade, J.E., 2008. *Legionella* and the Prevention of Legionellosis. *Emerging Infectious Diseases*, 14 (6), 1006a–1006.

Ofgem, 2018. *The Renewable Heat Incentive Scheme Regulations 2018*.

Shah, N. and Hewitt, N., 2015. High temperature heat pump operational experience as a retrofit technology in domestic sector. *In: EEE International Conference on Engineering, Technology and Innovation/ International Technology Management Conference (ICE/ITMC)*. Belfast, 1–7.

Singh, H., Muetze, A., and Eames, P.C., 2010. Factors influencing the uptake of heat pump technology by the UK domestic sector. *Renewable Energy*, 35 (4), 873–878.

Viessmann, 2012. VITOCAL-Technical Guide.

Zhang, Y., 2009. 'Parallel' EnergyPlus and the Development of a Parametric Analysis Tool. *Eleventh International IBPSA Conference*, 1382–1388.