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Towards NetZero Cities: Mixed Methods Approach for Investigating the Challenges of the Decarbonisation of Heating and Transportation in Urban Environments

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Abstract

The UK's commitment to achieving net-zero carbon emissions by 2050 has driven a national shift towards the electrification of heating and transport sectors, with heat pumps (HPs) and electric vehicles (EVs) playing a pivotal role. However, the mass adoption of these technologies presents significant challenges, particularly concerning the capacity and stability of the national electricity grid. This thesis investigates the potential impacts of large-scale deployment of HPs and EVs on the UK grid, alongside exploring the technical performance of HPs across different housing types and insulation levels, as well as the public's awareness and acceptance of this technology; with focus on defrost cycles of the heat pumps from the technical aspects.

To address these challenges, a test rig for air source heat pump (ASHP) was constructed and used to validate a Simulink model, enabling the simulation of ASHP performance under varying conditions, such as house types and insulation standards. The research then extends to an exploration of user experience through two case studies with heat pump users and a public questionnaire aimed at understanding the awareness and perceptions surrounding HP technology. This comprehensive approach highlights the technical, behavioural, and socio-economic factors that influence HP adoption.

Another case study of the Nottingham Ice Centre evaluates the use of HPs and thermal storages for heat recovery, assessing their potential as a potential alternative to district heating in large-scale commercial environments. The findings from this case study suggest that HPs can significantly reduce reliance on district heating, however, at the cost of increased electricity consumption. Whereas with the use of thermal storages, the reliance on district heating will not be eliminated but it would aid in reducing energy cost for commercial buildings. This demonstrates HPs and thermal storages' potential in diverse applications beyond residential use.

Finally, the thesis undertakes an extensive simulation to explore the combined effects of EV adoption on the UK's national grid. Results indicate that while the grid could handle the initial phases of electrification at current adoption rate, however significant upgrades, including advanced demand-response systems and energy storage solutions, will be required to maintain grid stability during peak demand periods, particularly in winter.

In conclusion, this thesis provides critical insights into the technical and infrastructural challenges of HP and EV adoption in the UK. It emphasises the importance of grid modernisation, enhanced public awareness, and targeted policy interventions to ensure that the nation's net-zero goals can be achieved without compromising grid reliability or energy affordability.

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Declaration

I hereby declare that this thesis is submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy (PhD) from Nottingham Trent University (NTU) and is entitled "***Towards NetZero Cities: Mixed Methods Approach for Investigating the Challenges of the Decarbonisation of Heating and Transportation in Urban Environments***". All ethics procedures and guidelines have been followed in the preparation of this thesis.

The listed publications (Page VI) play a significant role in supporting various chapters of the thesis, providing both conceptual and technical contributions.

The article:

[*Milev, G., Al-Habaibeh, A., Fanshawe, S., Siena, F. L. (2023) 'Investigating the effect of the defrost cycles of air-source heat pumps on their electricity demand in residential buildings', Energy and Buildings, 300, p. 113656. https://doi.org/10.1016/j.enbuild.2023.113656*.]

is linked to Chapters 4 and 5 of the thesis. This publication provides technical data about defrost cycles in heat pumps, which directly informs the technical analysis in Chapter 4 on heat pumps power consumption. Chapter 5 builds on these insights to explore grid demand fluctuations due to defrost cycles, emphasising their broader impact on energy infrastructure and grid strain.

The paper:

[*Milev, G., & Al-Habaibeh, A. (2023). The 'Mousetrap': Challenges of The Fluctuating Demand on The Electricity Grid in The UK. In Energy and Sustainable Futures: Proceedings of the 3rd ICESF, 2022. Coventry University & Doctorial Training Alliance (DTA).*]

aligns with Chapter 9, which investigates the challenges of managing energy demand due to increasing electrification, including the introduction of electric vehicles and heat pumps. This work provides a conceptual foundation for understanding the dynamics of grid demand and supports the analysis of managing peak loads during winter, as discussed in Chapter 9.

The publications focusing on electric vehicles (EVs), namely

[*Milev, G., Al-Habaibeh, A., & Shin, H. D. (2020). Impact of Replacing Conventional Cars with Electric Vehicles on UK Electricity Grid and Carbon Emissions. In International Conference on Energy and Sustainable Futures (ICESF2020). University of Hertfordshire & University Alliance DTA in Energy.*]

and

[*Milev, G., & Al-Habaibeh, A. (2020). "If all cars were electric, UK carbon emissions would drop by 12%". The Conversation. Available at: https://theconversation.com/if-all-cars-were-electric-uk-carbon-emissions-would-drop-by-12-139155*.]

are directly tied to Chapter 9 as well. These papers offer critical data for evaluating the environmental and infrastructural implications of transitioning to EVs in the UK. The technical evaluations within these works contribute to the quantitative analysis in Chapter 9 regarding the UK's electricity demand and carbon emissions, providing insights into both the benefits and challenges of large-scale EV adoption.

Finally, the paper related to the Scottish case study on EVs and the grid,

[*Milev, G., Hastings, A., & Al-Habaibeh, A. (2020). The environmental and financial implications of expanding the use of electric cars - A Case study of Scotland. Energy and Built Environment.* *https://doi.org/10.1016/j.enbenv.2020.07.005* *(partially related).*]

which is partially related, also informs Chapter 9. In this paper, in relation to this PhD work, a new novel method of using infrared thermography and temperature sensors to estimate the energy needed to heat the cars during winter and their effect on the range of vehicles is presented. This work is expanded in this thesis to include the UK on national level.

Each publication offers both technical and conceptual contributions that enrich the analysis within the relevant thesis chapters.

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Abbreviation list

A – Amperes

AC – Alternate Current

ACH – Air Changes

ALCA – Attributional Life Cycle Assessment

ASHP – Air source heat pump

BREDEM – Building Research Establishment Domestic Energy Model

BS EN – British Standard European

CAN Bus – Controller Area Network Bus

CAN-I/O45 – Controller Area Network (Input and Output; model 45)

CCS – Carbon Capture and Storage

CFC – Chloro-Fluoro-Carbons

CGB – Combined Gas Boiler

CI – Confidence Interval

CLCA – Consequential Life Cycle Assessment

CLT – Central Limit Theorem

CMI – Control Monitoring Interface

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

COP – Coefficient of Performance

COVID-19 – Coronavirus Disease

DC – Direct Current

DH – District Heating

DL-Bus – Data Line Bus

DTA – Doctoral Training Alliance

EIA – Energy Information Administration

EV – Electric vehicle

FC – Fluorocarbons

FLIR – Forward Looking Infrared

GBP – Great British Pound

GHG – Greenhouse Gas

GSHP – Ground Source Heat Pump

GW – Gigawatt

GWh – Gigawatt hour

GWP – Global Warming Potential

HC – Hydrocarbons

HCFC – Hydro-Chloro-Fluoro-Carbons

HFC – Hydro-Fluoro-Carbons

HP – Heat pump

HVAC – Heating, Ventilation, and Air Conditioning

ICESF – International Conference on Energy and Sustainable Futures

ISO – International Organisation for Standardisation

kW – Kilowatt

kWh – Kilowatt hour

LCA – Life Cycle Assessment

LCD – Liquid Crystal Display

LPA – Liquid Pressure Amplification

LPG – Liquified Petroleum Gas

M-Bus – Meter Bus

MW – Megawatt

MWh – Megawatt hour

NIC – National Ice Centre

NO_x – Nitric Oxide

NTU – Nottingham Trent University

ODP – Ozone Depletion Potential

ORC – Organic Rankine Cycle

PC – Personal Computer

PCM – Phase Change Material

PV – Photovoltaic

PVGIS – Photovoltaic Geographical Information System

RH – Relative Humidity

RHI – Renewable Heat Incentive

SCOP – Seasonal Coefficient of Performance

SI – International System of Units

STDEV – Standard Deviation

TW – Terawatt

TWh - Terawatt hour

UK – United Kingdom

US – United States

UVR – Universal Controller

V – Voltage

V2G – Vehicle to Grid

VI – Vapour Injection

VIS – Vapour Injection using injected sub-cooling

Nomenclature

%Difference – percentage difference between heat output and thermal energy demand by NIC per month (unitless)

$\%EVP_{power}$ - percentage of the heat pump evaporation power (%)

ε_{hot} – emissivity of glass (0.93) and iron/aluminium (0.29) (unitless)

3.8054 - convection heat transfer coefficient ($W/m^2.K$)

333.55 - heat fusion of ice (kJ/kg)

A – Area (m^2)

ACH - air change rate per hour (unitless)

ADT – Annual distance travelled (km)

A_{evp} - heat exchanger area (m^2)

A_{ts} - area of the thermal storage (m^2)

c - specific heat capacity of the air inside the car ($J/kg.^oC$)

C_{hlc} – Total contribution of heat loss coefficient (W)

CI – Carbon intensity ($kgCO_2/km$)

CO_2 – Carbon emissions ($kgCO_2$)

COP – Coefficient of Performance (unitless)

Cp_{water} – Specific heat capacity of water (4.18 kJ/kg.K)

DH – Thermal energy required by district heating (kW)

$DHtC_{year}$ – District heating energy required per year (kWh)

dT/dx – Temperature gradient (K/m)

E - energy required to reach the desired temperature (J)

Em – Carbon emissions (kg)

ES – Energy produced by electricity source (kWh)

h – convective heat transfer coefficient ($W/m^2.K$)

h_1 – Inlet enthalpy of the evaporator (kJ/kg)

h_2 – Outlet enthalpy of the evaporator (kJ/kg)

h_3 – Outlet enthalpy of the compressor (kJ/kg)

h_4 – Outlet enthalpy of the condenser (kJ/kg)

$Heat_{reject}$ - rejected heat from cooling tower (MWh)

HP COP – Heat pump coefficient of performance (unitless)

$HP_{electricity}$ - electricity required by each heat pump per month (MWh)

$HP_{electricity\ cost}$ – Energy cost to run each heat pump per month (£/month)

$HP_{EvpPower}$ - evaporation power of the proposed heat pumps (kW)

$HP_{heat\ out}$ - heat output (MWh)

HR – Humidity ratio (kg/kg)

k – Thermal conductivity of materials (W/m.K)

m – mass (kg)

$\dot{m}$ - Refrigerant mass flow rate (kg/s)

m_{ice} - mass of frost layer (kg)

$NIC_{heat\ demand}$ – National Ice Centre heat demand per month (MWh)

P - thermal power loss through convection and radiation in (W/m^2)

P_{com} – Compressor power (kW)

P_{comp} - compressor power rating (kW)

P_{sh} - power demand for space heating (kW)

Q – Volumetric flow rate (l/s)

Q_c – Condenser heat capacity (kW)

Q_{cond} – Heat transfer through conductivity (W)

Q_{ev} – Evaporator heat capacity (kW)

Q_{HPout} - heat output capacity of the heat pump (kW)

Q_{hw} - heat required for the hot water in thermal storage (kWh)

$Q_{ice\text{-}rem}$ - heat needed to remove ice deposition on the outdoor unit (kWh)

Q_r - recommended hot water tank thermal capacity (kW)

Q_{rad} – Heat transfer by radiation (W)

$Q_{removeIce}$ - heat needed to remove the ice build-up on the outdoor unit (kJ)

S_a - evaporator air velocity (m/s)

T – Temperature (K)

t - time of frost accumulation (s)

T_∞ is the temperature of the surroundings (K)

T_c – Initial temperature (^{o}C)

T_d – Desired temperature (^oC)

T_i – Surface temperature (K)

T_{out} – Ambient temperature (K)

T_s is the surface temperature of the object (K)

TtC_{day} – Times to charge thermal storage per day (unitless)

TtC_{year} – Times to charge thermal storage per year (unitless)

TTE – Time to heat thermal storage (min)

TTE_{hr} – Time to heat thermal storage (hours)

U – heat transfer/loss coefficient ($W/m^2.K$)

U_{ts} - U-value of the thermal storage ($W/m^2 \cdot K$)

V – Volume (m^3)

V_h - house volume (m^3)

V_{hx} - outdoor heat exchanger volume (m^3)

V_{ice} - the volume of the ice layer (m^3)

V_{sp} - refrigerant specific volume (m^3/kg)

V_{Sw} – Compressor swept volume (m^3/h)

V_{Sw1} – Swept volume per second (m^3/s)

V_{ts} - volume of thermal storage (m^3)

δ_{ice} – Frost accumulation (m^3)

ΔT - the temperature difference (K)

ϵ - Emissivity of materials (dimensionless, ranges from 0 to 1)

ϑ - wind speed (m/s).

ρ – Density (kg/m^3)

ρ_{air} - air density (kg/m^3)

ρ_{ice} - the density of the ice layer (kg/m^3)

ρ_w - density of water (kg/m^3)

σ is Stefa-Boltzmann constant = 5.67×10^{-8} $W/m^2.K^4$

1. Introduction

1.1 Background and Context

The United Kingdom has committed to achieving net-zero greenhouse gas emissions by 2050, a goal that necessitates profound changes across all sectors of the economy. The decarbonization of the heating sector is a critical component of this transition, as residential and commercial heating currently accounts for a substantial portion of the UK's total energy use and carbon emissions. The majority of UK homes are heated by natural gas, a fossil fuel that, while convenient and reliable, contributes significantly to national carbon output. Shifting away from gas boilers to cleaner, electric heating systems is therefore vital in the country's efforts to reduce its carbon footprint and combat climate change.

At the forefront of this transition is the deployment of air source heat pumps (ASHPs), which are widely regarded as one of the most efficient and sustainable alternatives to conventional heating systems. ASHPs work by extracting heat from the air and transferring it indoors for space heating and water heating. This process can provide heat even at low outdoor temperatures, making them a suitable option for the UK's relatively mild climate. ASHPs are also compatible with renewable electricity sources, such as wind and solar, making them a key technology in the shift toward cleaner energy systems.

The government has set ambitious targets for the installation of heat pumps. By 2028, the UK aims to install 600,000 heat pumps annually as part of a wider strategy to phase out gas boilers and electrify heating (UK Government, 2023). These goals are supported by policies such as the Clean Heat Grant, which provides financial incentives to encourage homeowners to switch to heat pumps. Alongside heat pumps, other technologies such as district heating, hydrogen boilers, and electric resistance heating are also being explored as part of the broader decarbonization effort.

However, despite these efforts, the adoption of ASHPs remains limited. In 2021, approximately 35,000 heat pumps were installed in the UK, a fraction of the government's target (Lyden et al., 2024). This slow uptake can be attributed to a variety of factors, including high upfront costs, technical challenges, and a general lack of public awareness about the benefits of heat pumps. Furthermore, the UK's aging housing stock presents unique challenges for heat pump installation, as many homes are not sufficiently insulated to allow ASHPs to operate at their most efficient level.

The transition to ASHPs also ties into broader efforts to electrify other sectors, such as transport. The increasing adoption of electric vehicles (EVs), alongside the electrification of heating, represents a significant shift in the way energy is consumed in the UK. This convergence of electrification across sectors underscores the importance of modernizing the national grid to cope with increased demand, improve energy efficiency, and integrate renewable energy sources. Achieving a smooth transition will require not only technological innovation but also widespread behavioural change, improved infrastructure, and sustained policy support.

Given these challenges, this thesis seeks to evaluate the feasibility of large-scale ASHP deployment in the UK, considering the technical, economic, and social factors that influence adoption. The study also explores how heat pumps perform in real-world conditions, how homeowners perceive the transition, and what impact widespread adoption would have on the national power grid. Furthermore, the potential of heat recovery methods, such as those used in commercial settings like the Nottingham Ice Centre, is investigated as part of a broader strategy to reduce reliance on fossil fuels in both residential and commercial sectors.

1.2 Challenges in Electrification

The electrification of heating systems, particularly through the adoption of air source heat pumps, presents a range of challenges that must be addressed to meet the UK's net-zero emissions targets. These challenges span technical, economic, infrastructural, and social dimensions, each of which plays a significant role in determining the success of the transition from gas-based systems to electric heating solutions.

1.2.1 Technical Challenges

One of the foremost technical challenges in the electrification of heating is the performance of ASHPs in varying climates, particularly during colder periods. Although heat pumps are designed to work efficiently in mild to moderate climates, their performance can degrade significantly in sub-zero temperatures. As outdoor temperatures drop, the efficiency of ASHPs (measured by the coefficient of performance, or COP) decreases, resulting in higher energy consumption to maintain the same indoor temperatures. This issue is particularly relevant in parts of the UK where winters are cold, although not extreme compared to other countries. Defrost cycles also present a challenge, as frequent defrosting of the outdoor unit can further reduce the overall efficiency of the system.

In addition to performance concerns, the physical suitability of UK homes for heat pump installation is another major technical hurdle. Much of the UK's housing stock was built before modern insulation standards were introduced, and many homes are poorly insulated. ASHPs are most effective in well-insulated homes where heat loss is minimal, and they often work best in conjunction with low-temperature heating systems, such as underfloor heating or larger radiators. In homes with poor insulation or incompatible heating systems, ASHPs may struggle to maintain comfortable indoor temperatures, leading to increased energy consumption and potentially higher bills for homeowners. Upgrading the insulation and heating infrastructure in older homes is therefore a prerequisite for maximizing the benefits of heat pumps.

Furthermore, the installation of ASHPs requires significant upfront investment in both equipment and labour. Retrofitting an older home to accommodate a heat pump can be complex, requiring changes to the heating distribution system (such as installing larger radiators or underfloor heating) as well as improvements to the building's thermal envelope (e.g., adding insulation or replacing windows). These factors contribute to the high costs of heat pump installations, which can be a deterrent for many homeowners.

1.2.2 Economic Challenges

The economic challenges associated with the electrification of heating are closely tied to the high capital costs of ASHP systems. While heat pumps could offer lower operating costs compared to gas boilers over the long term, the initial investment required for installation remains a significant barrier for many households. The average cost of installing an ASHP in the UK can range from £7,000 to £15,000, depending on the size of the system and the extent of any necessary home improvements. Although government grants and incentives, such as the Clean Heat Grant and the Renewable Heat Incentive (RHI), aim to offset some of these costs, they may not be enough to encourage widespread adoption, particularly among low- and middle-income households.

Moreover, there is a perceived lack of cost competitiveness between ASHPs and traditional gas boilers. Despite rising gas prices and the volatility of global energy markets, gas remains a relatively affordable heating fuel in the UK. For many homeowners, the financial analysis in general favours retaining existing gas boilers over investing in new heat pump systems, particularly if they are unaware of the long-term savings that heat pumps can offer. This economic challenge is exacerbated by the relatively high cost of electricity in the UK compared to natural gas, which can discourage the switch to electric heating systems.

Commercial and industrial settings face similar economic challenges. For example, in the case of the Nottingham Ice Centre, as will be discussed later in this thesis, the cost of installing heat recovery systems and heat pumps is substantial, despite the potential long-term savings from reduced energy consumption. Without significant government subsidies or private investment, the upfront costs may discourage the adoption of such technologies in commercial applications.

1.2.3 Grid Infrastructure and Energy Supply Challenges

The large-scale electrification of heating through ASHPs and other electric technologies will have profound implications for the UK's power grid. As more homes and businesses transition from gas-based heating to electric systems, the demand for electricity is expected to rise significantly. This increased demand will not only occur during winter months, when heating needs are highest, but also during periods of extreme weather, which can strain grid capacity. The existing grid infrastructure, designed primarily for a more predictable and less variable load, may struggle to cope with the new demands placed upon it by millions of ASHPs and electric vehicles.

The issue of peak demand is particularly pressing. If large numbers of heat pumps are running simultaneously during a cold snap, it could lead to periods of peak electricity consumption that far exceed the grid's capacity, risking blackouts or necessitating expensive grid upgrades. Moreover, as the UK continues to decarbonize its electricity supply by increasing the share of renewables in the energy mix, the variability of renewable energy sources (such as wind and solar) poses additional challenges. Grid operators will need to implement sophisticated demand-response strategies and invest in energy storage solutions to balance supply and demand, particularly during periods when renewable generation is low, and heating demand is high.

1.2.4 Social and Behavioural Challenges

Another significant challenge in the electrification of heating is the social acceptance of new technologies such as ASHPs. Gas boilers have been the dominant form of heating in the UK for decades, and many homeowners are reluctant to switch to heat pumps, which they may perceive as unproven or less reliable. The comfort, convenience, and familiarity of gas boilers make them a difficult competitor for heat pumps, even when the environmental and long-term economic benefits are clear.

There is also a lack of awareness and understanding among homeowners about how ASHPs work and what benefits they offer. Many people are unfamiliar with heat pump technology and are unsure about its efficiency, performance in cold weather, and potential cost savings. This lack of knowledge can lead to hesitation in adopting the technology, even when financial incentives are available. Furthermore, concerns about the disruption caused by installing a heat pump (e.g., the need for larger radiators or underfloor heating, or the installation of outdoor units) can further deter potential adopters.

For electrification to succeed, widespread public engagement and education will be needed to build trust in heat pump technology. Homeowners must be reassured that ASHPs can meet their heating needs reliably and efficiently, even in colder weather. In addition, targeted financial incentives and policies must be in place to make the transition to heat pumps more affordable and appealing to a broader demographic, especially low- and middle-income households.

1.3 Main Issues Addressed

The research addresses four core issues critical to the successful deployment of ASHPs:

1. **Impact of Housing Stock**: Understanding how varying house types and insulation levels affect the energy demand and heating efficiency of ASHPs. This is crucial for assessing whether the current UK housing stock is prepared for the widespread transition to electric heating. The thesis will also investigate the defrost cycle and the associated energy consumption, a scenario that will cause further increase in energy demand on the grid in cold winters.
2. **Grid Stability and Energy Demand**: Exploring the potential strain that large-scale ASHP adoption would place on the UK power grid, particularly during peak demand times, and identifying strategies for managing this additional load.
3. **Homeowner Acceptance**: Investigating why homeowners continue to prefer gas boilers over ASHPs, despite the potential environmental and long-term cost benefits of the latter. This includes exploring social, economic, and informational barriers to adoption.
4. **Performance in Commercial and Industrial Settings**: Through a case study of the Nottingham Ice Centre, evaluating the potential for ASHPs and heat recovery systems to reduce energy demand from district heating and improve overall energy efficiency in large facilities.

1.4 Research Questions

The central research questions guiding this thesis are:

1. How the defrost cycles might affect the operation of the ASHP and therefore the sudden change of demand on the grid.
2. What is the current attitude and public engagement towards heat pumps?
3. What is the satisfaction of current users of heat pumps and how are they using it?

4. How electric cars will influence the grid and what is the possible effect of cold weather on the range and additional energy needed?
5. What are the challenges of using heat recovery in buildings with support from heat pumps vs district heating technology?
6. What are the challenges and changes needed to balance the grid?

These questions not only address the technical feasibility of ASHP adoption in residential housing but also touches on the socio-economic implications and the broader infrastructure impacts of electrification in the heating sector.

1.5 Research Aim and Objectives

The primary aim of this research is to examine some of the challenges towards the decarbonisation of heating in buildings and transportation towards NetZero; it addresses the technology, social and implementation aspects.

This research work valuates the feasibility, challenges, and opportunities presented by the large-scale deployment of ASHPs in the UK, focusing on both residential and commercial sectors. This includes an in-depth analysis of heating demand across different dwelling types, an assessment of grid impacts, and an exploration of homeowner attitudes toward heat pump technology. Additionally, the research evaluates alternative applications of HPs in commercial settings, such as the Nottingham Ice Centre case study, where heat recovery systems play a crucial role. Furthermore, the electrification of the transportation sector needs to be explored and investigate the effect of mass implementation of electric vehicles on the grid in cold weather. The thesis also compares the UK with other global locations for a better understanding of the global challenges.

To achieve this aim, the following objectives were established:

1. To Understand and simulate the effect of defrost cycles and ASHP energy demand during different weather and energy demand conditions and the influence this will bring on the electric energy consumption.

- ➢ Building a complete ASHP test rig system to validate the simulation model and experiment in future design ideas.
- ➢ Building a simulation model of ASHP that is validated using the experimental work.
- ➢ Testing defrost cycles in the UK and other countries based on different weather conditions and average buildings type and the effect of that on energy consumption

2. To understand public attitude and engagement towards heat pumps.

- ➢ Develop a survey to understand people’s understanding, awareness and concerns.

- Examine the use of ASHP in-situ in two cases study in residential buildings including an interview with the residents and experimental monitoring.

3. To assess heat recovery or heat pump use via competitive technologies such as district heating in non-residential building.

- To conduct a case study of the Nottingham Ice Centre, focusing on heat recovery systems using ASHPs and thermal storages as alternatives to district heating.
- To monitor the energy consumption and performance of heat recovery systems in a commercial setting, assessing their potential for large-scale application.

4. To explore the effect of the change of EV range in cold weather and the effect on the grid.

1.6 Justification of Objectives

The objectives outlined above are designed to provide a comprehensive understanding of the critical factors influencing the adoption and performance of ASHPs in the UK and globally. The Simulink simulations provide essential insights into the technical viability of ASHPs in varying housing scenarios and their potential impact on the national grid. By simulating multiple housing types, insulation levels, and climate conditions, the research provides data that is directly relevant to policymakers and industry stakeholders, helping them to assess the infrastructure requirements for widespread ASHP deployment.

The homeowner survey and questionnaire address the socio-economic barriers to ASHP adoption. By understanding why homeowners resist switching to heat pumps, this research aims to identify key areas where government intervention or public education could drive higher adoption rates. The survey also offers insights into the satisfaction levels of current ASHP users, providing practical feedback for manufacturers and installers on the performance of ASHPs in real-world settings.

The Nottingham Ice Centre case study explores the application of ASHP technology in a commercial environment, where heat recovery plays a central role in reducing reliance on district heating. This case study is critical for understanding how ASHPs and thermal storages can be used not only in residential settings but also in large-scale industrial and commercial applications. The findings from this case study provide valuable lessons for the broader energy sector, particularly in optimising energy recovery and improving the efficiency of large energy-intensive facilities.

Together, these objectives offer a holistic approach to understanding the technical, economic, and social dimensions of ASHP adoption in the UK. By addressing both residential and commercial applications, the research provides a broad perspective on the opportunities and challenges of electrifying the heating sector, contributing valuable insights to the UK's net-zero goals.

Thesis Structure:

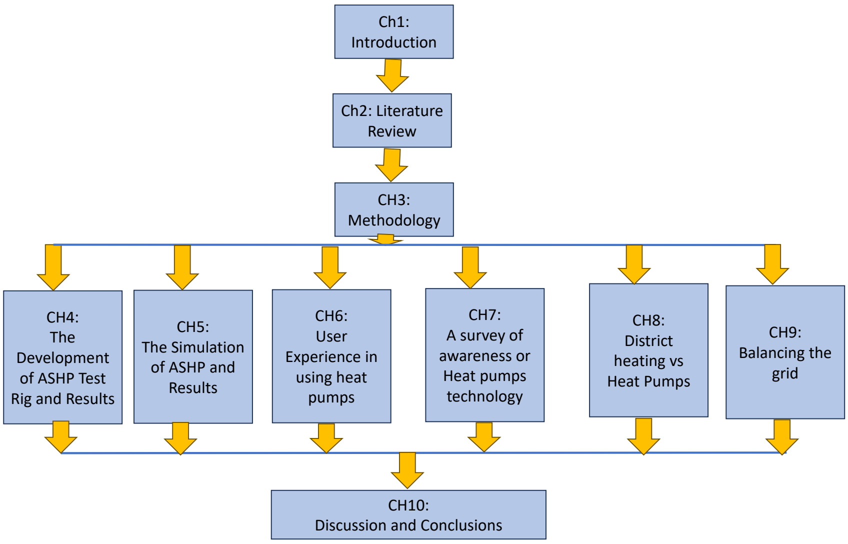


Figure 1. 1 - *The thesis structure and the subjects of the following chapters.*

The thesis structure is organised based on Figure 1.1, as follows:

Chapter 1: This chapter included the introduction to the thesis. It highlights the aims and objectives of the thesis.

Chapter 2: This chapter reviews the relevant literature and identifies the gaps in the secondary research.

Chapter 3: This chapter highlights the methodology applied in this PhD research, using mixed-method approach to address the gaps, identified in Chapter 2.

Chapter 4: This chapter highlights the development of an air source heat pump test rig, and the following test conducted on it in regards to energy consumption, heat output, and frost accumulation.

Chapter 5: This chapter includes the development of a simulation model based on the test rig from Chapter 4. The same tests were conducted on the model to validate it and further expand the research on the effect of heat pumps and defrost cycles on the electricity grid in the UK and other global cities.

Chapter 6: This chapter focuses on two case studies with heat pump users to understand first hand their experience in using such technology in cold weather.

Chapter 7: This chapter explores the user engagement and awareness of using heat pump technology in a domestic environment through a questionnaire.
Chapter 8: This chapter investigates other competitive technologies, such as district heating, in commercial buildings, and what role heat pumps and thermal storages could play to reach Net Zero targets.
Chapter 9: This chapter explores the fluctuations on the electricity grid and the effect of mass implementation of heat pumps and electric vehicles in cold weather.
Chapter 10: This chapter discusses the results acquired in Chapters 4 to 9, identifies the limitations, and provides directions for future research.

2. Literature Review

2.1. Overview of Electrification in Heating and Transport

The shift towards electrification in heating and transport is a cornerstone of contemporary efforts to reduce carbon emissions and combat climate change. Chapter 2 provides a broad overview of this transformative transition, focusing on the adoption of electric technologies such as air source heat pumps (ASHPs) and electric vehicles (EVs). It introduces the driving factors behind electrification, including the need for sustainable energy solutions and advancements in technology. The chapter also outlines the potential benefits, such as reduced greenhouse gas emissions and improved energy efficiency, while addressing the associated challenges, including the impact on electricity grid infrastructure and the variability in energy demand. By setting the context for the electrification of these sectors, Chapter 2establishes a foundational understanding necessary for exploring the detailed aspects of this transition in subsequent chapters.

2.1.1. Historical context and evolution of electrification in heating and transport.

The heat pump as it is known today made its first appearance in 1856 (Finn Geothermal, 2019). Peter von Rittinger was experimenting on the usage of latent heat produced by water vapour, which was used to evaporate salt brine. Consequently, while he was conducting that experiment, he discovered the principle on which today's heat pumps work (Finn Geothermal, 2019).

In the UK, the first pump was built in 1945 by John Sumner (Finn Geothermal, 2019). Surprisingly for that time, the device reached a thermal delivery of 147 kW on average with a peak output of 234 kW. It was designed to circulate hot water around a heat emitting system of a building with a temperature averaging around 52.5 C^{o}. Although, this technology proved to be more efficient it did not become very popular in the UK at that time because of the cheap price of coal and other fossil fuels (Finn Geothermal, 2019).

At the end of the 19th century, electric vehicles were commonly used due to the simplicity of the technology. Furthermore, by 1899, at least 90% of taxi cars in New York were electric (Hiskey, D., 2011).

2.1.2. Current state and future projections for electrification in the UK.

In an effort to achieve the 2050 net zero goals, many countries including UK, New Zealand, Canada, South Korea, Japan, etc. have stated targets in their energy related policies (UK Parliament, 2021). There are still many countries that rely on fossil fuels to provide heating. Particularly, in the UK around 70% of heating is provided via natural gas (Gross & Hanna, 2019). In order for the country to achieve the 2050 targets, the UK government has set a target of 600,000 units to be installed per year by 2028. For 2022, only around 72,000 units have been installed (Harris & Walker, 2023). Electrification of the heating sector is one of the key elements for decarbonisation. However, some of the main challenges related to that process are sources of electricity and the magnitude of the electricity demand (Waite & Modi, 2020). This means that the electricity system should be comprised of renewable sources (Cole et al., 2021), and the power grid must be expanded and reinforced (Tröndle et al., 2020).

Keskar et al. (2023) explored the increasing importance of planning for power systems that peak in the winter, particularly as decarbonization and climate change reshape energy demand. Traditionally, many regions in the U.S. experience peak electricity demand during summer, but some regions are becoming dual peaking (both summer and winter peaks) or winter peaking due to the increasing use of electric heating and extreme cold events (Keskar et al., 2023). Keskar et al. (2023) analysed peak demand trends from 2016 to 2021 across multiple regional and subregional levels, using datasets such as U.S. Energy Information Administration (EIA) demand data and spatial data on home heating sources. Their study highlights how electrification, especially through the adoption of electric heat pumps, is contributing to winter peak loads. They also examined the reliability challenges posed by winter conditions, such as cold weather impacts on fossil fuel systems (as seen during Winter Storm Uri in Texas) and the limitations of solar and battery technologies during winter. Some of the findings from the research by Keskar et al. (2023) include the need for regulators and utilities to anticipate and plan for both gradual shifts in seasonal demand due to electrification and more extreme cold events. They stress the importance of including winter resource adequacy in energy planning and improving the resilience of both renewable and fossil fuel systems during winter peaks. The study also emphasises the potential role of demand response and energy efficiency programs, such as controlling electric heating and water heaters during peak times, to manage demand surges in the winter. The lack of a similar study focusing on the UK's power systems during winter could be considered a research gap. The UK faces similar challenges to the U.S., such as increasing electrification, climate change, and extreme weather events, which could shift peak electricity demand from summer to winter. However, the UK's climate, energy mix, and regulatory environment differ considerably from the U.S. Keskar et al. (2023), meaning that the findings from the Keskar, Galik, and Johnson study might not directly apply to the UK. While the UK has explored aspects of winter demand like the National Grid's "Winter Outlook Reports" (Slye, 2023), there has not been a comprehensive academic study equivalent to the U.S.-focused research, particularly one that evaluates the impact of electrification, extreme weather, and decarbonization on long-term grid resilience in winter. Addressing this gap would provide valuable insights for UK policymakers, especially given the country's growing reliance on renewable energy sources, its aggressive decarbonization goals, and the adoption of electric heating systems.

Mellot et al. (2024) addressed the challenge of winter electricity shortages in Switzerland due to the country's increasing reliance on renewable energy, particularly photovoltaic (PV) systems. The study investigates strategies to alleviate these deficits, especially during winter months when solar power is less effective (Mellot et al., 2024). The authors employed a comprehensive energy modelling approach that integrates multiple sectors (electricity, heating, and transport) and considers Switzerland's interactions with neighbouring countries. They analysed various mitigation strategies, such as the use of gas-fired power plants, wind turbines, and alpine PV installations. The study found that a combination of gas-fired plants, alpine solar, and wind turbines could reduce Switzerland's winter electricity shortfalls without significantly increasing energy system costs. Importing electricity from neighbouring countries was also considered but came with increased costs compared to domestic generation strategies. The analysis revealed that expanding these renewable sources, especially alpine PV and wind power, is critical to achieving a reliable and renewable winter energy supply for Switzerland (Mellot et al., 2024). As for the UK's winter power planning, the absence of a similar detailed study focused on mitigating winter electricity deficits can be considered a research gap. The UK's energy challenges, particularly rising demand from electrified heating, extreme winter weather, and increased reliance on intermittent renewable sources, parallel those faced by Switzerland. Yet, the UK lacks a comparable case study that comprehensively examines winter-specific power supply issues, particularly in the context of transitioning to net-zero emissions. Such research could help the UK address potential winter electricity deficits, offering tailored strategies that align with its specific climate, energy mix, and policy goals.

Therefore, conducting similar research for the UK would be invaluable for future energy planning.

2.1.3. Policy frameworks and governmental initiatives supporting electrification.

There are three main types of heat pumps depending on the source, whereby they extract the heat are from Air, water and ground source HPs. The performance of all three vary depending on the mode they work on, the ambient temperature, the size of the building they are heating or cooling and of course the size of the unit itself. The cost of installation and payback period are also key factors when comparing heat pumps.

The Renewable Heat Incentive (RHI) and its role to the heat pump owners must be noted. RHI is a scheme established by the UK Government, which provides financial support to householders who own renewable heat systems. It was estimated that this scheme contributed to approximately 12 per cent in 2020. The size of the support from RHI varies depending on the type of heat pump, the size of the building that will be heated or cooled, and the thermal energy required to perform the task (Energy Saving Trust, 2019).

Table 2.5 and 2.6 represent the available tariffs for renewable heat systems, the applications for the amount of money has been submitted for the period between 01/04/2019 and 30/06/2019 including and the updated tariffs for 2021.

Table 2. 1*- Summary of the latest available tariffs for renewable thermal energy technology (Energy Saving Trust, 2019).*

	Air source HP	Ground source HP	Solar thermal	Biomass
Tariff (p/ kWh renewable heat)	10.71	20.89	21.09	6.88

It is also worth mentioning that the UK Government provides grands to encourage homeowners to replace their existing gas boilers with heat pumps (Ahmed & Vekony, 2024). The amount that is providers to owners varies, but for air-source HPs the grand usually covers up to £7,500 off the cost and installation of the device (UK Government, 2022).

Government policies and regulatory frameworks play a crucial role in accelerating the transition towards electrification in the heating and transport sectors. In the UK, a range of strategic initiatives and legislative measures have been established to foster the adoption of electric technologies and reduce reliance on fossil fuels (Department for Business, Energy & Industrial Strategy, 2021). This section explores the key policy frameworks, including targets for carbon reduction, financial incentives, and support programs designed to promote the use of air source heat pumps (ASHPs) and electric vehicles (EVs). By examining these governmental efforts, it can be further understand how policy shapes the electrification landscape and drives progress toward a sustainable energy future.

A study that focused on evaluating the cost competitiveness of heat pumps and battery electric vehicles in Germany, examined how different policy measures affect their levelized costs (George et al., 2024). Through levelised cost calculation, data collection and assumption, scenario and sensitivity analysis, the authors estimated that both heat pumps and battery electric vehicles are becoming increasingly cost-competitive due to technological advancements and economies of scale (George et al., 2024). The levelised cost of heating for HPs and levelised cost of driving for electric cars are influenced significantly by energy prices, investment costs, and policy measures. According to the authors, various policy measures, such as subsidies, tax incentives, and energy tariffs, play a crucial role in determining the economic viability of heat pumps and electric vehicles (George et al., 2024). They highlight the importance of a stable and long-term policy framework to enhance market uptake and investor confidence. After examining multiple scenarios to assess the impact of different policy framework and market conditions, their sensitive analysis provided an understanding on how changes in key parameters like electricity prices and investment costs affect the competitiveness of these technologies. The adoption of heat pumps and electric vehicles contribute significantly to carbon emission reduction, aligning with Germany's climate goals (George et al., 2024). These environmental benefits can be maximised when HPs and EVs are coupled with renewable sources of energy (George et al., 2024). However, the authors do not explicitly break down the detailed effects of different dwelling types and levels of insulation on heating demand and the heat pumps' energy consumption. This gap could be addressed to provide a more comprehensive understanding of the cost and energy implications of deploying heat pumps across different housing types and insulation standards.

2.2. Air Source Heat Pumps (ASHPs) in the UK

Air source heat pumps (ASHPs) have emerged as a key technology in the UK's transition towards a low-carbon heating system. Chapter 2.2 provides a comprehensive overview of ASHPs, detailing their technical principles, operational mechanisms, and the current state of their adoption across the UK. This chapter explores how ASHPs function by extracting heat from the outside air and transferring it indoors, highlighting their advantages over conventional heating systems in terms of efficiency and environmental impact. Additionally, it reviews the factors influencing their uptake, including geographic distribution, market trends, and recent policy developments. By examining these aspects, the chapter aims to establish a foundational understanding of ASHPs, setting the stage for a deeper analysis of their performance, challenges, and potential within the broader context of electrification and grid management.

2.2.1. Technical principles and working mechanisms of ASHPs.

A heat pump is a device that transfers thermal energy from a lower temperature source to a higher temperature sink, effectively heating or cooling a space (Çengel et al., 2019). There are several types of heat pumps, with air source heat pumps (ASHPs), ground source heat pumps (GSHPs), and water source heat pumps (WSHPs) being the most common (Langley, 2001). ASHPs extract heat from the ambient air. The technical principles of ASHPs involve the refrigeration cycle, which consists of four main components: an evaporator, a compressor, a condenser, and an expansion valve. In heating mode, the evaporator absorbs heat from the outside air, causing the refrigerant to evaporate. The compressor then increases the pressure and temperature of the refrigerant vapor, which releases heat when it condenses in the indoor coil. Finally, the expansion valve reduces the pressure of the refrigerant, allowing it to absorb heat again from the outside air. This cycle is reversed for cooling (Langley, 2001).

Ground source heat pumps (GSHPs), also known as geothermal heat pumps, utilize the stable temperature of the ground to exchange heat. They are generally more efficient than ASHPs due to the constant ground temperature but involve higher installation costs due to the need for ground loop systems (Çengel et al., 2019). Water source heat pumps (WSHPs) use bodies of water such as lakes or wells as their heat exchange medium (Langley, 2001). These systems can be highly efficient but are dependent on the availability of an adequate water source (Çengel et al., 2019). Each type of heat pump is selected based on factors such as climate, ground or water availability, and installation costs.

2.2.2. Refrigerants

Refrigerants are substances that are utilised in refrigeration systems, such as heat pumps or refrigerators. In such systems it goes through phase change from gas to a liquid and vice-versa. The main purpose of the refrigerant is to collect thermal energy from a heat source and transport it to a heat sink. All these processes require temperature and pressure fluctuations in the refrigerant in order to undergo the phase changes and successfully maintain the cycle (Haaf and Hendrici, 2000).

Ideally the fluid possesses certain properties, such as being noncorrosive to any metal parts or mechanisms in the system, having a moderate density in a liquid phase state, and considerably high density as a gas (Dinçer, 2017). Pressure affects parameters such as density and boiling point. Depending on the heat pump system, various refrigerants may be used to satisfy the output. Refrigerants possess different properties regarding the thermodynamics, operating pressure, and boiling point (Haaf and Hendrici, 2000).

There are over 100,000 blends of refrigerants existing (Calleja-Anta et al., 2020). They are divided into three classes regarding their physical and thermodynamic properties.

One of the most commonly used refrigerants is R-134a also known as 1,1,1,2-Tetrafluoroethane (US EPA, 2019). A single molecule of that substance consists of two carbon, two hydrogen and four fluorine atoms representing the tetrafluoroethane's empirical formula. In this case, the suffix "a" in the code shows the unbalance in the compound's structure by one atom (US EPA, 2019).

In general, coolants are divided into groups. Those groups are determined by the refrigerants' chemical composition. These groups are Chloro-Fluoro-Carbons (CFC), Hydro-Chloro-Fluoro-Carbons (HCFC), Hydro-Fluoro-Carbons (HFC), Fluorocarbons (FC), Hydrocarbons (HC), Ammonia and Carbon Dioxide (Swep, 2019) (Dinçer, 2017).

Table 2. 2 *- Advantages and disadvantages of refrigerants used in heat pump systems (Industrial heat pumps, n.d.)*

Refrigerant	***Advantages***	***Disadvantages***
R134a	Offers higher efficiency than R407c and R410a	Low pressure; Higher investment cost
R407C and R410A	Lower investment cost; Efficient in low temperature HPs	Low efficiency compared to R134a
R600 and R600a	Efficient for high temperature HPs; Lower pressure increase with high operational temperatures	Explosiveness, flammability
R717	Natural refrigerant; Efficient in low temperature HPs; No global warming potential (GWP) and no ozone depletion potential (ODP); Inflammable	Toxic
R718	Natural refrigerant; No harm to the environment;	High condensation temperature; Low density in gaseous state
R744	Natural refrigerant; Low GWP; No ODP	Low operational temperature

In a heat pump system, the refrigerant can affect the COP of the device as shown in the reproduced figure 2.1 from a study conducted by (Natarajan and Vanitha, 2015) in a performance investigation of refrigeration system using environmentally friendly working fluids. According to these results, R134a provides better efficiency compared to R290/R600a blends (Please see figure 2.1).

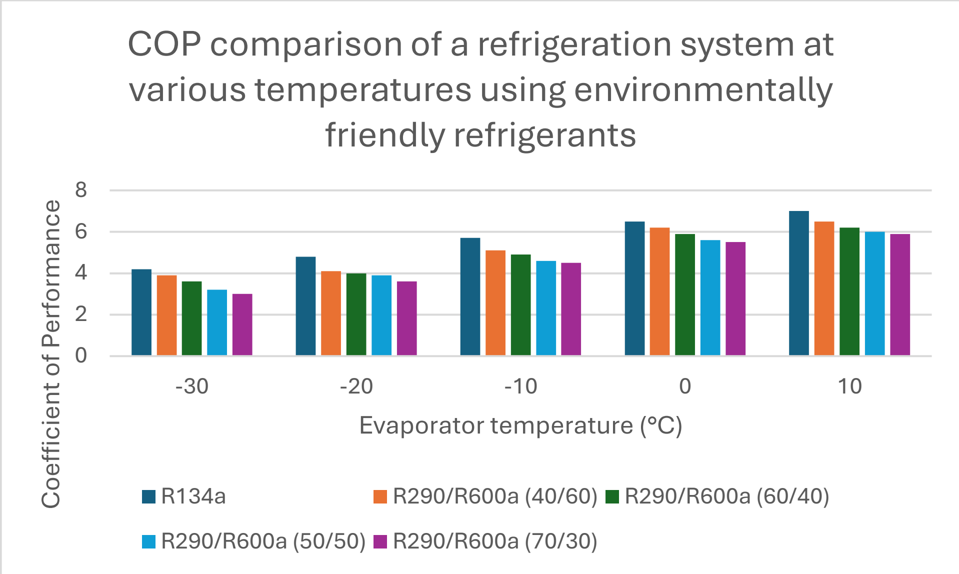


Figure 2. 1 *- COP of a refrigeration system at various evaporation temperatures using environmentally friendly refrigerants (reproduced - Natarajan and Vanitha, 2015).*

From the study conducted by Natarajan and Vanitha (2015), it can be noticed that the higher the evaporation temperature is, the higher the efficiency of the systems.

2.2.3. Current adoption rates and geographic distribution of ASHPs in the UK.

Ever since the Russia - Ukraine conflict, which had an impact on energy cost, particularly in Europe, many countries have shifted their attention to heat pump systems to provide heating as an alternative to gas. Countries such as France, Czech Republic, and Poland have doubled the installation of heat pumps over the last year (Monschauer et al., 2023). In the UK, more than 85 percent of buildings rely on natural gas for heating, and installation of heat pumps remains low (Filippidou et al., 2019). The government has set a target of 600,000 heat pumps to be installed per year by 2028 (Lyden et al., 2024). Despite the existing incentives in the UK, around 35,000 units are installed per year, compared to 1.5 million gas boilers per annum (Lyden et al., 2024). A study focused on understanding concerns of adopting shared-loop ground source heat pumps have conducted interviews with industrial experts, households who utilise such shared-loop GSHP system, and households relying on gas for heating (Brown et al., 2024). It was found that among homeowners that the main reasons for the slow adoption rate of such systems was due to higher upfront costs and awareness of the impact of such technology. However, the study does not mention air source heat pump users, whose number is considerably higher compared to GSHP users as showcased in Figure 1 (*Number of heat* *pump units in the UK between 2013 – 2019 (Published by Statista Research Department & 8, 2023))*. It is not mentioned what ASHP users' opinion is and what is their satisfaction level of using air source heat pump for space and water heating. The reasons for adopting or not such technology instead of gas needs to be investigated further in the UK. That is why through objective 2, this research will address this gap to better understand the reasons behind the current adoption rate of heat pump technology and what is the satisfaction level of using such devices in the cold weather in the UK.

For comparison, countries such as Norway, Finland, Sweden, and Estonia have one of the highest heat pump adoption rates in Europe, with approximately 300, 240, 230, and 170 units per 1000 people, respectively. As of 2022, UK has the lowest adoption rate with 6 heat pumps per 1000 people (Olympios et al., 2024). In addition, the electricity-to-gas price ratio in Sweden has reached 1, suggesting that gas and electricity cost is roughly the same, which could indicate the increasing interest in switching to heat pumps for heating supply instead of gas. In Estonia that ratio is also decreasing (Olympios et al., 2024). Currently, in the UK electricity is approximately 3 times more expensive than natural gas. Norway and Finland do not have widespread infrastructure for gas distribution (Olympios et al., 2024).

It has been noticed that the number of installed heat pumps across Europe and the UK has been increasing for the last 6 years. This can be showcased by figures 2.2 and 2.3 indicating a considerable rise of installed units.

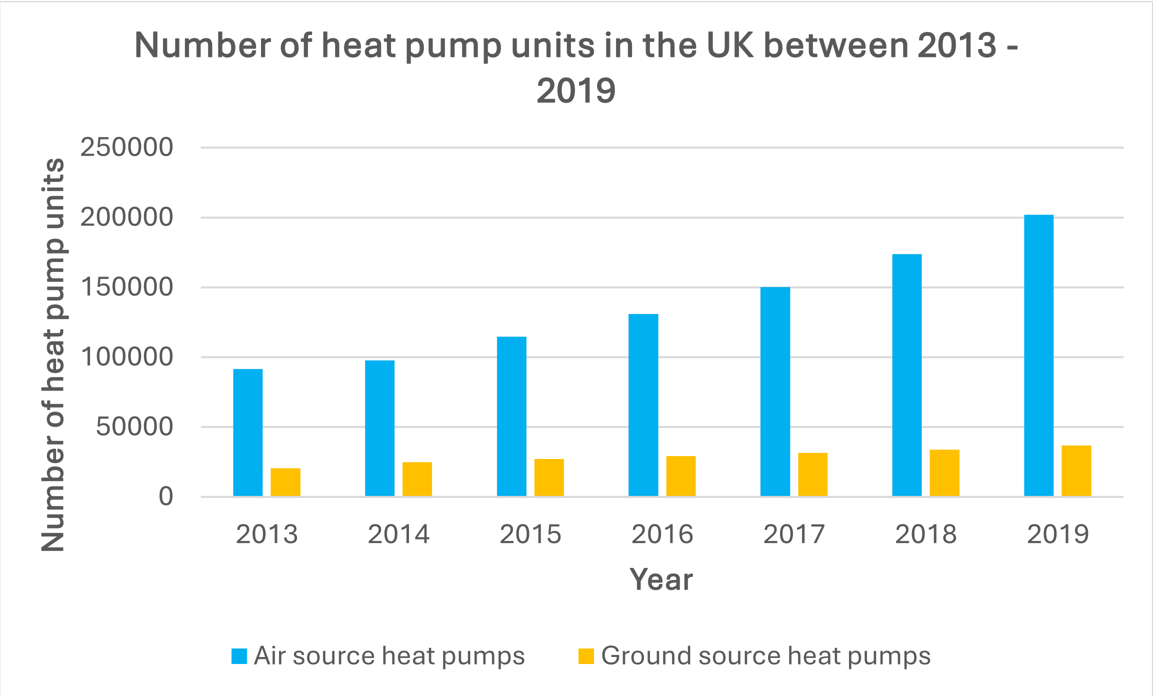


Figure 2. 2 *- Number of heat pump units in the UK between 2013 – 2019 (Published by Statista Research Department, 2023)*

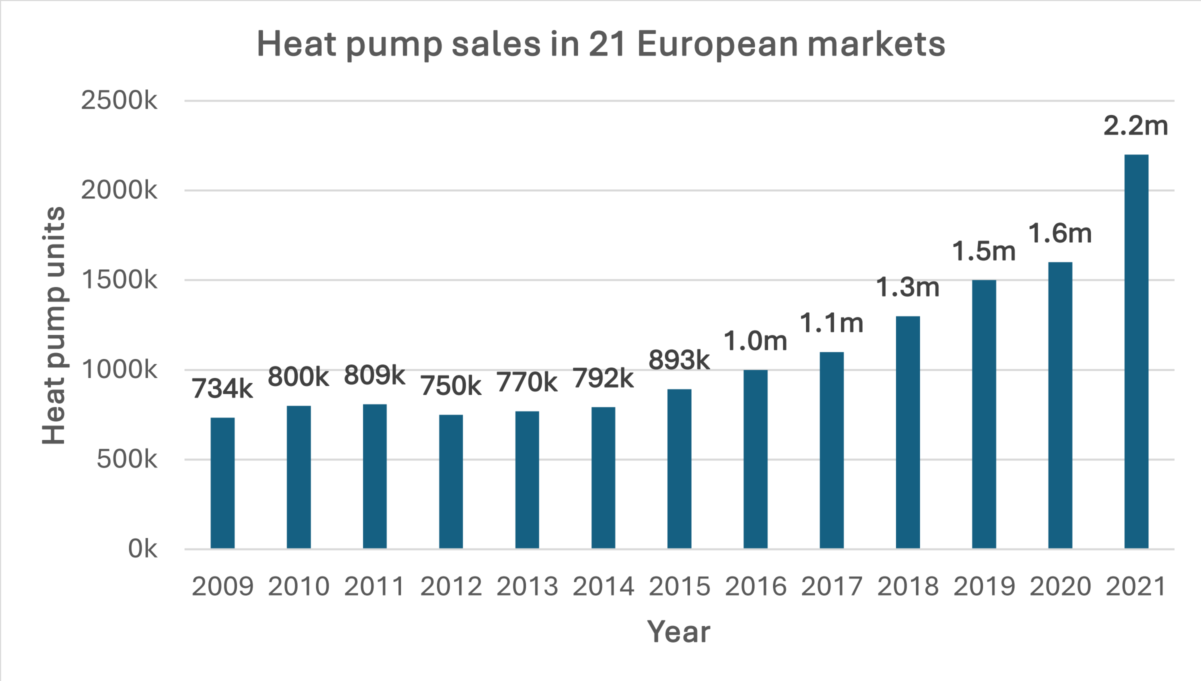


Figure 2. 3 *- Heat pump sales in 21 European markets (Nowak & Westring, 2023)*

Although, an increase of installed heat pumps has been reported until 2022, another report shows that since the start of 2024 the units has seen a sales fall (Azau, 2024). Particularly, countries like Italy, Finland, and Poland have seen the highest fall of sales. For instance, the sales of heat pumps in Poland have dropped by 46 percent in 2023 (Azau, 2024). One of the reasons for that is the fall of gas prices (Niranjan, 2024). In the UK the heat pump market share is even lower than that of Poland (Nowak & Westring, 2023). Which begs the question for the reason behind this. One of the reasons could be due to the fall of gas prices, poor insulation, radiator sizes, initial cost (Wheeler, 2023). High electricity prices also contribute to the slow adoption and conversion to heat pumps as a main heating source in dwellings (Boydell, 2024). This contradicts with later reports of users being satisfied with their investment (Scopeliti, 2024; Ambrose, 2023). The report sharing the satisfaction level of heat pump users shows that 81 percent of homeowners who took part in the survey were satisfied with the installation of the unit (Taylor et al., 2023). However, the survey was conducted in late 2022. Since then, the prices of both gas and electricity have fluctuated which could impact the satisfaction level of heat pump users. In addition, the reasons why users decided to swich or remain on gas heating was not investigated which further highlights the gap in the research. Particularly, the popularity of heat pumps in the UK is not thoroughly researched to showcase the reasons why users swich or remain on gas heating. Objective 2 will address this gap through a more detailed survey among heat pump and gas boiler users.

A research by Pither & Doyle (2005) on UK home owners using heat pumps reported the satisfaction level of using such devices and its effect on fuel costs (Pither & Doyle, 2005). Particularly, 66 percent of surveyed homeowners pointed out that heat pump systems are affordable, and 34 percent sharing such technology is expensive (Pither & Doyle, 2005). However, the survey of the research had a sample size of 18, which is a considerably low response rate to draw significant conclusions (Blair et al., 2023). In addition, the study took place in 2005 and energy prices and understanding from the general population behind the technology may have changed. To address this, Objective 2 that involves a survey distributed to homeowners to understand their satisfaction with their heating system and their opinion on heat pumps will be conducted. In addition, Objective 2 will further support Objective 2 via two case studies, investigating the satisfaction level of heat pump owners, one air-to-air and another air-to-water, to determine if the devices are providing enough heating and are reliable at providing comfortable room temperatures, and if the units help in reducing the energy bills. Furthermore, another study by Singh et al. (2010) that investigated the factors influencing the uptake of heat pump systems in the UK, discussed some of the technological issues related to air source heat pumps in the country (Singh et al., 2010). Particularly, the research mentioned that climate, low temperatures in cold weather in particular, can affect the COP of the system. The study suggests that one way to mitigate the low performance is to install a ventilation system that allows for room temperature exhaust air to be delivered to the heat exchanger coils (Singh et al., 2010). Another reason for the low COP of air source heat pumps is also the poor insulation properties of dwellings. This can play a pivotal role in the heating demand and overall electricity consumption by the heat pump unit. To address this gap, the thesis will perform a simulation (Objective 1) to investigate the impact of insulation and climate on the heat output and energy consumption by air source heat pumps.

In a similar study by Lamb & Elmes (2024) identified key barriers to heat pump adoption, including the technical readiness of homes, cost concerns, and a lack of homeowner awareness. The authors reveal several key findings: many homes are technically unprepared for heat pumps due to insufficient insulation and existing heating configurations; the high upfront cost of heat pumps and concerns about their financial benefits hinder adoption; and there is a notable lack of awareness about heat pumps among homeowners (Lamb & Elmes, 2024). The findings were derived from a national survey of homeowners with gas boilers, along with interviews with industry experts and a review of existing literature (Lamb & Elmes, 2024). However, the study did not include heat pump owners, missing insights into their satisfaction with thermal comfort and energy costs. To addressing this gap, a survey that also includes heat pump owners will be distributed (Objective 2). This could provide valuable data on the actual performance and benefits of heat pumps, helping to inform and reassure potential adopters.

2.2.4. Comparative analysis of ASHPs versus other heating technologies (e.g., gas boilers, ground source heat pumps).

Depending on the ambient temperature and the type of heat pump, the COP can vary. Below in figure 2.4 is a chart that shows how the coefficient of performance varies according to the temperature outside and the type of HP that is used.

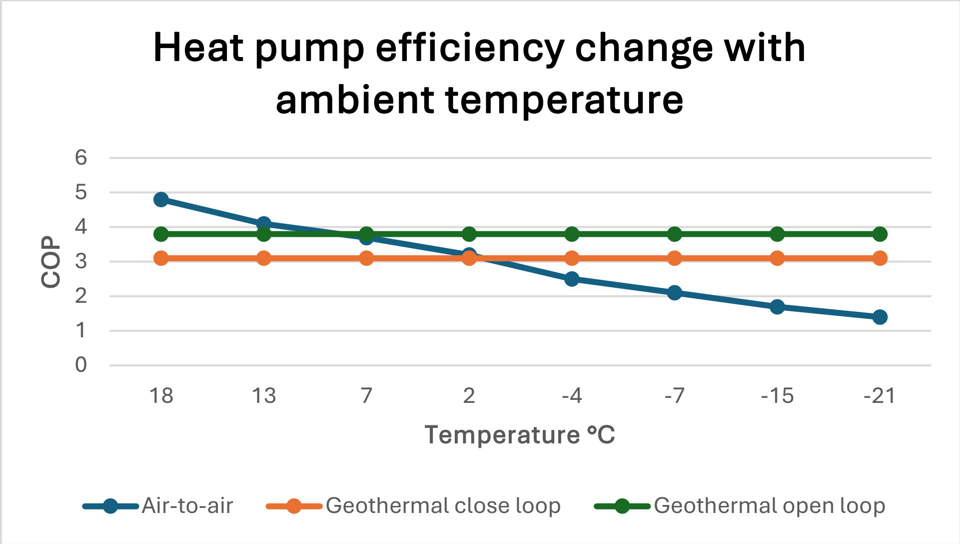


Figure 2. 4 *- Heat pump efficiencies in various ambient temperature (reproduced-Brown, 2017)*

The data utilised in figure 2.4 above was taken from COP tests of an ATW-65 air-to-air heat pump, and equivalent W-65 Geothermal HPs with open and closed loops (Brown, 2017). The figure clearly shows that the performance of the air source heat pump is more affected by the ambient temperature.

Air source heat pumps can achieve higher COP compared to gas (Terry & Galvin, 2023) although it depends on several factors such as output temperature, radiator size and heat source temperature (Terry & Galvin, 2023). Gas boilers can usually supply water temperatures to radiators between 70-80°C (Terry & Galvin, 2023). This is where the challenge comes to air source heat pumps, they usually operate at temperatures between approximately 45-55°C which helps in maintaining higher performance. There are high temperature ASHP that can supply hot water at around 80°C, however, they are more expensive and are less efficient (Terry & Galvin, 2023). That is why, with low temperature ASHPs, larger radiators are necessary to compensate for the lower supply temperatures (Terry & Galvin, 2023). For ASHP, the standard assessment procedure that is utilised for energy performance certificates in the UK is the same as for gas boilers with the main exception that on colder days, for heat pumps the heating hours will increase (BRE, 2022). A study done by (Terry & Galvin, 2023) investigates the heating pattern change, comparing gas boilers and heat pumps in dwellings in Aberdeen, Finningley, and Gatwick. Different types of houses (i.e. terraced, semi-detached, etc.) were compared including the wall types (i.e. solid walls, cavity walls, etc.). They confirm the fact that the heat loss of a house can increase the heat demand by the heat pump. They also concluded that when households switch from a gas boiler to a heat pump, changes in heating patterns are necessary, allowing for longer heating times. The study suggests that this can be achieved by lowering the thermostat temperature by around 2-5°C than the desired thermal comfort temperature. This in turn increases the heating and electricity demand by the heat pump by around 15%. This is a preferable scenario, as heating only for a short period of time can further increase the heating demand. However, when it comes to insulation, in their analysis the authors estimated heating pattern changes with only loft insulation in place (Terry & Galvin, 2023). In addition, factors such as humidity were not discussed. This is important as this could have a considerable effect on how much frost accumulates on the outdoor heat exchanger for ASHPs, and in turn affecting the performance of the device depending on the defrost cycle's duration. To address these gaps, Objective 1 will help determine how the level of insulation, climate, and defrost cycles can affect the heating and electricity demand in dwellings using ASHPs.

Heat pump systems' performance can also be affected depending on whether they are used independently in different dwellings or as district heating (Wang, 2018). A research by Wang (2018) that compared the efficiency and feasibility of individual heat pumps versus district heating systems utilising heat pumps examined performance, cost-effectiveness, carbon emissions, infrastructure, and scalability (Wang, 2018). Through data collection, simulation models on energy consumption and cost, and comparative analysis, the author demonstrated that district-level heat pump systems generally offer higher energy efficiency and can be more cost-effective in densely populated areas compared to individual heat pump systems. In addition, their findings indicate that district heating systems can significantly reduce carbon emissions, especially when combined with renewable energy sources, compared to individual systems. The author also suggests that while district heating can provide substantial benefits, the initial investment and infrastructure overhaul can be substantial barriers (Wang, 2018). The research also considers house types and insulation levels on the heating demand and energy consumption; however, it does not delve deeply into the nuances of how each specific house type and different insulation levels affect the outcomes. Addressing this gap would require a more detailed investigation focusing on the granular impacts of these factors.

Gas boilers and heat pumps are often compared when it comes to efficiency, carbon emissions, and running costs. In a related paper, the authors investigated the environmental impacts associated with domestic heat pumps and their implications for the UK (Greening & Azapagic, 2012). Through inventory analysis, data on all inputs (materials, energy, etc.) and outputs (emissions, waste, etc.) associated with heat pumps throughout their life cycle was collected, and by evaluating the potential environmental impacts based on the inventory data, the authors examined the life cycle environmental impact, greenhouse gas emissions, energy consumption and impact of electricity grid mix. The authors evaluated the entire life cycle of domestic heat pump types, including air, ground and water source, from production to disposal and compared their environmental impact with that of conventional heating systems such as gas boilers. They found that heat pumps have the potential to significantly reduce greenhouse gas emissions compared to traditional gas boilers, assuming the electricity used is sourced from low-carbon or renewable energy. The study also highlights that heat pumps consume less primary energy compared to conventional heating systems due to their high efficiency. In addition, the environmental benefits of heat pumps are heavily influenced by the carbon intensity of the electricity grid. Cleaner electricity generation translates into greater environmental benefits from heat pump usage (Greening & Azapagic, 2012). However, the authors do not provide detailed examination of different house types and insulation levels in relation to heating demand and energy consumption by heat pumps and gas boilers. Addressing this gap could provide more insights into the real-world performance of heat pumps and help optimise their deployment in various housing conditions to maximise energy efficiency and minimise environmental impacts.

2.3. Impacts of Electrification on the Electricity Grid

The transition to electrification in heating and transport sectors, with a particular focus on technologies such as air source heat pumps, presents both opportunities and challenges for the electricity grid. Chapter 2.3 explores the multifaceted impacts of this transition on grid infrastructure and performance. As more homes and businesses adopt electrified heating and transportation solutions, understanding the resulting changes in energy demand and grid load becomes critical. This chapter investigates how increased electricity consumption from HPs and electric vehicles influences peak demand, load distribution, and overall grid stability. Additionally, it examines the strategies and technologies necessary to accommodate these changes, ensuring that the grid remains reliable and resilient. By providing a detailed analysis of these impacts, the chapter aims to offer a comprehensive view of how electrification can be managed to support a sustainable and efficient energy system.

2.3.1. Overview of the UK electricity grid structure and capacity.

The UK still relies on gas to generate a higher portion of its electricity. On average, gas used to generate approximately 38 percent of the electrical energy, followed by wind at around 28 percent, and nuclear at roughly 15 percent, as seen on figure 2.5 (Martin, 2023).

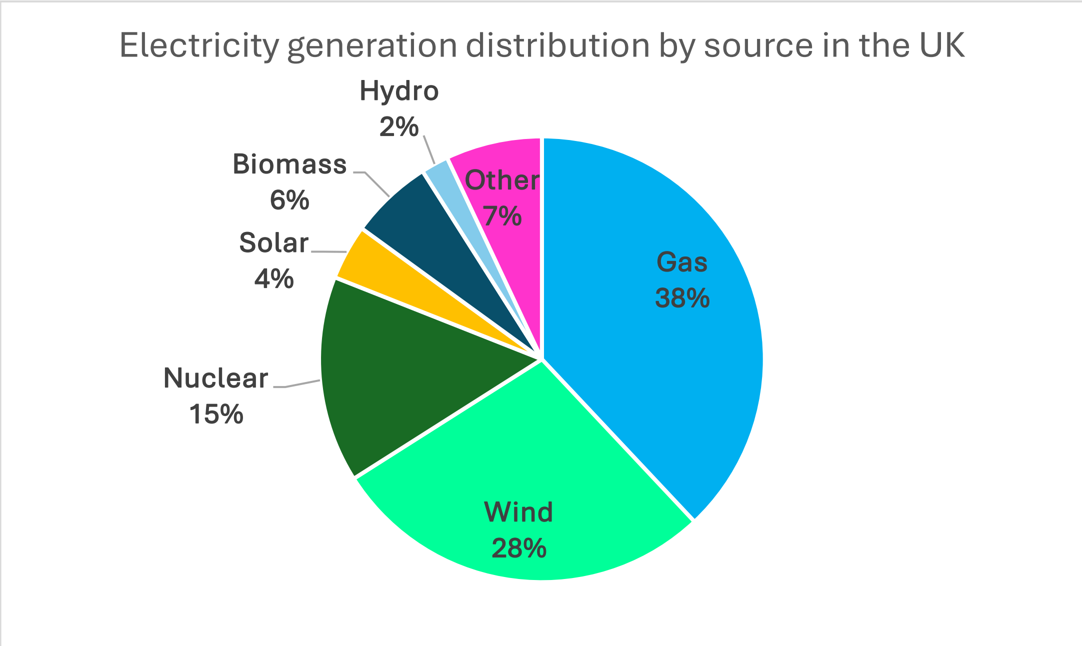


Figure 2. 5 *- Electricity generation mix in the UK (Martin, 2023)*

The electricity demand in 2022 has decreased by approximately 4 percent compared to 2021 (Martin, 2023). Despite that, the electricity generation in the UK in 2022 increase by about 5 percent compared to the previous year, which allowed the country to switch to be a net exporter for the first time in 40 years (Martin, 2023). For the past 12 years the generation of electricity from fossil fuels has fallen by approximately 54 percent, while generation from renewables is five times higher than 12 years ago in the UK (Martin, 2023). The country has also incorporated strategies to ensure decarbonisation of the energy and transport sector. For example, The Clean Growth Strategy outlines the government's plan to decarbonise all sectors of the country's economy from 2020 (Department for Business, Energy and Industrial Strategy, 2017).

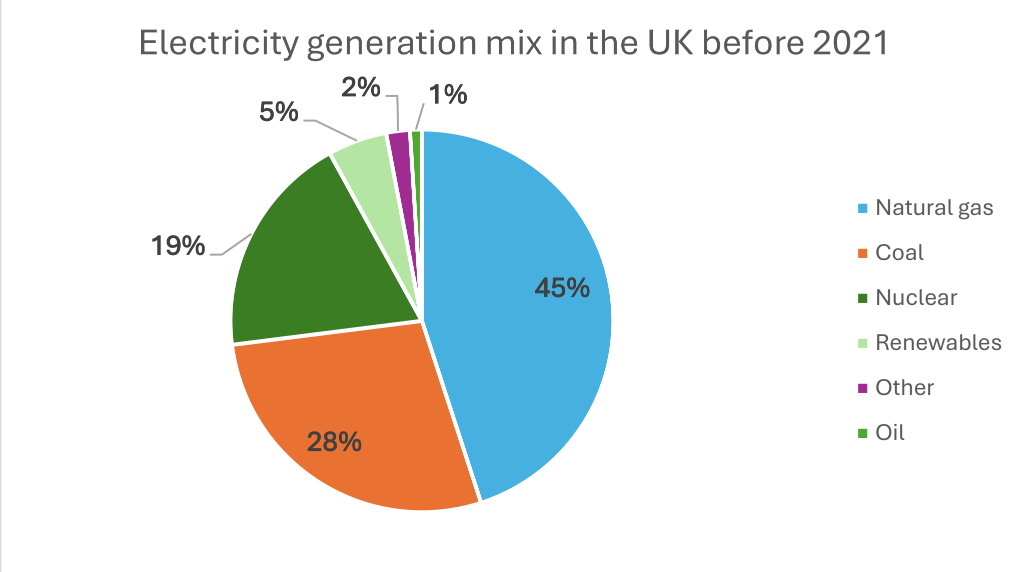


Figure 2. 6 *- Electricity generation mix in the UK (reproduced - DECC, 2010)*

Comparing figure 2.5 and 2.6 it can be concluded that in the recent the UK has reduced its reliance on fossil fuels to generate electricity (Martin, 2023).

Electrifying the transport and heating sectors would have a considerable impact on the energy grid system, not only in the UK but also worldwide. A study conducted in the UK, where 700 domestic heat pumps have been monitored to determine the effect on the grid network, estimated that the peak grid demand grew by approximately 7.5 GW or roughly 14 percent (Love et al., 2017). However, the insulation levels and building elements (i.e. type of walls, windows glazing) were not looked at details as this may affect how long the heat pump operates affecting the energy demand by the units. Another study investigated the unit thermal energy costs of different heating options before and during the energy crisis periods triggered by the Ukraine – Russia conflict (Zhou et al., 2024). It was revealed that heat pumps had a lower running cost than the majority of off-gas heating methods pre-crisis period, standing at below £0.07/kWh. However, during energy crisis period heat pumps reached £0.1/kWh becoming less competitive than LPG and Biomass as heating options but still have lower running cost than heating oil and coal (Zhou et al., 2024). However, the same gap is identified, as it is not clear how exactly this cost could be affected by UK dwellings insulation. To address this gap Objective 2 was developed, utilising case study interviews and a survey to determine how heating demand is affected by the building elements and how this impacts the electricity demand by the heat pumps. Additionally, research conducted by the author estimates how building elements affect the heating demand and how defrost cycles can affect that (Milev et al., 2023). A simulation of 550 thousand statistically representative dwellings in the US was conducted to determine how CO_2 emissions are affected and also the cost effectiveness of air source heat pumps (Wilson et al., 2024). It was revealed that the national carbon emissions would drop by approximately 5 to 9 percent. In addition, it was reported that air-to-air heat pumps could be cost-effective in around 60 percent of households without subsidies, however, efficiency and house insulation could play important roles. The climate in the UK is not the same as in the US, which suggests that heat pumps and heating demand overall will be affected differently. In addition, other factors such as level of insulation and heat pump sizing need to be investigated. That is why objective 1 has an important role in this thesis in finding out how exactly the heating demand and energy efficiency is affected for UK residents who utilise a heat pump in their home.

2.3.2. Analysis of load patterns and peak demand issues caused by electrification.

Despite the efforts by the government to promote heat pumps as an alternative to gas boilers, and the ongoing decarbonisation of the power grid in the UK, there are challenges in relation to the electrification of the heating and transportation sectors in the country. Furthermore, the country aims to decarbonise the electricity supply to achieve 80 percent reduction in carbon emissions as part of the requirements of the 2008 Climate Change Act (UK Parliament, 2008). The increased electricity demand presents challenges at a national level when it comes to electricity generation and the distribution infrastructure (Baruah et al., 2014).

Furthermore, it is expected that electricity demand will increase substantially with the use of heat pumps (Watson et al., 2023). The study acquired data from operational 550 heat pumps in the UK and estimated that with an assumed 100% uptake of heat pumps, the annual electricity demand in the country would increase by approximately 189 TWh in cold weather similar to the year 2020 (Watson et al., 2023). The study has determined this by estimating the COP of the units as a function of the outdoor temperature (Watson et al., 2023). However, they did not take into account how the house and wall type, along with insulation properties can impact the performance of the heat pumps and the electricity demand. A gap which this thesis will address through objectives 1, and 2.

A study that investigates the impact on the UK grid from large-scale installation of domestic heat pumps in the UK has incorporated a Building Research Establishment Domestic Energy Model (BREDEM) (Gupta & Irving, 2014). This model looked at the performance of heat pumps based on data from English Housing Survey from 2007 and analysed to predict what would be the electricity consumption between 2020 and 2050. Their model predicted that by

2020 the number of heat pumps installed would range between 560,000 to 1.8 million (Gupta & Irving, 2014). As of July 2024, only around 240,000 units have been installed in the UK (Harris & Walker, 2023), (Olympios et al., 2024). Furthermore, according to the English Housing Survey (2021-2022) (Department for Levelling Up, Housing & Communities, 2023) about 90 percent of space heating is supplied through gas boilers. The research by Gupta and Irving uses English Housing survey data from 2007 (Communities and Local Government, 2009). The sample size of the 2007 survey has approximately 2 million less houses included. In addition, at that time the majority of the dwellings were at ratings D and E (approx. 72% of the surveyed houses), whereas as of 2021, approximately 43 percent of the surveyed dwellings are within the A to C energy ratings, suggesting an improved insulation properties in the housing elements (Department for Levelling Up, Housing & Communities, 2023). Insulation can affect the heating demand and how much electricity is consumed by heat pump devices. A gap which has not been appropriately addressed by Gupta & Irwing in their study. To address this, a simulation model was developed to estimate the electricity consumption of an air source heat pump based on the insulation properties of a dwelling and the effect of the climate on the heating demand of the house (Milev et al., 2023) (Objective 1).

Another research has looked at the heat and electricity demand in detached dwellings in Germany and Italy, equipped with heat pumps and PV panels (Guo et al., 2024). They estimated the demand based on the heat pumps' performance. In their simulation they also included weather data. However, it is not clear what the wall types in the dwellings are and what exactly the insulation in the houses is. The study divided the insulation into three categories: high, medium, and low U-values, which does not clearly indicate the insulation properties of the dwellings. In addition, only detached houses were included in the analysis (Guo et al., 2024). To address this gap, different types of houses could be included, as this can also affect the heat and electricity demand by the heat pump in the dwelling.

2.3.3. Defrost cycles of air source heat pumps and their effect on the power grid

Defrost cycles are a crucial operational aspect of air source heat pumps (ASHPs), especially in colder climates where frost accumulation on the outdoor heat exchanger can impair efficiency. During defrost cycles, the ASHP temporarily reverses or disrupts its operation to melt the accumulated frost, which can lead to a significant, albeit temporary, increase in power consumption. This increase can contribute to peak load issues and impose additional strain on the power grid. Understanding the frequency, duration, and impact of defrost cycles is essential for accurately modelling ASHP performance and predicting their effects on grid stability. This sub-chapter explores the mechanics of defrost cycles, their influence on energy consumption, and the broader implications for grid management and planning in the context of widespread ASHP deployment in the UK.

The two common methods for removing frost from the outdoor heat exchanger in air source heat pumps are reverse-cycle and hot gas bypass methods (Huang et al., 2009). During reverse-cycle, the direction of the vapour compression cycle is reversed when defrost operation is initiated. Which means the indoor heat exchangers act as the evaporator and the outdoor as the condenser. With the hot gas bypass method, the refrigerant skips the condenser line, and the heat is re-directed to the outdoor heat exchanger (Huang et al., 2009).

A study comparing the two methods investigated which of the two is more efficient when it comes to defrost time and energy consumption (Huang et al., 2009). Through series of experimental tests on air-to-water heat pump, the authors fount that hot-gas bypass is more efficient than reverse-cycle in terms of defrosting speed and energy consumption. According to the authors findings, hot-gas bypass has a shorter defrost duration. In addition, this method maintains a more stable supply water temperature, providing more consistent heating performance. In addition, using this defrost method, according to the study's findings, leads to lower total energy consumption (Huang et al., 2009). However, the findings from this study do not provide a detailed analysis of how different defrost methods affect the overall power demand of the heat pump system.

Another study reviewed the defrosting of an air source heat pump using heat exchanger with phase change material (PCM) (Shen et al., 2019). According to the research's findings, using phase change materials can potentially improve the efficiency and reliability of ASHPs during frost conditions, and help maintain a more stable temperature, reducing the frequency of and duration of defrost cycles. Furthermore, according to the authors, the integration of PCMs can lead to a significant energy savings and improve the overall performance of the system, especially in colder climates (Shen et al., 2019). The authors acknowledge that defrost cycles typically lead to increased power demand in air source heat pump. However, they do not provide a detailed analysis of the exact increase in power demand during frost removal operations and the specific extent to which PCMs can mitigate this.

A method for determining the optimal start time for defrost cycles in air source heat pumps was also investigated in a study conducted by (Chung et al., 2021). The authors proposed a method for optimal defrost initiation time by tracking the amount of frost accumulation. The method relies on real-time monitoring of frost build-up. By quantifying the amount of ice on the evaporator, the proposed system can predict when defrosting will become necessary, optimising the timing and frequency of frost removal cycles. Furthermore, according to the authors, the proposed method reduced the operational cost and energy consumption associated with excessively or poorly timed defrost cycles (Chung et al., 2021). While their research addressed the optimisation of defrost cycles to enhance overall system performance, it does not delve deeply into the impact of these defrost cycles on power demand. Addressing this gap could provide an insight into the relationship between frost removal operations of air source heat pumps and power demand fluctuations and the effect on the power grid.

Another study comparing air source heat pumps equipped with a scroll and a reciprocating compressor, investigated the performance of defrost cycles (Payne & O'Neal, 1995). Through experimental setup with both types of compressors conducted tests on the air source heat pumps and compared the defrost cycle performance. According to their findings, scroll compressors tend to have different energy profiles, which impacts overall system efficiency and operating costs. Furthermore, scroll compressors were found to achieve faster defrost cycles, clearing frost from the coils more quickly, contributing to higher efficiency during frost removal operation. The authors report that the reason for the overall better performance of the scroll compressor during defrost cycles is due to its operational characteristics which can handle variations in load more effectively and generally have better performance in managing energy consumption during frost removal (Payne & O'Neal, 1995). The study provides valuable insights into the performance of different compressors, a more detailed analysis of how defrost cycles impact grid stability and overall power demand could help in understanding how widespread adoption of heat pumps might affect energy infrastructure, particularly in regions with high heating needs.

A study conducted by (Ma et al., 2023) presents a sophisticated dynamic modelling framework that accurately simulates air-source heat pumps (ASHPs) during frosting and reverse-cycle defrosting events. This model was validated against experimental data, ensuring its reliability in predicting heat pump performance under real-world conditions (Ma et al., 2023). While the framework effectively captures the impact of frosting and defrosting cycles on heat pump efficiency and power consumption, it does not extensively analyse the broader implications of these cycles on power demand and grid stability. This research gap suggests the need for further investigation into how defrost cycles influence overall power demand and grid dynamics, which could inform the design of more grid-compatible heat pump systems and strategies for managing peak loads.

Another research (Guo et al., 2008) that investigates the effects of frost accumulation on the performance of air source heat pumps (ASHPs), reports that frost significantly reduces heat transfer efficiency and overall system performance. Various defrosting strategies are evaluated, highlighting their importance in maintaining optimal efficiency. These findings were acquired through a series of controlled experiments using a test rig to simulate real-world conditions, collecting data on temperature, pressure, frost thickness, and system performance metrics (Guo et al., 2008). However, the paper does not delve into the detailed impact of defrost cycles on power demand and their influence on the power grid, which is a notable research gap. Addressing this gap would involve a quantitative analysis of power consumption patterns during defrost cycles and exploring their effects on grid stability, particularly during peak demand periods, to optimize defrost strategies for better grid efficiency.

2.3.4. Case studies or simulations of grid performance with increased ASHP and electric vehicle (EV) adoption.

A study that investigated the impact of uncontrolled charging of electric vehicles and utilisation of heat pumps in the UK, particularly in the city of Nottingham, provided a realistic simulation to understand the impact on the electricity grid from the increase numbers of EVs and HPs in the UK (Dik et al., 2024). In their research their focus was on semi-detached houses as these represent approximately 3 million in numbers compared to the total estimation of 30 million dwellings in the country (Dik et al., 2024). However, there are different types of houses in the country which could have different impacts on the heating demand by the heat pump depending on the house type and insulation level. That is why this gap needs to be addressed. Through objective 1, this PhD research will identify an approximate distribution of house types in the UK in percentage and how that affects their energy bills and heating satisfaction level. To further address this gap, this thesis also includes a study that has been conducted to better understand how house types and insulation affects the heating demand and energy usage by an air source heat pump in residential buildings the UK (Milev et al., 2023).

Another research by Milev et al. (2021) that investigates the environmental and financial implications of the mass adoption of electric vehicles in Scotland, highlights that increasing electric vehicle (EV) adoption in Scotland could significantly reduce greenhouse gas emissions and air pollutants, while also offering long-term financial savings due to lower fuel and maintenance costs. These findings were derived through data analysis, scenario modelling, and a case study approach focusing on Scotland's current EV market and energy grid (Milev et al., 2021). The paper notes that while the increased demand on the power grid is manageable with current technologies and grid improvements, it acknowledges a gap in the detailed examination of how peak load impacts and infrastructure requirements will be specifically addressed. To address this gap, these technical aspects could be explored in depth to provide a clearer roadmap for grid management and ensure a smooth transition to widespread EV use.

A research conducted by Leinonen et al. (2024) focuses on measuring the emissions of light-duty vehicles under real subfreezing conditions. The study took place in Finland, where the researchers used a mobile laboratory to "chase" vehicles and measure their emissions. Six vehicles (three diesel and three gasoline) were tested across different driving scenarios: cold starts, preheated cold starts, and hot starts. The researchers measured both gas emissions (CO, CO2, NOx) and particle emissions (size, black carbon concentration, etc.) under temperatures ranging from -9°C to -28°C. The goal was to assess real-world emissions under harsh winter conditions, with minimal external disturbances such as wind or road dust (Leinonen et al., 2024). There is no specific mention of research directly replicating this Finnish study under UK winter conditions. However, the cold weather performance of electric vehicles and their range in winter has been a topic of interest globally. Cold climates significantly affect EV battery performance, leading to reduced range and efficiency. While the UK does not face the extreme subfreezing conditions seen in Finland, winter still affects EVs. Research into this, particularly under UK conditions, could indeed be considered a gap, especially as the country moves toward widespread EV adoption. Addressing how winter conditions impact battery capacity and vehicle range in the UK would be essential for infrastructure planning and consumer confidence. Objective 4 will address this research gap.

2.4. Energy Efficiency and Demand Management

Effective energy efficiency and demand management are crucial for optimizing the performance of air source heat pumps and ensuring their successful integration into residential heating systems. Chapter 2.4 focuses on strategies to enhance energy efficiency within buildings equipped with ASHPs, examining how various approaches can minimize heating demand and maximize system effectiveness. This chapter covers key topics such as improving building insulation, optimizing ventilation, and implementing advanced control technologies. By addressing these aspects, the chapter aims to provide insights into how energy efficiency measures can contribute to lower operational costs, reduced energy consumption, and overall system performance. Additionally, it explores the role of demand management in balancing energy use, particularly during peak periods, to support a stable and reliable electricity grid.

2.4.1. Strategies for improving energy efficiency in buildings using ASHPs.

Enhancing energy efficiency in buildings is a critical component of maximizing the benefits of air source heat pumps (ASHPs). Efficient building design and retrofitting can significantly reduce the heating demand, enabling ASHPs to operate more effectively and economically (Eicker, 2014). Strategies such as improving insulation, sealing air leaks, and optimizing ventilation systems play a vital role in minimizing heat loss and maintaining comfortable indoor temperatures (Eicker, 2014). Additionally, integrating advanced controls and smart thermostats can further optimize ASHP performance by adjusting heating schedules based on occupancy and weather conditions (Langley, 2001). This sub-chapter explores various strategies for boosting energy efficiency in buildings equipped with ASHPs, emphasizing the importance of a holistic approach to building design and energy management to achieve substantial energy savings and enhance overall system performance.

A study by Sezen & Gungor (2022) investigated how environmental conditions impact the performance of air source heat pumps. The study employs a detailed mathematical model to analyse the effects of outside temperature and relative humidity on the coefficient of performance and heating capacity of ASHPs. The findings reveal that both the COP and heating capacity decrease with lower outside temperatures and higher humidity levels, which can lead to frost formation and further efficiency reductions (Sezen & Gungor, 2022). However, the research does not explore the impact of different house types and insulation levels on heating demand and energy consumption by heat pumps, identifying a gap that can be addressed by incorporating building characteristics into performance evaluations to provide more comprehensive and practical guidance on ASHP efficiency in various residential settings.

In a research by Hewitt et al. (2011), involving a rotary compressor combined with a vapour injection and the effect on an air source heat pump performance in cold weather while maintaining high indoor and radiator temperatures was investigated (Hewitt et al., 2011). The study confirms the fact that retrofitting ASHP in dwellings with undersized underfloor heating can be challenging for the device to deliver high temperatures, satisfy the heating demand, and maintain high performance in cold weather. There it was also mentioned the importance of lower electricity demand by the compressor to reduce strain on the grid (Hewitt et al., 2011). However, the research did not address this gap in detail. Specifically, how power demand by the ASHP can be reduced and how to satisfy the heating demand and maintain the desired indoor temperature. Factors such as house insulation and appropriate radiator sizes and their effect on the HP performance and electricity demand were not discussed either (Hewitt et al., 2011).

Another study investigated how environmental conditions, specifically outside temperature and relative humidity impact the performance of air source heat pumps. The study employs a detailed mathematical model to analyse the effects of outside temperature and relative humidity on the coefficient of performance and heating capacity of ASHPs. The findings reveal that both the COP and heating capacity decrease with lower outside temperatures and higher humidity levels, which can lead to frost formation and further efficiency reductions. However, the research does not explore the impact of different house types and insulation levels on heating demand and energy consumption by heat pumps, identifying a gap that can be addressed by incorporating building characteristics into performance evaluations to provide more comprehensive and practical guidance on ASHP efficiency in various residential settings.

2.4.2. Demand-side management techniques to mitigate peak loads.

In order to achieve sufficient understanding of heat pumps, it is important to become familiar with the heat demand in the UK. It was estimated that approximately 47 per cent of the total energy consumption in the United Kingdom was utilised for heating in 2012 (DECC, 2013). Domestic usage of heat contributed for 57 per cent of the total heat energy that has been used in that period, the industry and service sector has used 24 and 19 per cent respectively. A closer look at the domestic sector for 2012 reveals that 63 per cent of the heat utilised was for space heating and 14 per cent for water heating processes. In the UK for 2012, heat was generated through the usage of gas (71 per cent) and electricity (15 per cent), the rest 14 per cent were allocated to oil, solid fuel, and bioenergy (DECC, 2013). 70 per cent of the thermal energy used for space heating in the UK for 2012 was from the domestic sector (DECC, 2013). This data reveals that the domestic sector consumes heat energy the most. The available data for 2020 shows similar results. Around 33 per cent of the gas was consumed by the domestic sector, approximately 28 per cent was utilised from power stations, and around 10 per cent used by the industrial sector (Department for Business, Energy & Industrial Strategy, 2021).

A study conducted in Derby examined the heating consumption in a residential house (Eames et al., 2014). Figure 2.7 estimates the profile of the heat generation by a heat pump and the load shifting on the electrical grid allowed by the inclusion of a thermal storage with a capacity of 36 kWh (Eames et al., 2014). The capacity of the Heat Pump used by the house is 6 kW and the COP is 2 (Eames et al., 2014).

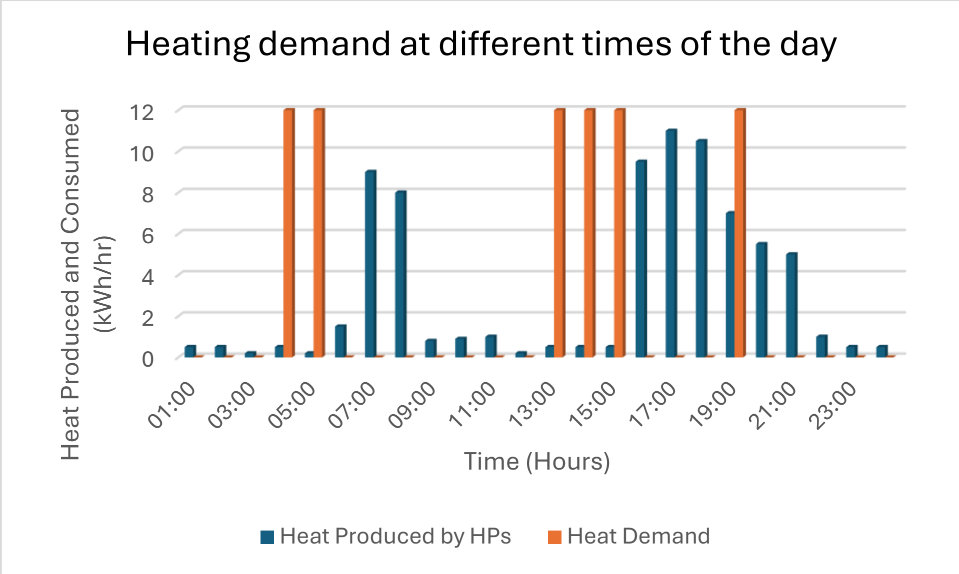


Figure 2. 7 *- Heat generated by HP and the load shifting utilised to reduce the electrical loads (reproduced graph, Eames et al., 2014).*

While the report by (Eames et al., 2014) covers many aspects of thermal energy storage technology and its integration into the UK energy system, it might not delve deeply into specific scenarios of how the power grid will cope with the transition towards higher heat pump adoption. This could be considered a potential gap, as a more detailed analysis of grid strain under different adoption scenarios and specific mitigation measures could provide further insights for policymakers and energy planners.

Sensible heat storage has a major part in the thermal storage systems in the UK, even though latent-heat storage is more efficient. The volumes of the systems can reach up to 70,000 m3 (Eames et al., 2014). A case study in Pimlico district heating conducted by Eames et al. (2014) revealed that thermal storage systems have the advantage of balancing the supply and demand of thermal energy and in ensuring that all residents' buildings and houses that are connected to supply system are provided with hot water and heat efficiently and their needs are met (Eames et al., 2014).

A study has shown that air source heat pumps combined with domestic hot water systems can be very efficient, but it is important to determine whether a centralized or individual system is more efficient. An individual system means that each house or apartment has air source HP and a water tank, whereas the centralized is a building or houses sharing one air source HP with higher capacity and one water tank with higher volume or several HPs with less capacity and several water tanks with smaller volumes (Guo and Goumba, 2018). Each location/apartment within a building or the house is connected to the shared heat network if centralized system is used. The study has shown that the COP of the individual system is 2.83, whereas the centralized one has reached 3.02 (Guo and Goumba, 2018). The reason for that is the over-sizing factor of smaller tanks. In addition, there is less heat loss from the tanks in a centralized system compared to all the individual water storages combined. The reason for that is the so called "scale effect", storage tanks with larger volumes are not exposed to high thermal loss at the boundaries (Guo and Goumba, 2018). For the same energy consumption of 16,770 kWh, the centralised installation requires overall less generation of electricity and there are also reduced thermal losses of the tanks in the combined class system (Guo and Goumba, 2018).

2.4.3. Role of smart grids and advanced metering infrastructure in balancing demand and supply.

A recent trend among heat pump technologies is the fact they can be connected to a smart grid or network, where electricity and heating is generated by renewable energy. There is a growth of wind turbine and photovoltaic plants (PV) usage (Fischer and Madani, 2017). In some cases, individual households utilise personal turbines, but in most cases the number of PVs is significantly higher compared to wind generators. In such cases, this would result in the supply and demand of electricity at different slots of time, which therefore could help shifting the electric energy demand (Behrangrad, 2015). The Paris Climate Change Conference in 2015 (COP21) set out an agreement to limit the rise of global warming temperatures to 1.5 – 2 °C (European Commission, 2015). This means that not only the reduction of coal-fired power is required but also the decrease of carbon emissions from the electricity production and heating sectors as a whole. That stimulates the usage of renewable energy further and the operation of heat pumps connected to a smart gird (Fischer and Madani, 2017). Simulations conducted in Germany, which investigated and analysed various pathways for renewable energy in the country, revealed that HPs can have a major contribution when it comes to the de-carbonisation of the thermal energy sector (Henning and Palzer, 2014). Another analysis case in Denmark revealed that a combination of heat and electricity plants with district heating schemes and personal HPs would allow an optimal solution for the transformation of residential thermal energy sectors in a direction to lower carbon emissions (Lund et al., 2010). In the UK, a simulation was conducted to investigate the relation between heat pumps and carbon emissions in a scenario involving long time-period. It was revealed that there is a high potential for the reduction of carbon dioxide emissions (Cockroft and Kelly, 2006). The major issue that comes with the increased utilisation of renewable energy is their considerably low power capacity and the possibility to satisfy the needs of the user, to supply residents with enough electricity, and with the increasing number of heat pumps, the demand for more electrical energy will increase as well (Vittal, 2010). Generally, there are fluctuations of the production and utilisation of electricity (Lund et al., 2015). In order to balance these fluctuations of the production and demand and to promote flexibility between them, the implementation of thermal and electrical storage systems is necessary (Weitemeyer et al., 2015).

Heat pumps into buildings, can not only aid in shifting the load during peak times, but they can also improve the efficiency of thermal storages presented and provide with additional heat if needed (Fischer and Madani, 2017). If water is utilised to distribute heat, it allows thermal energy to be easily storaged in tanks and also enables the building to be used as a storage, its ground and walls can contribute for maintaining the room temperatures by conducting additional heat that has been storaged (Hong et al., 2012). It was also estimated that in the building stock for the UK, it is possible to stop the work of heat pumps for approximately one hour and a half without interrupting the heat comfort of the residence. The reason for this is the proper thermal energy storage systems allowing more heat to be storaged for longer periods of times, but that also requires the installation of buffer tanks and optimal insulation in the building (Hong et al., 2012). It was also concluded that the composition and the size of the flooring material, and the size of the floor itself can affect the comfort of the indoor space during the time of shifting the load performed by HPs. A combination between phase-change materials and the materials used for flooring and covering the walls can improve the comfort and offer more flexibility (Cabrol and Rowley, 2012). An experiment combining the active storage of tanks and the passive storage of the building mass (i.e., walls, floor), which are made in an existing building, revealed that the efficiency of thermal storage was higher and also more effective regarding the cost when using only accumulated thermal energy from tanks. In that experiment the flexibility of heat pumps was utilised to implement energy generated by wind turbines (Hedegaard et al., 2012). In Europe, there are buildings that are equipped with HPs. In such cases it is more optimal to connect the heat pumps to hydronic systems presented in the buildings and to a heat storage tank. The tanks are utilised as a buffer for domestic hot water provision and also for space heating. (Rink, Gourishankar and Zaheeruddin, 1988).

It was estimate that in 90 per cent of existing buildings and in approximately 80 per cent of new or recently constructed buildings in Germany, with heat pumps installed, are also equipped with heat storage tanks (Platt, Exner and Bracke, 2010).

Ground source HPs can operate in a combination with electricity from renewable resources systems whether they are wind generators or PVs. That kind of combination allows the conversion of electric energy from the renewable sources to thermal energy and that heat can be storaged in the borehole for later use (De Ridder et al., 2011).

The performance of the heat pumps can be affected by regulating their capacity and the variability of the heat demand plays a vital role in that influence. Heat pumps, which do not operate at fixed speeds, allow for their compressors to be regulated, which consequently affects the performance of the whole system. It also permits for better control over electric energy demand and the heat output (Fischer and Madani, 2017). In cases where it is possible to increase or reduce the consumption of electricity from the smart grid applications, that enables the operation of the system with higher flexibility, which consequently improves the energy quality (Dallmer-Zerbe et al., 2016).

It is possible to combine heat pump systems with other heat sources such as mono-energetic systems (i.e., electric heaters) or bi-valent systems (i.e., gas boilers) to cover the peaks on the demand of thermal energy. If only heat pumps are utilised for thermal energy provision, the system is known as monovalent. Depending on the source of the additional heat system, the SCOP and carbon emissions can be affected (Fischer and Madani, 2017).

There are issues that could cause limitations on the flexibility of heat pumps. The potential of the flexibility is affected by various factors (Fischer and Madani, 2017). Thermal demand in residential buildings is defined as the sum of heat load and hot water demand for domestic utilisation. There are some factors that determine the range of the energy demand throughout the year. These factors are the location of the building, type of the building and the behaviour of the residents (Fischer and Madani, 2017). The capacity of heat pumps poses limitations regarding the ability to simply increase or reduce the electricity consumption of the HP by turning it off or on. Generally, there is a difference between the generation of heat by the HP system and the actual thermal energy demand, and that difference determines the fluctuation of the storage's thermal content (Fischer and Madani, 2017). In cases, where the capacity of the heat pump is lower than the heat demand, the only option that would allow flexibility is to decrease the thermal energy generation by the HP, and that would only be possible if the thermal storage is not empty. If the heat pump's capacity is higher than the thermal energy demand, it would be possible to raise the heat output of the heat pump, allowing the storage to be charged (Fischer and Madani, 2017). The efficiency and maximum heat capacity of the air source HP is affected by the ambient temperature, which means the flexibility available fluctuates throughout the year. In order for the heat pump to help increase the indoors temperature, the system requires the heating circuit to operate with higher temperatures, which consequently can impact the HP's capacity and COP by decreasing them, and that additionally lowers the possibility for a flexibility during peaks in thermal energy demand (Fischer et al., 2014). Thermal storage systems, and their capacity and type specifically, can affect the amount of energy that can be shifted for a particular time-period. The heat pump temperature determines the maximum temperature of a water tank, which is a limitation for the thermal storage systems such as the water tank (Fischer and Madani, 2017). An important factor for the flexibility of the load shift is the dynamic settings of the heat pump. The speed of the compressor limits the response speed, which consequently changes the rate of the electricity consumption over a specific time-period. Most of the HP units are equipped with a minimum run and pause-time, which additionally reduces the flexibility (Fischer and Madani, 2017).

UK's National Grid has predicted that by 2040, between 1 and 8 million heat pump units will be utilised in the United Kingdom (National Grid, 2017). Heat pumps are considered as a solution for decentralised supply of multi-energy and their massive utilisation will increase the overlap between thermal and electric systems, which consequently will increase the implementation of renewable energy (Liu et al., 2016). Introducing energy storage systems is a way to mitigate the renewable energy output's gaps. The combination of battery usage and photovoltaic systems is one of the solutions for the wide use of applied energy storage (Parra and Patel, 2016).

It has been predicted that the wide usage of heat pumps will cause changes in the demand pattern, and they will also affect the integration of photovoltaics, which consequently will affect the energy storage revenue (Liu et al., 2019). The implementation of HP systems will impact the load profiles of the users, and they will probably cause the variability of the net-load to raise, which will be reflected mostly during mid-season periods (Liu et al., 2019). A simulation of the introduction of heat pumps into a grid with a combination of PVs revealed that the wide usage of HPs will increase the self-consumption ratio from the energy consumption of the midday overflow from PVs and the battery storage's optimal capacity will be reduced (Liu et al., 2019). In order to achieve an optimum point for the design and integration of multi-energy district, it is important to consider the energy storage's interdependency, and the technologies required to convert the distributed energy that will change the demand's pattern (Liu et al., 2019).

The research conducted by (Fischer and Madani, 2017; Henning and Palzer, 2014; Cockroft and Kelly, 2006; Vittal, 2010; Weitemeyer et al., 2015) collectively cover aspects of integrating renewable energy, grid performance, and heat pump technology but may not specifically focus on the detailed strain caused by the mass adoption of heat pumps or provide comprehensive mitigation strategies for this issue. Addressing the specific impact of heat pumps on grid strain and developing targeted strategies for mitigation, such as through advanced grid management techniques, demand response programs, or specific storage solutions, might be valuable areas for further investigation.

2.5. Integration of Renewable Energy Sources

In light of combating climate change and reducing carbon emissions, many countries plan to electrify the transport and heating sectors (Dik et al., 2023). This suggests that the additional electricity demand would require careful management. Specifically, what sources will be used to meet the new electricity loads. It is expected that large proportions would be met by renewable sources (i.e. solar, wind) in order to limit carbon emissions from the energy sector as much as possible (Dik et al., 2023).

2.5.1. Potential for integrating ASHPs with renewable energy sources (e.g., solar, wind).

Currently, the transport and residential sectors account for approximately 26% and 16% of the UK's total carbon emissions, respectively (Waite, 2023). These two sectors in particular are difficult to decarbonise (Dik et al., 2023). As pointed out by (Dik et al., 2023), large-scale renewable energy system integration could pose challenges on the stability and reliability of the grid. In their study, the authors suggest a solution, where electric vehicles can be utilised to supply homes with power at peak times (between 5 pm and 9pm in the evening, and between 6 am and 8am in the morning). In addition, in their study (Dik et al., 2023) also consider solar-assisted air source heat pumps to further reduce the strain on the grid itself. They utilised data from (Owen & Foreman, 2012), which monitored 26 dwellings over a period of 1 year to estimate their annual energy consumption and determine the average daily power demand profile. The annual consumption was estimated for each type of dwelling (i.e, terraced, detached, etc.) and an average annual energy demand was determined. However, electric heating was excluded from both the study conducted by (Owen & Foreman, 2012). In the end (Dik et al., 2023) concluded that solar assisted ASHP's COP can reach 2.8 on a cold day, reducing the electricity demand by the device by roughly 13.2%. In addition, the solar assisted HP would allow up to 1 extra hour for the EV discharging for the house's electrical demand. However, the authors have not taken into consideration the insulation levels of the house included in their study. Poor insulation properties may have an impact on the heating demand of the dwelling, therefore affecting the HP's power demand. In addition, defrost cycles of ASHPs could also have an effect on the power consumption by these devices.

2.5.2. Challenges and opportunities in achieving a low-carbon grid.

Power demand is necessary to maintain the current modern lifestyle. While maintaining a reliable power supply, low carbon should also be achieved at the same time. One of the ways to do that is through the Smart grids. A smart grid is an advanced electrical grid that utilises digital technology to communicate, monitor, and manage the flow of electrical energy from power plants to consumers. It improves the reliability, efficiency, and sustainability of electricity services through the integration of renewable sources of energy, allowing real-time data exchange, and enabling automated control and optimisation of the power supply (Drtil et al., 2023). A study exploring the integration of smart grid technology with the modern energy industry for achieving low-carbon development, concluded that such implementation not only would achieve low-carbon grids, but also the need for a holistic approach that considers technical, economic and regulatory aspects to ensure an efficient and sustainable energy future (Zheng, 2024). However, the author did not mention the role of heat pumps, and it misses a considerable component of how smart grid systems can further enhance energy efficiency and contribute to low-carbon development. Heat pumps are an essential technology that could play a crucial role in smart grids. Particularly, in managing heating and cooling demands efficiently. Gas still remains one of the major sources of heat in the UK, even with the changing prices. However, to reach the low carbon targets, the country is set to reduce its reliance on fossil fuels, including for heating (Gross & Hanna, 2019) (Hoseinpoori et al., 2023). Some of the low-carbon heating alternatives include heat pump and hydrogen boilers. However, they require higher upfront investment than the existing fossil fuel heat supply (Sahni et al., 2017). This in turn can pose a challenge for the adoption of low-carbon alternatives for heating. In a study comparing alternative pathways for the future of the gas grid and how it can be integrated in a low-carbon infrastructure, hydrogen and heat pumps were examined to determine which would be better to achieve low carbon emissions and reduce strain on the grid network (Hoseinpoori et al., 2023). Through scenario analysis and techno-economic modelling, the authors found out that hydrogen can be a viable option for heating if low-carbon methods for production are used. However, according to their findings, significant changes in infrastructure and advancements in hydrogen production technology are required (Hoseinpoori et al., 2023). Furthermore, in their research, they estimated that direct electrification through heat pumps present the highest potential for decarbonisation as it leverages existing renewable electricity. However, according to their findings, fully electrifying the heating supply via heat pumps necessitates substantial upgrades to the electrical grid and increased electricity generation capacity will be needed (Hoseinpoori et al., 2023). However, the authors do not address hydrogen production and its implication for electricity demand. They acknowledge that producing hydrogen, particularly through electrolysis, requires a considerable amount of electricity. However, this increased electricity demand could pose a larger strain on the grid network, particularly if the hydrogen is utilised for heating at a large scale. Furthermore, the study does not explicitly analyse how defrost cycles of air source heat pumps can affect their energy consumption and overall efficiency. In addition, the research by (Hoseinpoori et al., 2023) does not provide a detailed examination of how the type of dwelling and their insulation properties impact heating demand and the overall performance of the heat pump. A detailed analysis of how defrost cycles and varying insulation properties influence the efficiency and energy consumption of air source heat pumps could provide a better understanding of the challenges and requirements for integrating low-carbon heating solutions into the existing infrastructure.

Another paper studied the potential of heat pumps to reduce carbon emissions in the context of China's carbon neutrality goals (Dong et al., 2023). The authors examined different scenarios and models to estimate the potential carbon savings from large scale adoption of heat pumps. They confirm that these devices can significantly reduce carbon emissions in China, especially if they are powered by renewable energy sources (Dong et al., 2023). However, they do not provide detailed analysis or differentiation based on house types or insulation levels and how these factors can affect heating demand and energy consumption by the heat pumps. Instead, their research focuses on a macro-level analysis of heat pumps across different sectors in China, primarily considering total heating demand and carbon reduction potential at a national scale. Addressing this gap would involve analysing the impact of building characteristics and evaluating how variation in heating demand due to these factors influence energy consumption and efficiency of heat pumps.

2.5.3. Impact of renewables on grid stability and reliability.

As the energy and transportation sectors account for the majority of carbon emissions globally, many countries in Europe are set to adopt electric vehicles and heat pumps to achieve low-carbon levels in these sectors (Damianakis et al., 2023). With low carbon technologies that rely on electrical energy to be powered, it is expected huge electric load to occur in future distribution grids. Particularly, in the UK there are peaks in power demand in the morning and in the evening. Even with COVID-19 restrictions, the demand curve did not change considerably (Milev & Al-Habaibeh, 2023). Electrifying the energy and transport sectors could put further strain on the power grid.

A study assessing the impact of electric vehicles, heat pumps and PVs on the low voltage distribution grid in the Netherlands determined through simulation models involving EV charging and HP operation that increased EV penetration could lead to higher peak loads and potential grid congestion. With heat pumps, the electrical demand will significantly increase in winter, and PV systems can contribute to voltage fluctuations and power quality issues due to their intermittent nature (Damianakis et al., 2023). The authors mention that their simulation model considers building specifications and insulation models. However, it does not provide detailed differentiation between various house types and specific insulation levels. Instead, they use generalised parameters for thermal capacity and building volume in their simulator. Addressing this gap could improve the accuracy of predicting dwellings' heating demand and energy consumption by heat pumps.

In a similar study, a detailed analysis on the impact of emerging technologies on the electricity load profiles in German residential areas was conducted (Fischer et al., 2020). Through the Stochastic Bottom-Up model, the authors have estimated the energy demand profiles for electric cars, domestic hot water, and space heating. Furthermore, through randomisation, heat pump performance, and behavioural model for EVs, the authors not only considered the differences in building types, energy types in the heat load profiles, but also estimated the heat pump performance and maximum thermal output based on the temperature difference between the heat source and heat sink. In addition, in their research (Fischer et al., 2020) used data from over 70,000 vehicle trips to simulate EV usage. In their findings, the authors estimated that heat pumps can significantly increase electricity demand in single-family homes, leading to approximately 13.27 MWh/year energy demand depending on the building class. Furthermore, in their findings, the authors estimated that EVs can further increase annual electricity demand by a factor of 1.6 (Fischer et al., 2020). The study findings indicate that heating demand is influenced by the type, energy standard, and orientation of buildings. However, the research does not provide a detailed breakdown of the specific insulation elements used in the buildings. Instead, it treats insulation as one of several factors that are randomised to generate variability in heat profiles. The lack of detailed analysis on specific insulation elements presents a potential research gap. Addressing it could provide more precise information into how different insulation materials can influence heating demand and heat pumps' energy consumption.

Another study that examined the future implications of increased electric vehicle and heat pump adoption on low voltage distribution networks focused on projected electricity demand and the subsequent impact on network performance (Oliyide & Cipcigan, 2021). Through historical and projection data on electricity demand, different scenario analysis for EVs and

HPs adoption, and load profiling and simulation the authors forecast a significant increase in electricity demand due to the widespread adoption of electric cars and heat pumps. Additionally, their analysis shows that the additional loads from electric cars and heat pumps will increase the loading on network feeders, leading to potential voltage deviations, especially in peak times. The study also identifies variations in electricity demand across different seasons and times of the day, showcasing the need for network adaptations to manage these fluctuations (Oliyide & Cipcigan, 2021). However, their research does not include detailed analysis of house types and insulation levels on dwellings' heating demand and subsequent energy consumption by heat pumps. Investigating the specific impacts of different house types (i.e., detached, semi-detached, etc.) on heating demand, analysing the role of varying insulation levels to manage heating demand and improve heat pump efficiency, and exploring how these factors interact with projected increase in EV and HP adoption can address these gaps and it would provide a more comprehensive understanding of the factors affecting residential electricity demand.

2.6. Economic and Environmental Impacts

As the adoption of air source heat pumps becomes more widespread, understanding their economic and environmental impacts is essential for evaluating their overall effectiveness and sustainability. Chapter 2.6 focuses on two critical aspects: lifecycle emissions and the economic implications of deploying ASHPs. This chapter provides an in-depth analysis of the lifecycle emissions associated with ASHPs, from production to disposal, and compares them with traditional heating systems. Additionally, it explores the economic considerations, including cost-effectiveness for ASHP adoption. By examining these factors, the chapter aims to offer a comprehensive perspective on the role of ASHPs in achieving a sustainable, low-carbon future while addressing financial viability and environmental impact.

2.6.1. Cost-benefit analysis of ASHP adoption for consumers and utilities.

Heat pumps benefit from higher performance compared to other heating methods (Langley, 2001). However, these devices run on electricity. Between May 2020 and August 2022, the price of electricity has increased from around £24/MWh to approximately £364/MWh (Statista, 2024). Since May 2023 the cost per MWh has slowly been decreasing. As of April 2024, the cost of electricity is approximately £60/MWh which is still higher compared to pre-2021 period (Statista, 2024). Currently in the UK, the cost of gas is approximately 5 times lower per/kWh compared to electricity. These factors, combined with the cost-of-living crisis and the higher initial cost of heat pumps (Ahmed & Vekony, 2024) could explain the lower adoption rate of these devices in the UK as discussed in Chapter 2.2. In addition, locational pricing can also have an impact on the number of heat pumps being installed (Eicke and Schittekatte, 2022). Locational pricing is a market structure for different electricity prices which is based on the location used within the grid network (Liu et al., 2009). Such pricing could create market conditions that better reflect the actual cost of generating and distributing electricity, but it could also lead to higher operational cost for heat pumps in regions with higher heat demand projections (Lyden et al., 2024). Due to varying electricity prices from locational pricing across different regions in the UK could result in significant geographical disparities in heat pump running cost (Lyden et al., 2024).

A study investigating the optimal sizing and operation of a combined PV, battery energy storage system, and a heat pump system for a townhouse located in Lahti, Finland, focused on reducing the life cycle costs of the energy system. The examined period was over 30 years while maintaining energy efficiency and sustainability (Meriläinen et al., 2023). An hourly simulation model was developed in MATLAB and the data for the simulation included measured electricity consumption, simulated heat generation that was based on annual oil consumption and simulated solar PV power generation. The research found that a 60% partial-powered-dimensioned ground source heat pump combined with a solar PV system resulted in the lowest life cycle cost. Furthermore, the cost-effectiveness of a battery energy storage system is evident at 2022 electricity prices, resulting in substantial cost savings (Meriläinen et al., 2023). The study showed that improvements in building envelope insulation could significantly reduce heating demand, especially in colder months. While the study provides a comprehensive analysis of the cost-optimal dimensioning and operation of a combined energy system, it does not delve deeply into the specific effects of different housing elements (i.e., wall thickness, wall insulation, etc.) on heating demand by the dwelling and the energy consumption by heat pumps (Meriläinen et al., 2023). Addressing this gap could lead to more tailored and effective energy efficiency measures, further optimising the performance of heat pumps in various housing types.

In another study the performance and cost-effectiveness of heating systems using a heat pump and latent thermal energy storage in a single house in Croatia was investigated (Torbarina et al., 2024). The authors conducted a simulation using TRNSYS software. The simulation was based on a reference house in Croatia built between 1971 and 1986 with a net usable area of 200 m², and meteorological data from Zagreb was used with the heating season defined from late October until early April. The U-values for different elements (i.e., walls, doors, windows, roofs) were also included in the analysis (Torbarina et al., 2024). The authors compared the system with various configurations of phase change materials and solar collector areas. They conclude that the heating system integrated with a heat pump and latent thermal energy storage is both cost-effective and efficient in cold weather conditions (Torbarina et al., 2024). However, the study focuses on a single house type with specified U-values based on current technical regulations. It does not explore the impact of different insulation levels or variations in house types on heating demand and energy consumption. Addressing this gap would provide more understanding of the system's efficiency and how it can be influenced by different insulation levels.

Another study investigated the cost-effectiveness of the fabric-first approach to residential decarbonisation in Ireland. The authors employed the TIMES-Ireland Model to evaluate the entire energy system and its independencies (Mc Guire et al., 2024). Through their study, the authors found out that the current fabric-first approach requires extensive thermal retrofit, in particular approximately 22 times more than alternative pathways to meet climate targets. This is associated with higher initial costs, significant disruptions, and potentially higher decarbonisation costs (Mc Guire et al., 2024). According to the findings, higher heat loss indicator threshold for heat pump subsidies could reduce costs significantly. The authors addressed a significant gap by scrutinising the cost-effectiveness of the fabric-first approach and proposed alternative strategies (Mc Guire et al., 2024). However, it could be considered that more granular analysis or a broader range of insulation scenarios might further illuminate optimal pathways. In particular, the study could delve deeper into the long-term effects of different insulation levels on heat pump efficiency and overall energy consumption.

Thermal storage systems could influence the running cost of heat pumps and offer cost-effective solutions for electrifying the heating sector (Iñigo Agirre-Muñoz et al., 2024). Another study that investigated the performance and scalability of a latent heat energy storage system designed for use with heat pumps, provides a comprehensive evaluation of a novel energy storage technology (Iñigo Agirre-Muñoz et al., 2024). The authors reported that macro-encapsulating phase change material systems can help reduce material cost and simplify the manufacturing process. Their research shows that the system can be scaled up without significant loss of efficiency, making it suitable for both residential and commercial use. The authors have included practical aspects such as insulation, maintenance, and integration with existing heat pump systems, indicating that the macro-encapsulated phase change material system is a feasible and practical solution for enhancing the efficiency of heat pumps (Iñigo

Agirre-Muñoz et al., 2024). Although the focus of the paper is primarily on the experimental performance and upscaling potential of this novel technology that can improve heat pump performance, the specific effects of different house types and insulation levels on heating demand and heat pump energy consumption have not been accounted for in detail. Addressing this gap would provide a better understanding of the system's performance in real-world applications and help optimise its integration into diverse residential settings.

House insulation can improve energy bills, especially in a scenario where heating is electrified through heat pumps (Wilson et al., 2024). A study examining the costs and benefits on how residential air-source heat pumps in the US focused on how different factors, such as attic insulation levels can impact the running cost and overall effectiveness of heat pumps (Wilson et al., 2024). The authors evaluated the economic viability and energy efficiency of ASHPs across US regions using a combination of simulation models and empirical data to estimate heating demand and energy consumption. They found out that homes with better attic insulation experience lower running costs and more efficient operation of HPs (Wilson et al., 2024). The research provides valuable insights into how attic insulation levels influence the running cost and efficiency of residential ASPHs in the US, taking into account various house types and insulation levels. However, there remains a gap in the comprehensive analysis of other insulation types and their interaction with additional energy efficiency measures.

2.6.2. Lifecycle emissions and sustainability considerations of ASHPs.

Evaluating the lifecycle emissions and sustainability of air source heat pumps (ASHPs) is crucial for understanding their true environmental impact compared to traditional heating systems. Lifecycle analysis involves assessing emissions from the production, installation, operation, and disposal phases of ASHPs. While ASHPs significantly reduce operational carbon emissions by utilizing renewable electricity (Naumann et al., 2022), their overall sustainability also depends on factors such as the materials used in their manufacture and the energy sources powering the grid. Additionally, considerations around the end-of-life disposal and potential for recycling components are essential for minimizing environmental impact. This sub-chapter delves into the comprehensive assessment of ASHP lifecycle emissions, comparing them to conventional heating methods, and explores strategies to enhance the sustainability of ASHPs throughout their lifespan.

A study conducted by (Naumann et al., 2022) compared the environmental impacts of an air-source heat pump (ASHP) and a condensing gas boiler (CGB) using both attributional and consequential life cycle assessment (LCA) approaches. The findings indicate that ASHPs generally exhibit lower greenhouse gas (GHG) emissions than CGBs, especially when powered by renewable energy. The attributional LCA (ALCA) assesses the current environmental impact, while the consequential LCA (CLCA) considers future scenarios and market changes, highlighting the significant influence of energy policy and grid decarbonization on the benefits of ASHPs (Naumann et al., 2022). The research identifies a gap in the detailed discussion of specific measures and policies needed to support the integration of renewable energy with heat pump technology. Addressing this gap requires exploration of grid decarbonization strategies, policy recommendations, and infrastructure requirements to facilitate the mass adoption of renewable energy-powered heat pumps.

A research by Saoud et al. (2021) presents a cradle-to-grave life cycle assessment of air-to-water heat pumps (AWHPs) in the Lebanese context, comparing their environmental impacts with solar and conventional electric water heaters. The study found that AWHPs generally have a lower environmental footprint in terms of greenhouse gas emissions compared to conventional electric heaters, though solar water heaters performed even better due to their reliance on renewable energy. The LCA was conducted by evaluating impacts from production through disposal, using metrics like energy consumption and emissions. However, the paper does not explore how integrating AWHPs with renewable energy sources could further enhance their environmental benefits or how mass adoption might influence sector-wide emissions. Addressing this gap could involve on the synergistic effects of combining AWHPs with renewable energy, offering a clearer picture of their potential for reducing overall emissions and supporting a transition to a more sustainable energy system.

2.7. Technological Innovations and Future Trends

The rapid advancement of technology is pivotal in shaping the future of energy systems and addressing the challenges associated with the widespread adoption of air source heat pumps. Chapter 2.7 delves into the latest innovations and emerging trends that have the potential to transform the energy landscape. This chapter explores the cutting-edge developments in grid storage technologies, vehicle-to-grid (V2G) systems, and distributed energy resources, which are critical for enhancing grid resilience and efficiency. Additionally, the chapter examines the potential for technological advancements to improve the performance and integration of ASHPs. By evaluating these innovations, this chapter aims to provide a comprehensive understanding of how future technologies can support the transition to a low-carbon energy system, mitigate grid strain, and optimize the benefits of electrification initiatives.

2.7.1. Advances in ASHP technology and efficiency improvements.

The rapid evolution of air source heat pump technology plays a crucial role in enhancing the efficiency and viability of electrified heating systems. Recent innovations have focused on improving the performance of ASHPs, particularly in colder climates, with the goal of expanding their applicability and effectiveness in diverse environmental conditions. Advancements in compressor technology, refrigerants, and integration with smart home systems are driving significant efficiency gains, reducing operational costs, and increasing user adoption. This section delves into the latest technological developments in ASHPs, highlighting key improvements and their implications for the broader adoption of ASHPs in the UK's transition to a low-carbon heating sector.

As demonstrated by Markides (2013), heat pump technology and waste heat recovery can aid in enhancing the energy efficiency and sustainability in the UK’s energy system. The research conducted by (Markides, 2013) explores the potential contribution of various heat technologies, including heat pumps and waste heat recovery systems, with the goal to achieve a sustainable and high-efficiency energy future for the UK. Through theoretical analysis, case studies, and scenario modelling, the author found out that heat pumps can significantly reduce the carbon footprint of heating in residential and commercial buildings (Markides, 2013). In addition, waste heat recovery presents a substantial opportunity to enhance energy efficiency in industrial sectors. Integration of these technologies can help meet the UK’s targets for reducing greenhouse gas emissions as well (Burnett et al., 2023). The research by (Markides, 2013) discusses the influence of building type and insulation level on heating demand and energy consumption, however, the extent to which these factors are comprehensively modelled or quantified might not be thorough. To address this gap, more detailed and granular analysis of different building archetypes and varying insulation standards could provide a clearer picture of efficiency gains and cost implications.

In another study by Li et al. (2024), the authors evaluated the performance of an innovative heating system that integrates solar energy with a multi-source heat pump. The authors designed and implemented a heating system that combines solar thermal energy with a multi-source heat pump, along with a thermal storage unit. They reported that their innovative technology demonstrated high energy efficiency in the public building where it was installed. The building’s heating demand and overall energy consumption was significantly reduced using their novel system, compared to a traditional heating system. Not only that, but the implementation of the novel heating system resulted in a notable carbon emissions reduction, and it showed stable and reliable performance throughout different seasons, indicating its suitability for varied climate conditions in Hull (Li et al., 2024). However, the authors did not extensively examine the influence of building type and insulation level on heating demand and energy consumption in detail. Addressing this gap could provide more insights into the system's applicability and efficiency across divers building types and insulation standards, further validating its broader implementation potential.

2.7.2. Heat recovery using heat pumps

Bai et al. (2024) looked at a thermodynamic analysis of using an absorption heat pump system to recover exhaust waste heat. The system integrates an open absorption heat pump with exhaust gases to improve energy efficiency. The study shows that such a system can significantly enhance waste heat recovery and optimize the overall energy efficiency of industrial processes (Tao Bai et al., 2024).

Xu et al. (2024) explored a two-stage ventilation heat recovery system combining heat pipes and heat pumps. It evaluates the system's performance in recovering ventilation heat and demonstrates improved energy recovery efficiency by utilizing a composite structure. The findings highlight that such systems can substantially reduce energy consumption in HVAC systems (Xu et al., 2024).

Liu et al. (2024) investigated the integration of heat pumps into a carbon capture system for a coal-fired power plant. The study focuses on recovering steam condenser heat to assist sorption-based carbon capture. The research finds that this approach enhances carbon capture efficiency and reduces the overall energy penalty of decarbonizing coal plants (Liu et al., 2024).

Ravindran et al. (2024) examined a reversible system combining a high-temperature heat pump and an Organic Rankine Cycle (ORC) for recovering industrial waste heat. The findings indicate that the system effectively converts waste heat into usable energy, improving overall efficiency in industrial applications (Ravindran et al., 2024).

Wu et al. (2024) explored the selection of working fluid pairs in a thermally integrated pumped thermal electricity storage system designed for waste heat recovery and energy storage. The findings suggest that selecting optimal working fluid pairs enhances the system's efficiency and energy storage capacity (Wu et al., 2024).

All these studies (Tao Bai et al., 2024; Xu et al., 2024; Liu et al., 2024; Ravindran et al., 2024; Wu et al., 2024) focus on heat recovery using heat pump technology, aiming to improve energy efficiency in different industrial and power systems. Heat pumps are commonly employed as part of waste heat recovery strategies in these studies, showing their versatility in various applications.

However, there is limited research specifically on heat recovery from ice skating centres using heat pump systems. These centres generate significant waste heat through chiller systems used to maintain the ice. Recovering and repurposing this heat could provide substantial energy savings, such as heating buildings or water. A focused study on utilising heat pumps to capture and use this waste heat in ice skating rinks could indeed be considered a research gap, especially given the potential energy and cost savings. This gap presents an opportunity for objective 3 to explore how waste heat recovery systems, such as those involving heat pumps, could be adapted and optimised for ice skating facilities.

2.7.2.1. Heat recovery from wastewater systems using heat pumps

Some of the goals for the improvement of the environment are to reach a sustainable management of the planet's resources and minimise the generated waste. It is possible to utilise wastewater for energy recovery, including thermal energy. Some coastal cities and towns are able to use the heat from seawater and through district heating systems that thermal energy can be delivered for utility uses (Guy et al., 2016). People in Stockholm use one of the largest heat pump units available, and their seawater is utilised for heat recovery. The temperature of the inlet is approximately 3°C, and enough heat can be recovered to satisfy around 26 per cent of the thermal energy demand in the Swedish capital (Sköldberg and Rydén, 2014). It is not always possible to use seawater for heat recovery, because not all cities are located near the coast, and even if they are, some coastlines are under environmental laws, forbidding the usage of seawater in order to prevent any actions which could harm marine organisms (Đurđević, Balić and Franković, 2019). In cases like this it is possible to utilise the wastewater from the treatment plants. It is considered that residential wastewater has the highest rate of thermal energy loss (Đurđević, Balić and Franković, 2019). A study conducted in Switzerland revealed that approximately 15 per cent of heat is lost via the wastewater (Schmid, 2009). Water carries thermal energy when it is released in the wastewater system (Frijns, Hofman and Nederlof, 2013). A study revealed that approximately 30 per cent thermal energy can be recovered from the wastewater, if heat pump units are used for the process (Alnahhal and Spremberg, 2016). During the study, an experiment was set up to test how much thermal energy can be captured from the wastewater and how much money can be saved using this method. The results from that experiment revealed that approximately 40 kWh of heat was recovered per day from the household wastewater, and also that savings of around €230 per day were achieved (Alnahhal and Spremberg, 2016). In another experiment, involving heat capture from resident shower wastewater, revealed a thermal energy recovery between 4 and 15 per cent of the total demand

(Wong, Mui and Guan, 2010). Another research study has found that the temperature of the wastewater in northern and southern countries is not that different (Alnahhal and Spremberg, 2016). For example, in Berlin, the temperature of the sewage water remains approximately 15 °C, which suggests that wastewater is a good option for a source of heat, which can be recovered and reutilised for utility heating and cooling (Alnahhal and Spremberg, 2016). In an investigation study (Đurđević, Balić and Franković, 2019), theoretical calculations made for the city or Rijeka in Croatia, presented the possibility of wastewater heat recovery with the help of heat pumps to reach a capacity of approximately 75 MW. The theoretical calculations also revealed that the COP of the system could range between 2.87 and 4.7 (Đurđević, Balić and Franković, 2019).

2.7.2.2. Waste heat recovery from high temperature heat pump using hydrocarbon as a refrigerant

Generally, there are heat losses in almost every heat pump system. That wasted heat is discharged into the environment as a by-product from heat provision processes, but it can be considered as an energy resource to provide heat to the industry or residential buildings (Johnson, Choater and Dillich, 2008). The reason why it is considered as wasted heat is because, the temperature of that discharged thermal energy is lower than the demand of heat required (Bamigbetan et al., 2019). Some studies suggest that a mixture of butane and pentane in the refrigeration system of a high temperature heat pump device, could deliver favourable results for the desired temperature range (Bamigbetan et al., 2016). An experiment involving a heat pump with a capacity of 20 kW was made to test the thermal energy recover from the unit, using hydrocarbons as working fluids. It was found that the system can recover heat and reach temperatures of up to 55 – 65 °C. The COP of the unit was also tested. For a temperature rise of 98 – 101 K the coefficient of performance reached 2.1 and for the temperature increase of 58 – 72 K, the HP's COP maintained 3.1 on average, proving it is a better choice for heating and heat recovery compared to gas boilers. The reason for that is because of its lower CO_2 emissions and lower electricity consumption. The tests from the operation of the compressor used in the experiment revealed that the compression efficiency maintained at 74 per cent on average (Bamigbetan et al., 2019).

2.7.2.3. Ground source heat pump combined with a cooling tower

GSHPs have been widely developed over the past decade and more and more people prefer to use them, providing they have the possibility to install one, even though the initial cost of the pump is higher (Zhou et al., 2017). In areas where high temperature differences between summer and winter are present, and ground source HPs are utilised, researchers have found that could lead to significant variation on the temperature of the ground (Zhou et al., 2017). When the system is used in cooling mode for a long period of time, there is a high chance for the ground temperature in the area to increase and therefore reduce the efficiency of the GSHP system installed there (Geng et al., 2013). In that regards, an improvement of the ground source heat pump systems in such areas has been made, and that includes an application of hybrid GSHPs. This hybrid provides an assisted heating/cooling tower to the heat pump, the idea of which is to improve the efficiency of the system (Qi et al., 2014). A simulation test has been conducted in Chongqing, China, where a high difference of summer and winter temperatures is present, to test how GSHP affect the ground temperature and whether a heating/cooling tower can aid in improving that factor and also help in increasing the efficiency of the system. For the 20 years simulation, ran by a TRANSYS software, it was revealed that there is a gradual increase of the ground temperature and consequent decrease of efficiency of the heat pump system (Zhou et al., 2017). The simulation also found that if an auxiliary/cooling tower is added to the system, this could really aid in maintaining the ground temperatures constant throughout the year, and also improving the operating performance of the HP (Zhou et al., 2017).

2.7.2.4 Liquid and vapour injection

An investigation on vapour injection (VI) has been made in heat pump technology to determine whether it would increase the system's COP. VI has been utilised with screw compressors, and various tests revealed that this method helps improving the COP and the capacity of the system (Jain, Jain and Bullard, 2004). The reason for these improvements is because the vapour injection divides the operation of the compressor in two stages, one which reduces the work done by the compressor and the other stage is decreasing the quality of the inlet to the evaporator (Jain, Jain and Bullard, 2004). It is considered that VI method has some advantages in residential air conditioning systems, in systems where the high temperature lift is present, such as space and water heating, vapour injection provides large benefits (Jain, Jain and Bullard, 2004). A simulation of a heat pump system equipped with a scroll compressor has been conducted to test the influence of the VI on the COP of the unit. The results predicted an increase of the COP by approximately 6-8 per cent and a decrease of the displacement of the compressor of around 16 per cent for air-conditioning systems (Jain, Jain and Bullard, 2004).
In another case (Chen et al., 2018), the heating performance of refrigerants with low GWP was investigated with and without vapour injection. The results revealed that the COP of the system

was higher with VI implemented for all the coolants that have been utilised for the test (Chen et al., 2018).

Emerson Climate Technologies also reports the positive effect of the vapour injection into HP systems using scroll compressors. In a technical information about scroll compressors utilising VI methods, they report that in systems with low evaporating temperatures, the COP and the capacity are both improved (Emerson, n.d.).

In an experiment (Jie, Xianmin and Liping, 2017) involving an air source heat pump combined with a flash-tank utilising a vapour injection method was conducted. In that experiment a refrigerant R32 was utilised (Jie, Xianmin and Liping, 2017). It was found that with the increase of injection pressure, the heating capacity and the electricity consumption were increased as well, but the discharge temperature was reduced. The efficiency of the heating of the Flash-tank vapour injection system was low with the increase in injection pressure when the outdoor temperature was high. For lower ambient temperature, if the optimal pressure of injection is applied, the heating COP reached its highest point. It was also reported that the heat pump using flash-tank VI had a higher efficiency compared to a conventional air source HP unit at an ambient temperature of -3℃ or lower (Jie, Xianmin and Liping, 2017).

In another study (Cho et al., 2016) the heating and cooling performance of heat pumps utilising R410A and R32 coolants were compared, combined with sub-cooler vapour injection. Additional comparison with and without VI were made (Cho et al., 2016). In both, heating and cooling mode both refrigerants showed higher capacities and COPs with sub-cooler vapour injections present in the systems (Cho et al., 2016).

In a comparison experiment, a novel heat pump with vapour injection utilising injected sub-cooling (VIS) was tested and compared with a regular HP system using vapour injection and liquid injection system (Xu et al., 2018). The results revealed that the unit utilising VIS system reduced the compression discharge temperature, and the unit operated on evaporating temperatures of -20°C or lower. The efficiency of the system using VIS method was between 11.2 and 13.6 per cent higher than the unit utilising liquid injection (Xu et al., 2018).

Usually, oil is injected into the compressor chamber, especially in screw compressors, to seal any leakage gaps and also to cool down the gas that is compressed. This allows for a direct contact between the rotors and consequently the volumetric performance of the compressor is increased, as well as the adiabatic efficiency (Stosic, Kovacevic and K. Smith, 2005).

It is also possible to inject liquid refrigerant into the compression chamber. It is considered that the performance will be similar or the same as oil injection. The liquid coolant will also be able to seal any leakage gaps and also to lubricate the rotors. In addition, when it comes to the

cooling abilities, liquid injection can be even more efficient, because it will be able to evaporate faster during the compression operation (Stosic, Kovacevic and K. Smith, 2005).
Compressor's capacity can also be increased if a coolant in vaporous state is injected into the chamber at an optimal pressure, and this will also improve the efficiency of the compressor. This process is also known as superfeed. Liquid injection can be combined with superfeed to increase its effects on the system (Stosic, Kovacevic and K. Smith, 2005).
Liquid injection's effects may vary according to the refrigerant. In an experiment (Stosic, Kovacevic and K. Smith, 2005), various injection methods were studied to investigate the effect on a screw compressor and its compression chamber. Three different refrigerants were tested, and it was revealed that R407C and R717 provided the best results. Not only that, but liquid coolant injection can provide better cooling, lubrication and gaps sealing than oil (Stosic, Kovacevic and K. Smith, 2005).
A thermodynamic analysis and additional laboratory experiment have been made of liquid injection on a scroll compressor to determine what effect would have the injection on the capacity, internal temperature, and performance of the compressor (Ayub, Bush and Haller, 1992). In these experiments, the authors did not find any advantages related to efficiency of the system. Sizing and cost related advantages were found because of their experimental work (Ayub, Bush and Haller, 1992).
In another study the practical and fundamental influence of liquid working fluid injected into a scroll compressor working chamber has been investigated (Dutta, Yanagisawa and Fukuta, 2001). Theoretical and practical analysis have been done and the results from both were compared. In addition, the performance of liquid refrigerant that has been injected into the working chamber of the scroll compressor has been investigated as well as the performance of the condenser with less superheated vapour applied at the inlet of the condenser from the liquid coolant line of the compressor. In the fundamental test, the oil temperature was maintained constant. The temperature of the discharged refrigerant was reduced because of the increased injection ratio. The compressor's adiabatic efficiency dropped slowly, and the reason for that was the constant mass flow rate of the refrigerant suction line and of course the raised compression power had the biggest influence. For the practical experiment, the oil temperature was not controlled, which resulted in a positive effect on the adiabatic efficiency of the compressor, and therefore the mass flow rate of the refrigerant from the suction line was increased, but the compressor power did not increase. The negative effect of the practical experiment was the decrease of viscosity of the oil, which led to the issue where oil flowed out

of the casing, because the coolant experienced high dissolution (Dutta, Yanagisawa and Fukuta, 2001).

Providing the ambient temperature is above -8°C, vapour injection will work satisfactorily, but if the temperature drops below -8°C, a significant reduction of efficiency can occur (Anmar, 2013). The same results apply for cooling mode if the temperature rises above 35°C (Anmar, 2013). The idea of the vapour injection in a heat pump system is to increase the efficiency and the capacity and also to reduce the discharge temperature (Abdul Hadi, Faraj and Hasan, 2015). Experiments have proven that vapour injection can aid in improving the COP and the capacity of the system. In addition, tests involving liquid injection into the compressor's inlet revealed that the performance of the system was further optimised (Abdul Hadi, Faraj and Hasan, 2015). In another experiment (Vakiloroaya and Ha, 2014), a liquid pressure amplification (LPA) method was utilised for the improvement of the performance of the system. It was presented that the refrigerant in liquid state entering the liquid line experienced high pressure, generated by a centrifugal pump. The pressure loss between the receiver and the condenser was overcome by sufficient pressure from the centrifugal pump (Vakiloroaya and Ha, 2014). In an experimental work done by (Abdul Hadi, Faraj and Hasan, 2015) a heat pump was tested with vapour, liquid and hybrid injection to see which method would improve the efficiency of the system. A liquid injection reduced the temperature of the condenser inlet by 43 per cent and overall performance of the unit was increased by 27 per cent. Implementing both liquid and vapour injection methods with the appropriate volume ratios, it improved the system's efficiency by 33 per cent (Abdul Hadi, Faraj and Hasan, 2015).

2.7.3. Potential for innovation in grid storage, vehicle-to-grid (V2G) technology, and distributed energy resources (DERs).

The evolution of grid storage, vehicle-to-grid (V2G) technology, and distributed energy resources (DERs) represents a promising frontier for enhancing the resilience and efficiency of the electricity grid. Innovations in grid storage technologies, such as advanced batteries and pumped hydro storage, offer the potential to smooth out fluctuations in energy supply and demand, thereby alleviating pressure during peak periods. V2G technology, which enables electric vehicles (EVs) to return storaged energy to the grid, can provide additional flexibility and capacity. Meanwhile, DERs, including solar panels and small-scale wind turbines, can decentralize energy production and reduce reliance on traditional grid infrastructure. This sub-chapter examines the latest developments in these areas, assessing how they can be leveraged to support the integration of renewable energy sources, improve grid stability, and accommodate the increased load from electrification initiatives like widespread air source heat pump adoption.

A study conducted by (Goncearuc et al., 2024) identifies key barriers to V2G adoption, including technical challenges related to infrastructure and interoperability, economic issues such as high initial costs and uncertain benefits, and regulatory and social hurdles like inadequate policies and public awareness. These findings were acquired through a comprehensive review of existing literature, industry reports, and case studies. The paper also discusses the potential strain on the power grid from mass adoption of electric vehicles, noting the need for more detailed studies on grid capacity and management (Goncearuc et al., 2024). Addressing these gaps requires further research into the long-term impacts on grid infrastructure and development of advanced grid technologies and policies to ensure effective integration of V2G systems.

Another research investigated (Leippi et al., 2024) how to effectively integrate electric vehicle (EV) fleets into demand response programs to enhance grid stability and efficiency. The authors developed an optimization framework that balances the benefits of vehicle-to-grid (V2G) technology with fair compensation for battery degradation, using mathematical modelling and simulation techniques to derive their conclusions (Leippi et al., 2024). Although the study highlights significant economic and technical advantages of EV fleet integration, it provides limited insight into the long-term impacts of mass EV adoption on grid infrastructure. Addressing this gap could involve future research into the sustained effects of large-scale EV integration on grid reliability and capacity, as well as strategies for aligning V2G programs with renewable energy sources and evolving grid demands.

Another study highlights (Lehtola, 2024) that integrating solar and wind power with battery storage and V2G technologies enhances grid stability and efficiency. Using simulation models and data analysis, the study demonstrates that these combined approaches effectively manage intermittent renewable energy and improve cost-effectiveness (Lehtola, 2024). However, the paper also identifies a research gap concerning the strain on power grids from widespread electric vehicle (EV) adoption. While V2G systems provide benefits, further research is needed to explore their impact under extreme EV penetration scenarios. Addressing this gap involves developing detailed models for grid impact, upgrading infrastructure to support higher loads, and creating policies for a smooth transition to increased EV integration.

2.8. Case Studies and Real-world Applications

In a study simulating load shift of the heating from a heat pump, it was determined that with the usage of a buffer tank the heating and electrical energy were distributed more evenly throughout the day (Kelly et al., 2014). Instead of the divide directly supplying heating to the dwelling, a buffer tank was used to storage heat during off peak times. This further reduced the surges in power demand by the heat pump and heating can be provided even at peak times through the usage of a buffer tank. However, the authors also found out that the COP of the system decreased with the time shift management even though the heat output was higher with buffer storage. This further increased the electricity usage and the running cost of the divide (Kelly et al., 2014). A gap that the authors have not addressed is how other types of houses, such as terraced and semi-detached along with different insulation properties can affect the heat pump operation and therefore the electricity demand. This gap will be addressed through objective 1c**.**

Another research investigated the techno-economic aspect of heat pumps to potentially improve their adoption rate (Kokoni & Leach, 2021). Due to the higher initial and running cost, heat pumps numbers remain low in the UK (Novak and Westring, 2015). In addition, the price and size (kW) of heat pumps compared to other heating methods can make it less attractive for homeowners. For example, a 16kW ASHP can reach approximately £6700, whereas a 38kW gas-combi boiler would cost roughly £3000 (Kokoni & Leach, 2021). The findings from (Kokoni & Leach, 2021) showed that in the UK, the highest potential for heat pumps is in larger houses. The reason for that is their higher heating demand which leads to higher annual energy consumption. Especially, dwellings that use expensive fuel (i.e. oil), heat pumps can compete with such systems. The authors of that study also mentioned that the UK has one of the oldest housing stock in Europe (Palmer & Cooper, 2013). (Kokoni & Leach, 2021) also agree on the fact that old dwellings have poor insulation. However, they did not address the gap on how the heating and electricity demand by heat pumps would be affected based on the insulation properties of the majority of the current housing stock in the UK.

In another study, various retrofit strategies were compared for improving the energy efficiency of hard-to-treat homes in the UK (Mohammadpourkarbasi et al., 2023). In their research, the authors compared conventional retrofit involving standard energy efficiency measures, and enerPHit Standard which is a certification for retrofitting buildings to achieve the Passive House standard, ensuring high energy efficiency. Heat pump first approach prioritises the installation of heat pump before other energy efficiency measures, and fabric-first approach prioritises improvements to the building envelope (i.e., insulation) before installing a heat pump (Mohammadpourkarbasi et al., 2023). By conducting a life cycle assessment to evaluate the carbon impact of each retrofit strategy, the authors reported that EnerPHit Standard significantly reduces operational carbon emissions compared to conventional retrofit approaches. However, the embodied carbon emissions from materials and construction processes are higher using that strategy. In addition, the fabric first approach resulted in lower overall carbon emissions, while the heat pump first approach showed higher operational efficiency but may not contribute to a significant reduction in overall carbon emissions if the building envelope remains less efficient (Mohammadpourkarbasi et al., 2023). The paper does not provide detailed analysis on the impact of different house types and insulation levels on the heating demand and the energy consumption of heat pumps, which is a significant factor in retrofit strategies. Addressing this gap can provide better understanding how various factors influence the effectiveness and efficiency of different retrofit approaches. In addition, addressing this gap can help tailoring retrofit strategies to specific house types and conditions, potentially enhancing the overall effectiveness of decarbonisation efforts in the housing sector. Another research, the performance and feasibility of a groundwater heat pump system for district heating was examined (Sezer et al., 2024). Through numerical modelling, case study data, and simulation scenarios, the authors found out that groundwater heat pump system is an effective and sustainable solution for district heating, providing a significant reduction in carbon emissions compared to conventional heating methods. In addition, the system demonstrated high energy efficiency, and it contributed positively to environmental goals by utilising renewable energy sources and reducing the reliance on fossil fuels. The authors' analysis also showed that the system is economically viable, with acceptable payback periods and cost savings over time (Sezer et al., 2024). However, the paper did not delve deeply into how different house archetypes and insulation levels affect dwellings' heating demand and energy consumption by the heat pump system. Addressing this gap could provide more tailored insights into optimising district heating systems by accounting for variations in building characteristics.

2.9. Conclusion and Research Gaps

2.9.1. Summary of key findings from the literature.

The key findings from the literature review primarily revolve around the evolving landscape of electrification in heating and transport, particularly in the UK. The review highlights the historical context of electrification, noting the early development of technologies such as heat pumps and electric vehicles, and their subsequent underutilisation due to the dominance of fossil fuels. Currently, with the UK's commitment to achieving net zero emissions by 2050, there is a significant push towards the widespread adoption of electrification in both sectors. However, the literature review identifies several challenges, including the need for expanding renewable energy sources, reinforcing the power grid, and overcoming economic and technical barriers to technologies such as Vehicle-to-Grid (V2G) systems and distributed energy resources (DERs). Furthermore, the review discusses policy frameworks, such as the Domestic Renewable Heat Incentive (RHI), Non-domestic Renewable Heat Incentive (RHI) and Green Deal (UK Government, 2015); and their role in supporting this transition, alongside the potential for innovation in energy storage and management to handle increased electrification demands. Overall, the literature underscores the importance of addressing these challenges through continued research, policy support, and technological advancement to realize the full potential of electrification in reducing carbon emissions.

2.9.2. Identification of research gaps and areas requiring further investigation.

The literature review identifies several research gaps and areas requiring further investigation to fully understand and optimise the transition to electrification in heating and transport. One key gap is the limited research and exploration of how different dwelling types and insulation levels affect the energy consumption and cost-effectiveness of heat pumps (Singh et al., 2010; Terry & Galvin, 2023; Wang, 2018; Greening & Azapagic, 2012; Wilson et al., 2024; Watson et al., 2023; Gupta & Irving, 2014), particularly in the UK where adoption rates remain low compared to other European countries. Additionally, there is insufficient research on the long-term user satisfaction and performance of air source heat pumps (ASHPs) under varying climatic conditions, especially considering fluctuating energy prices. Another significant gap is the lack of comprehensive studies on the socio-economic barriers to adopting electrification technologies, such as upfront costs, awareness, and behavioural factors influencing consumer choices between gas and electric heating systems (Lyden et al., 2024; Taylor et al., 2023; Pither & Doyle, 2005; Lamb & Elmes, 2024; Zhou et al., 2024). Addressing these gaps could provide deeper insights into optimizing policy frameworks, improving technology adoption, and enhancing the overall effectiveness of electrification strategies.

2.10. Addressing the Gaps

The literature surrounding air source heat pumps (ASHPs), electrification of heating, and energy grid impacts has expanded significantly in recent years. However, several key gaps remain that need to be addressed to fully understand the implications of widespread ASHP adoption in the UK, particularly in the context of the transition to net-zero carbon emissions. This section outlines the primary gaps identified in the literature and explains how this research directly contributes to filling those gaps.

2.10.1. Limited Empirical Data on ASHP Performance in Diverse Housing Types

While many studies have explored the theoretical performance of ASHPs under controlled conditions or in specific housing contexts, there is a distinct lack of empirical data on how ASHPs perform across the diverse range of housing types found in the UK. Much of the existing research focuses on new builds or well-insulated homes, which are typically more compatible with ASHP technology due to their lower heat loss and more modern heating systems. However, a significant portion of the UK's housing stock comprises older, poorly insulated buildings, where ASHPs may not perform as efficiently.

This thesis incorporates both experimental data from ASHP test rigs and simulations across different housing archetypes, including older and less energy-efficient homes. By examining the impact of factors such as insulation quality, building design, and heating system compatibility, this study provides a more comprehensive understanding of ASHP performance in a real-world, diverse housing landscape. The findings will help to inform future policies on retrofitting and adapting older homes for heat pump installations, thus offering practical solutions for maximizing ASHP efficiency across the housing spectrum.

2.10.2. Lack of Focus on Defrost Cycles and Cold-Weather Efficiency

While some research has investigated the general efficiency of ASHPs, particularly in moderate climates, there has been insufficient focus on how defrost cycles affect the performance of ASHPs in colder climates, like those experienced globally and in many parts of the UK. Frost accumulation on the outdoor heat exchanger can significantly reduce the efficiency of ASHPs, leading to higher energy consumption and operational costs. However, many studies overlook this issue or address it only in passing, leaving a gap in understanding how cold-weather conditions specifically impact ASHP operation.

This research investigates the operational challenges posed by cold weather, with a particular focus on the efficiency losses caused by frequent defrost cycles. Through the development of a test rig and detailed analysis of defrost mechanisms, this study quantifies the energy losses associated with frost accumulation and provides recommendations for mitigating these issues. By focusing on this underexplored aspect of ASHP performance, the research offers valuable insights for optimising ASHP operation in colder regions, which is critical for achieving widespread adoption in the UK.

2.10.3. Insufficient Analysis of the Interaction Between ASHPs and the National Grid

The transition to electric heating via ASHPs presents substantial challenges for the national grid, particularly in terms of peak demand management during cold weather. While some studies have modelled the increased electricity demand resulting from ASHP adoption, there is limited research on the interaction between widespread ASHP use and the grid's ability to integrate renewable energy sources. Additionally, the simultaneous growth of electric vehicle (EV) adoption further complicates this dynamic, yet few studies consider the combined effects of electrifying both heating and transportation systems.

This PhD thesis includes a detailed simulation of the impact of large-scale ASHP adoption on the UK's electricity grid, taking into account peak load scenarios and the integration of renewable energy sources. By simulating real-world scenarios where both ASHPs and EVs are in widespread use, the study highlights the potential strain on the grid and offers strategies for mitigating grid instability through demand-side management, energy storage, and smarter grid technologies. This contribution is essential for informing national energy planning and ensuring that the grid can accommodate the rising demand from both heating and transportation electrification.

2.10.4. Limited Understanding of Homeowner Perceptions and Adoption Barriers

While the technical aspects of ASHP performance have been relatively well-studied, less attention has been paid to the socio-economic factors influencing homeowner adoption of heat pumps. Homeowner perceptions, cost barriers, and concerns about the reliability and efficiency of ASHPs are critical factors that affect the uptake of the technology, yet these factors are underexplored in much of the existing literature. Without a clear understanding of these barriers, efforts to promote ASHP adoption may fail to achieve the desired outcomes.

This research addresses this gap by conducting a comprehensive survey of homeowners, assessing their perceptions of ASHP technology, the factors influencing their heating choices, and the economic and social barriers to adoption. By integrating these findings with the technical analysis, the research provides a more holistic view of the challenges facing ASHP deployment in the UK. The study's conclusions on the importance of education, financial incentives, and post-installation support contribute directly to ongoing policy debates about how best to encourage the transition to low-carbon heating systems.

2.10.5. Lack of Industrial and Commercial Applications of ASHPs in Comparison to District Heating

While much of the existing research focuses on residential applications of ASHPs, there is limited exploration of how these systems can be applied in industrial and commercial settings, where energy demand is often higher and more variable particularly with the viability of district heating. The potential for ASHPs to be integrated into larger heat recovery systems, such as those used in refrigeration-heavy facilities like ice rinks, has not been sufficiently studied. This represents a significant gap, as commercial and industrial applications of ASHPs could contribute substantially to national decarbonization goals.

The case study of the Nottingham Ice Centre, included in this research, addresses this gap by exploring how ASHPs and thermal storages can be used as part of a heat recovery system in a commercial setting. By demonstrating the practical benefits of heat recovery from refrigeration processes, the study provides a template for other industries with high energy demand to reduce their reliance on district heating and improve overall energy efficiency. This contribution extends the applicability of ASHP technology beyond the residential sector, showing its potential in diverse industrial and commercial environments.

2.11. Summary

The literature review identifies several research gaps and areas requiring further investigation to fully understand and optimise the transition to electrification in heating and transport. One key gap is the limited relationship and exploration of how different dwelling types and insulation levels affect the energy consumption and cost-effectiveness of heat pumps (Singh et al., 2010; Terry & Galvin, 2023; Wang, 2018; Greening & Azapagic, 2012; Wilson et al., 2024; Watson et al., 2023; Gupta & Irving, 2014), particularly in the UK where adoption rates remain low compared to other European countries. To address this gap, objective 1 will be applied to understand and simulate the effect if different dwelling types on air source heat pump energy consumption. Additionally, there is insufficient research on the long-term user satisfaction and performance of air source heat pumps (ASHPs) under varying climatic conditions, especially considering fluctuating energy prices. Another significant gap is the lack of comprehensive studies on the socio-economic barriers to adopting electrification technologies, such as upfront costs, awareness, and behavioural factors influencing consumer choices between gas and electric heating systems (Lyden et al., 2024; Taylor et al., 2023; Pither & Doyle, 2005; Lamb & Elmes, 2024; Zhou et al., 2024). To address this gap, objective 2 will be undertaken to understand public attitude and engagement towards heat pumps. Furthermore, objectives 3 and 4 will assess heat recovery or heat pump use via competitive technologies in commercial buildings, and also to explore the effect of electric vehicles' range in cold weather and the effect on the electricity grid, respectively.

3. Methodology

3.1. Introduction

In Chapter 2, a comprehensive review of the existing literature on the effects of heat pumps on the power grid is presented, with a particular emphasis on air source heat pumps (ASHPs) due to their prevalence in the UK (Statista Research Department & 8, 2023). ASHPs were given more attention because their coefficient of performance (COP) decreases as ambient temperatures drop (Brown, 2017). Additionally, at temperatures below freezing, frost accumulation occurs on the outdoor heat exchanger, making it more challenging to extract heat from the surrounding air (Huang et al., 2009). To mitigate this, ASHPs perform defrost cycles to melt the accumulated frost and allow the unit to resume normal operation and efficiently extract heat from the air (Huang et al., 2009).

With the potential for wider adoption of heat pumps in the UK, concerns arise regarding the stability of the power grid, especially when combined with the increased electrification of the vehicle fleet. This scenario could result in raised electricity demand, and without a corresponding increase in power capacity and grid stability, the electrification of the heating sector could lead to damage to the electricity network and potential blackouts. Moreover, heating demand from households may impact the energy consumption of heat pumps. However, the literature review (Chapter 2) reveals that not all factors influencing heating demand in UK dwellings have been fully explored. While the impact of ambient temperature on ASHP performance has been studied, the effects of wall types and insulation levels in houses have not been thoroughly investigated, highlighting a knowledge gap that this thesis aims to address.

To bridge this gap, the thesis includes a simulation model of an air source heat pump, validated by comparing it to its test rig counterpart. The simulation analyses the relationship between house wall type, insulation level, and energy consumption of heat pumps in the UK. Additionally, the simulation extends to include ten global cities, considering their respective average house sizes, insulation levels, and climates to estimate not only the relationship between housing stock in other countries but also how varying climate conditions influence heat pump energy consumption.

The UK government has set a target to increase heat pump installations by 600,000 units by 2028 (UK Government, 2023). However, the literature review in Chapter 2 indicates that current installation rates have not yet reached this target. To facilitate the electrification of the heating sector, promoting heat pump technology among homeowners is critical. Chapter 2 notes that approximately 35,000 units are installed annually in the UK (Lyden et al., 2024), but the literature has not sufficiently examined why adoption rates lag behind those of other countries, such as Norway, Sweden, and Finland (Olympios et al., 2024).

This PhD research will investigate the popularity of heat pumps among UK homeowners and explore the factors contributing to the slow adoption rate, addressing the research gaps identified in the literature. A survey will be distributed among UK homeowners to assess heat pump popularity and investigate any hesitancy towards heating electrification and its underlying causes. To supplement the survey, two semi-structured interviews will be conducted with homeowners currently using heat pumps, aiming to explore their experiences in detail and gauge their satisfaction with the technology. Furthermore, temperature data will be collected from the two dwellings to evaluate how indoor temperatures respond to ambient conditions, and whether the homeowners' thermal comfort and energy cost expectations are met through the use of heat pumps. Following sections and Figure 3.1 will detail the methodology employed in this aspect of the research.

3.2. The Implemented Methodology

Figure 3.1 presents the outline of the thesis structure and the implemented methodology.

A mixed method approach is used for each stage of this research as follows:

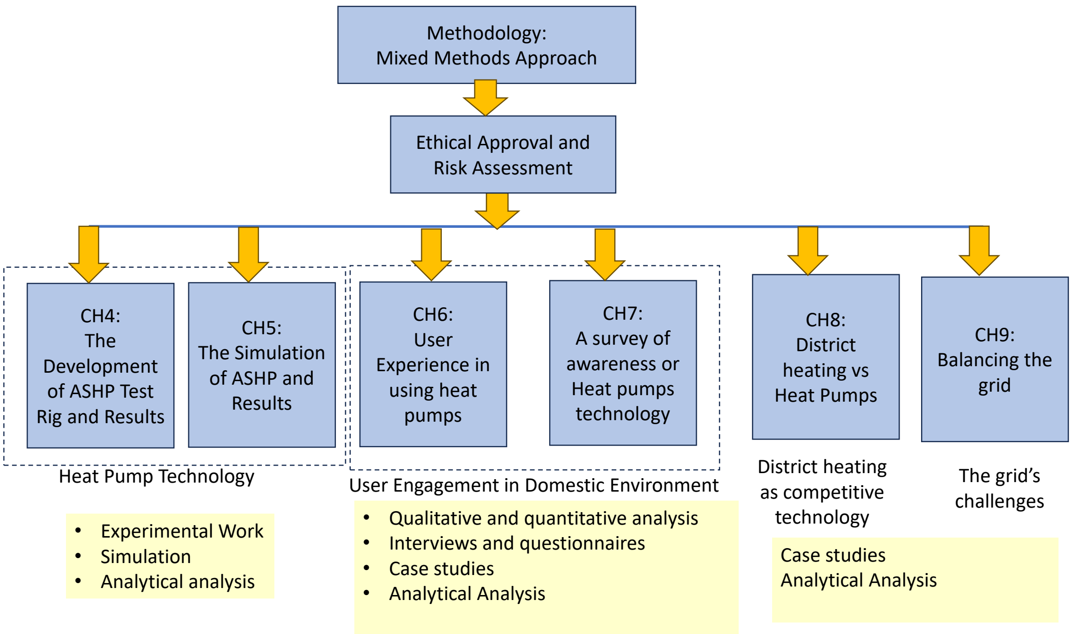


Figure 3. 1 *- Schematic diagram of the methodology used in this research*

Chapter 4 presents an experimental methodology where the full design and development of ASHP system is done to enable the validation of the simulation algorithm and develop the experimental work of novel internet-based communication and future development.

Chapter 5: Presents the simulation of the ASHP using Matlab and Simulink which has been validated using the test rig of Chapter 4.

Chapters 6 and 7 present the user engagement using qualitative and quantitative approach use questionnaires, interviews, two case studies with analytical analysis.

Chapter 8 and 9 includes Nottingham Ice Centre case study and analytical analysis of district heating vs heat recovery using heat pumps and the effect on the Grid from the energy demand from low carbon technology including electric vehicles.

Academic publications made by the author from Chapters 4, 5, and 9 support the chosen methodology and demonstrates a significant contribution to knowledge.

Chapters 4 and 5 were published in the Energy and Buildings journal (Volume 300) (Milev et al., 2023). This publication demonstrates the building of a custom air source heat pump test rig (Chapter 4) that was used to validate the simulation model (Chapter 5). This article also further demonstrates the effect of defrost cycles on the power demand by the ASHP, as well as how different house type and insulation level can affect the ASHP energy consumption at different temperatures.

Through Chapter 9, there have been three conference and one journal paper that have been published in the International Conference on Energy and Sustainable Futures 2021, 2022, and in the Energy and Built Environment journal (Volume 2, Issue, 2) (Milev et al., 2020a; Milev et al., 2021; Milev and Al-Habaibeh, 2020; Milev et al. 2020b; Milev and Al-Habaibeh, 2023). This chapter and related publications explore the effect on the power grid of massive implementation of heat pumps and electric cars in the UK. This demonstrates not only the suitability of the chosen methodology but also the outcomes' contribution to knowledge.

3.2.1. Research approaches and techniques

Research methodologies can be broadly classified into two types: quantitative and qualitative. According to Silverman (2005), methodology refers to the decisions made regarding which cases to study, the methods of data collection, and the forms of data analysis (Shibani, 2016). Neuman (2006) emphasizes that each approach comes with its own epistemological and ontological assumptions, which influence how data is collected and interpreted. In this study, both quantitative and qualitative approaches were chosen as they align with the research objectives. Blaxter et al. (2006) explain that the key distinction between these approaches is that "quantitative" refers to data in the form of numbers, while "qualitative" pertains to words and other forms of data (Shibani, 2016). Drawing from the work of Bryman and Bell (2007), quantitative researchers often view qualitative research as an exploratory method for conducting social inquiries (Shibani, 2016). The primary differences between the two approaches are as follows:

- Quantitative research focuses on understanding complex relationships between variables, whereas qualitative research prioritises explanation as the main goal.
- Qualitative research is seen as a tool for deriving meaning through in-depth interpretation.
- In quantitative research, the influence of the researcher is minimised, while in qualitative research, the researcher's influence is more pronounced.

To leverage the strengths of both approaches and minimise their limitations, this research adopts a mixed-methods approach to investigate the challenges of the decarbonisation of heating and transportation in urban environments. This combination is expected to allow each method to offset the shortcomings of the other.

The following sections of this chapter will include enabling methods, techniques and technologies that have been used in this thesis.

3.2.2. Ethical considerations

During this project, health and safety assessment and ethical approval was obtained to ensure compliance with university ethics requirements, specifically from the Nottingham Trent University’s Data Protection Officer. This included measures to protect participant privacy and confidentiality. The survey was designed to be short, taking about five minutes to complete, to minimise participant burden. Individual chapters have gone through the relevant Nottingham Trent University (School of Architecture, Design, and the Built Environment) ethics panel (Please see Appendix IX).

3.3. House type and heating demand relationship

This method is employed to investigate the effects of frost build-up on air-source heat pumps and their impact on heating demand and energy consumption. A custom simulation model was developed using Simulink to compare the performance of an air-source heat pump test rig with a corresponding simulation under various weather conditions. The research aims to address the gap identified in the literature by providing a comprehensive understanding of how ambient temperature, relative humidity, house wall type, and insulation standards influence heat pump performance.

From the relevant literature a research gap was identified. Particularly, if there is a relationship between the house type, insulation level and the dwelling heating demand. This can be a crucial factor determining the energy consumption by heat pumps. If this technology is to be massively adopted in the UK and meet the government’s plan to install 600,000 units per (UK Government, 2023), the effect on the grid must be explored as well as factors that may help in mitigating potential overload on the electricity network in the country. Objective 1 will help to explore what types of heat pumps are popular in the UK and why, as well as getting insights into the current housing stock and insulation properties in the country. Knowing this, a simulation can be modelled (please see Chapter 5) to explore the effect of house types and insulation level on dwellings heating demand and therefore on the heat pumps energy consumption.

This stage of the research employs a mixed-method approach, combining experimental work with numerical simulation to achieve a robust analysis of heat pump performance. The mixed-method approach was chosen to leverage the strengths of both experimental work and simulation validation, thereby providing a comprehensive understanding of heat pump behaviour under real-world conditions. This approach allows for the detailed observation of physical phenomena (e.g., frost formation) and the flexibility of simulating various scenarios beyond the experimental setup (Creswell & Plano Clark, 2018).

The experimental component involves a test rig that mimics the operation of an air-source heat pump under cold climate conditions, while the simulation component uses a Simulink model to replicate and extend these observations. This dual approach ensures that the results are both empirically grounded and generalisable across a range of scenarios, making the findings relevant for both practical applications and theoretical development (Mc Guire et al., 2024).

The control system, structure, and simulation model presented in the thesis form a critical foundation for evaluating the performance of air-source heat pumps. However, further verification of these elements is necessary to ensure their robustness, accuracy, and generalisability (Sargent, 2010). Verification could involve comparing the simulation model's outputs against additional empirical data from diverse operational settings, including varying climatic conditions and housing types not currently tested (Robinson, 1997). This would help confirm the model's ability to replicate real-world dynamics accurately (Kleijnen, 1995). Similarly, the control system's responsiveness and precision in managing temperature and humidity during test rig operations should be benchmarked against industry-standard systems to identify any deviations or potential improvements. Additionally, the structural framework of the simulation approach should be scrutinized to validate its assumptions, boundary conditions, and parameterization, particularly concerning the incorporation of transient behaviours like defrost cycles. These steps would strengthen the credibility of the methodology and provide a more solid foundation for the research conclusions and their application in both academic and practical contexts.

The test rig was developed (please see Chapter 4) to experimentally validate the Simulink model of the air-source heat pump (Objective 1). The rig replicates key components, such as the evaporator, compressor, and condenser, and measures critical performance metrics like heating capacity, input power, total heat output, and total energy consumption. The test rig operated under low ambient temperatures and high humidity levels to simulate real-world cold weather conditions, including those at the extremes of the selected temperature range. To validate the simulation model 20 test were conducted on the test rig. In some statistical methodologies, 20 samples can be considered adequate to observe trends and determine relationships between input and output variables, especially if the results align well with a normal distribution. Tools like the Central Limit Theorem (CLT) support this by suggesting that even a small number of independent and identically distributed samples can lead to a normal distribution of the sample mean, which supports accurate validation (Bejan, 2013). As Bejan (2013) discusses in their book, the validation of thermodynamic models and stresses that model validation depends more on the quality and range of experimental data rather than the volume. The same scenarios from the HP experimental works were fed into the simulation of the heat pump. The 20 tests conducted on the test rig as part of the Simulink model validation were not of the exact same duration due to the natural variability in frost build-up rates under different ambient temperatures and humidity conditions. The formation of frost is influenced by fluctuations in environmental factors, which can cause variations in how quickly the heat pump reaches conditions that trigger a defrost cycle. Additionally, the duration of defrost cycles was not consistent across all tests because the amount of accumulated frost varied, requiring different amounts of time for complete removal. This variability is essential to reflect real-world operating conditions and ensures that the model accurately captures the dynamic nature of heat pump performance, enhancing the validity and reliability of the simulation results.

The primary data inputs for both the experimental and simulation components were ambient temperature and relative humidity. These inputs were selected because they directly influence the frost formation rate on the heat pump’s outdoor unit, which in turn affects the system’s efficiency and energy consumption. Ambient temperature affects the heat exchange rate, while relative humidity impacts the amount of frost that can accumulate on the heat exchanger surfaces. Data for ambient temperature and relative humidity were collected from historical weather data sources and real-time sensors on the test rig, ensuring that the inputs reflect realistic operating conditions. The heating and input power capacities of both the test rig and the Simulink model were compared, as well as their total heat output and total energy consumption. These metrics were chosen because they provide a comprehensive assessment of the heat pump's performance under various conditions. A paired t-test (two-sample) was conducted to statistically analyse the differences between the experimental and simulation results. This test was selected due to its ability to compare two related samples, making it suitable for evaluating the consistency between the test rig and the simulation model (Devore, 2016). Once the t-test is completed, the author will look for statistical significance. Specifically, if both the air source heat pump and simulation model are significantly different or not, based on the total energy consumption, heat output, and water content after defrost cycles.

The primary data inputs were ambient temperature and relative humidity, collected from historical weather databases and real-time sensors on the test rig. These inputs directly affect frost build-up rates and heat pump efficiency, making them essential for accurately modelling performance. The data was used to simulate a wide range of operational conditions, including extreme cold scenarios that stress the heat pump's limits.

One of the research objectives (1) aims to analyse various house types and insulation levels from different countries and cities, as well as specific house types and insulation levels from the UK. This selection was based on the need to provide a comprehensive look-up table that represents the relationship between house type, insulation level, ambient temperature, and the heating demand and energy consumption by heat pumps. The chosen house types include traditional British house, old and very old uninsulated house with solid walls, uninsulated house with unfilled cavity wall, insulated house with solid walls, and insulated house with filled cavity wall which are common in the UK (Sen & Al-Habaibeh, 2021) (Table 3.1).

Table 3. 1 *- Typical house types and building elements U-values (Sen & Al-Habaibeh, 2021).*

House type	A_{house}	U_{walls}	U_{floor}	U_{roof}	U_{window}	ACH	A_{wall}	A_{window}	V_{house}
Traditional British house	76	1.5	0.13	0.16	2.7	0.5	80	20	240
Uninsulated very old house with solid walls	76	2.3	0.25	2.5	5.2	0.5	80	20	240
Uninsulated old house with solid walls	76	1.7	0.25	2.5	5.2	0.5	80	20	240
Uninsulated house with unfilled cavity walls	76	1.5	0.25	2.5	2.7	0.5	80	20	240
Insulated house with solid walls	76	0.32	0.13	0.18	0.7	0.5	80	20	240
Insulated house with filled cavity walls	76	0.25	0.13	0.16	0.7	0.5	80	20	240

Additionally, the research included 10 global cities to examine the impact of local climate and insulation standards on ASHP power consumption. The insulation standards were determined based on local building codes and the average U-values for walls, roofs, floors, and windows. This approach allowed for the simulation of heat pump performance across a realistic range of building characteristics. The choice of house types and insulation standards was justified by the need to address the variability in building stock across different regions. Different house types and insulation levels significantly impact the heating demand and energy consumption of heat pumps. For instance, well-insulated buildings with low U-values require less energy to maintain thermal comfort, thereby enhancing the efficiency of heat pumps. Conversely, poorly insulated buildings with high U-values demand more energy, especially in colder climates where heat loss is substantial.

Including house types and insulation levels from both international contexts and the UK allows the study to provide localized insights while also offering broader applicability. This dual approach supports the development of a look-up table that can be used by stakeholders, such as policymakers and heating, ventilation, and air conditioning (HVAC) professionals, to predict heat pump performance in various housing contexts. The heating demand and energy consumption for each house type were simulated using the developed Simulink model. The simulation considered local climate data, house type, insulation levels, and the occurrence of defrost cycles. This allowed for an accurate estimation of the heat pump's performance under realistic conditions, including the impact of varying insulation standards on energy efficiency. The results were used to generate a comprehensive look-up table that maps the relationship between house type, insulation level, ambient temperature, and heat pump energy consumption. The chosen temperature range of -20°C to 20°C is critical to understanding the performance of air-source heat pumps across a wide spectrum of operating conditions, including those not typically experienced in the UK. Although temperatures in the UK rarely reach as low as -20°C, it is important to explore this gradient. Air-source heat pumps are increasingly used in a variety of climates, including regions where temperatures can drop significantly below freezing. Understanding how heat pumps perform at these extreme low temperatures is essential, especially since frost build-up and defrost cycles are more frequent and have a greater impact on energy consumption and system efficiency at these temperatures. Even if such extreme conditions are rare in the UK, modelling them provides insights into potential scenarios that could arise during unusually cold winters or in similar climates. With the increasing unpredictability of weather patterns due to climate change, exploring a wide temperature gradient helps in future-proofing heating technologies. The UK has experienced cold snaps in recent history, and understanding the performance of heat pumps under extreme conditions can inform mitigation strategies and design improvements. This ensures that heat pumps remain reliable and efficient even during unforeseen temperature drops. The broader temperature range allows for a comparative analysis of heat pump performance in climates that the UK might aspire to match in terms of building standards or energy efficiency goals. By including temperatures as low as -20°C, the study aligns UK performance metrics with those from colder regions like Northern Europe or North America, providing a benchmark for assessing the robustness of UK heat pump installations against international standards. Testing the operational limits of heat pumps, including at -20°C, is crucial for understanding the engineering constraints and performance limits of these systems. This knowledge can inform the design of future heat pumps that are more resilient to frost and capable of maintaining efficiency even under severe conditions, thereby improving overall reliability.

Some of the key equations used in this section is heat transfer in conduction, convection and radiation:

$$Q_{cond} = -kA\frac{dT}{dx} \qquad \text{(Eq. 1)}$$

Where: Q_{cond} is the rate of heat transfer (W), k is the thermal conductivity of the material (W/m.K), A is the cross-sectional area through which heat is being conducted (m^2), and $\frac{dT}{dx}$ is the temperature gradient (K/m) in the direction of heat transfer. (Çengel & Boles, 2015)

For a one-dimensional system with a constant temperature gradient, the equation is as follows:

$$Q_{cond} = \frac{kA(T_1-T_2)}{L} \qquad \text{(Eq. 2)}$$

Where: T_1 and T_2 are the temperatures (K) at the two ends of the material, L is the thickness or length of the material (m). (Çengel & Boles, 2015)

$$Q_{conv} = hA(T_s - T_\infty) \qquad \text{(Eq. 3)}$$

Where Q_{conv} is the rate of heat transfer by convection (W), h is the convective heat transfer coefficient ($W/m^2.K$), A is the surface area exposed to the fluid (m^2), T_s is the surface temperature (K), and T_∞ is the temperature of the fluid far away from the surface (K). (Çengel & Boles, 2015)

$$Q_{rad} = \epsilon\, \sigma A(T_s^4 - T_\infty^4) \qquad \text{(Eq. 4)}$$

Where: Q_{rad} is the rate of heat transfer by radiation (W), ϵ is the emissivity of the surface (dimensionless, ranges from 0 to 1), σ is Stefa-Boltzmann constant = 5.67 x 10^{-8} $W/m^2.K^4$, A surface area of the emitting body (m^2), T_s is the surface temperature of the object (K), and T_∞ is the temperature of the surroundings (K). (Çengel & Boles, 2015)

Further details will be discussed in Chapters 4 and 5.
Further details on the survey will be discussed in Chapter 6.

3.4. Case studies

This stage of the research outlines the methodology for conducting two in-depth case studies involving homeowners who have adopted heat pump technology for heating their homes—one using an air-to-air heat pump and the other using an air-to-water heat pump. The case studies will combine semi-structured interviews and thermal comfort monitoring to provide a comprehensive understanding of the experiences, satisfaction levels, and actual performance of heat pumps in real-life settings. This mixed-methods approach aims to uncover both subjective insights from homeowners and objective data on indoor thermal comfort, allowing for a thorough analysis of the benefits and challenges associated with heat pump adoption. The findings from these case studies will also help to validate and expand upon the results of the broader homeowner survey described in Chapter 7. The mixed-methods approach described in this research methodology is highly suitable for a study involving both subjective experiences and objective data collection. This research aims to gain a holistic view of homeowners' experiences with heat pump technology. By combining semi-structured interviews (qualitative) with thermal comfort monitoring (quantitative), the methodology allows the researcher to capture both the subjective experiences of the homeowners (e.g., satisfaction, perceived benefits and challenges) and the objective performance of the heat pumps (e.g., actual thermal comfort). Mixed-methods approaches are ideal for studies where understanding the interaction between human behaviour and technology is crucial because they provide both breadth and depth of insight. Heat pump adoption and its perceived effectiveness are complex, involving not only technical factors (e.g., energy efficiency and performance) but also personal factors (e.g., comfort preferences, lifestyle, and expectations). By using mixed methods, the research can address the complexity of this issue from multiple perspectives, ensuring that both the technical performance and user satisfaction are adequately explored. The case studies serve an additional purpose of helping to validate and expand upon the results of a broader homeowner survey. A mixed-methods design is particularly useful in such cases, where qualitative insights from interviews can help explain trends found in quantitative survey data, while quantitative measurements from the thermal comfort monitoring can provide evidence to support or challenge qualitative findings. The use of case studies within the mixed-methods framework allows for contextualized understanding of how heat pump technologies perform in real-life settings. It enables the researcher to explore not just the "what" but also the "why" behind homeowners' experiences, uncovering factors that may not be evident from quantitative data alone. This is further supported by Creswell and Plano Clark (2018), suggesting that mixed methods offer both the depth of qualitative data and the generalisability of quantitative data. They highlight how this approach is particularly beneficial for exploring complex, multifaceted phenomena such as those involving technology adoption and user satisfaction.

The two houses included in the case study are located in Nottingham and in Brownhills. Participant A is located in Nottingham lives in a semi-detached house. They own an air-to-air heat pump used for space heating only. Participant B located in Brownhills lives in a detached house and owns an air-to-water heat pump used for both space heating and hot water.

Table 3.2 showcases the used sensors within both houses.

Table 3. 2 *- Humidity and temperature sensors inside and outside the participant's houses*

Sensor and units	**Participant A – sensors location**	**Participant B – sensors location**
OM-CP-RHTemp101A Humidity and temperature loggers (RH% and °C)	Ambient temperature and relative humidity (outdoors)	Ambient temperature and relative humidity (outdoors)
OM-CP-TC101A Temperature data logger (°C)	Indoor measurement	Indoor measurements

The accuracy of both OM-CP-TC101A and OM-CP-RHTemp101A is ±0.5°C for temperature and ±3.0% RH for humidity, respectively (Omega Engineering, 2024). The data loggers are calibrated through the provided by the supplier Omega software, which gives to option for devices calibration to ensure accuracy of the captured data. The longing rate of the sensors for both participants were adjusted for 1 hour. A 1-hour interval provides a balance between data granularity and storage efficiency. This rate is typically sufficient to capture daily and seasonal variations in temperature and humidity. It also allows for the detection of general trends, cycles, and patterns without the data becoming overwhelming in size, which can happen with shorter intervals.

The collected data took place between 1st December and 15th March. The reason to choose this period was to estimate both how thermal comfort was met in both households and how much energy was consumed from both heat pumps in cold weather.

In addition to the humidity and temperature loggers, electricity usage by the heat pumps was also collected from both participants. This would provide valuable information regarding their energy consumption to provide heat for their homes and establish appropriate estimation of the units' performance. For Participant A, a UK plug power meter AC230V~250V; 13A with an LCD display was provided to monitor the power consumption of the heat pump. This device was used because the air-to-air heat pump uses a 3-pin connection, and the unit does not collect any energy data.

Participant B has an air-to-water heat pump which provides the user with energy input and heat output data. The participant gave consent to provide this information to allow for the investigation of how the cold weather affected their thermal comfort and energy consumption.

3.4.1. Data Collection Methods

3.4.1.1. Semi-Structured Interviews

The first component of the case study methodology involves conducting semi-structured interviews with the two homeowners.

Semi-structured interviews provide a balance between having a structured framework of key questions and allowing flexibility to explore new topics that may emerge during the discussion (Wengraf, 2014). This is particularly important when exploring the subjective experiences of heat pump owners, as it allows to delve deeper into unexpected insights or issues that may not have been anticipated initially. This interview format allows for collecting rich, qualitative data that goes beyond surface-level responses (Wengraf, 2014). Homeowners can provide detailed accounts of their motivations for choosing heat pump technology, their satisfaction with thermal comfort and energy savings, and any challenges they face. Such depth is invaluable for understanding the complexities and challenges of using heat pumps. The semi-structured approach also allows for a direct comparison of experiences between the two case studies - one with an air-to-air heat pump and the other with an air-to-water heat pump. While maintaining a consistent set of core questions ensures comparability, the flexibility of the interviews enables a more in-depth exploration of unique factors related to each type of heat pump.

The data collected from the semi-structured interviews will be analysed using thematic analysis. Thematic analysis allows for systematically identifying and analysing themes across qualitative data (Wengraf, 2014). This approach ensures that the most significant insights related to homeowners' experiences with heat pumps are captured and clearly articulated. This method is highly flexible and can accommodate a wide range of qualitative research questions (Wengraf, 2014). It is particularly useful in exploring the subjective experiences of individuals, making it well-suited for analysing interview data where the responses may vary significantly. Thematic analysis complements the semi-structured interview format by enabling the identification of both expected and unexpected themes (Wengraf, 2014). This method allows to capture not only the pre-defined themes (e.g., reasons for adoption, satisfaction with heating demand, and energy bills) but also new themes that emerge organically during the interviews. Thematic analysis allows for comparing themes identified in the interviews with the findings from the broader homeowner questionnaire. This cross-validation helps determine whether the detailed insights from the case studies align with the general trends observed in the survey data, particularly regarding the adoption rates, satisfaction levels, and barriers to adopting heat pumps. Thematic analysis stands out as the most appropriate method for this research when compared to other qualitative analysis techniques due to its unique flexibility and adaptability. Unlike methods such as grounded theory or narrative analysis, thematic analysis is not bound by rigid frameworks or theoretical commitments, allowing it to accommodate a wide range of research questions (Wengraf, 2014). This flexibility is especially valuable when dealing with diverse data sources, such as semi-structured interviews, where the responses can vary significantly.

3.4.1.2. Thermal Comfort Monitoring Using Temperature Sensors

In addition to semi-structured interviews, temperature sensors will be used to collect temperature data inside and outside each home to monitor thermal comfort levels. This component adds a quantitative dimension to the case studies and provides several key benefits. Particularly, while homeowners' perceptions of thermal comfort are subjective, temperature sensors provide objective, real-time data on indoor thermal conditions. This data can help assess whether the heat pump systems maintain consistent and comfortable temperatures throughout the home, validating or challenging the homeowners' subjective experiences. By placing temperature sensors outdoors and indoors, the study can capture spatial variability in thermal comfort within the home. This information is crucial for understanding how heat is distributed by different types of heat pumps (air-to-air vs. air-to-water) and how effectively they maintain comfort levels.

Combining quantitative data from temperature sensors with qualitative data from interviews allows for a more comprehensive analysis of heat pump performance. For example, if a homeowner reports dissatisfaction with thermal comfort, temperature data can help pinpoint whether this dissatisfaction is due to actual temperature inconsistencies or other factors such as personal preferences or system settings. The thermal comfort data can be used to support or contradict the information provided by the homeowners during the interviews. If a homeowner claims their heat pump provides excellent thermal comfort, but the temperature data shows significant fluctuations, this discrepancy can provide valuable insights into potential issues, such as inadequate system sizing, poor insulation, or user settings.

Combining qualitative data from semi-structured interviews with quantitative data from temperature sensors provides a robust, multi-faceted approach to understanding heat pump performance even with a small sample size of interviews. The integration of quantitative data from temperature sensors strengthens the overall confidence in the findings by adding an objective layer of validation. Thematic analysis, as employed in this research, is highly flexible and well-suited for deep exploration of subjective experiences, allowing the researcher to uncover rich, nuanced themes even from a small sample size. With just two interviews, the goal is to capture in-depth insights from homeowners regarding their subjective experiences with heat pumps. Thematic analysis focuses not on the quantity of responses but on the quality of the data, aiming to identify significant themes that may either confirm or challenge broader patterns observed in larger datasets, such as those from the homeowner questionnaire. The richness of the data collected from semi-structured interviews, combined with objective temperature data, provides enough depth to explore key issues in heat pump performance and thermal comfort. The objective temperature data acts as a form of cross-validation that can help generalize findings beyond the two cases. Moreover, thematic analysis is designed to uncover emergent themes, which, when paired with quantitative data, allows for a deeper understanding that can provide useful insights even with a small qualitative sample. This is further supported by Creswell and Plano Clark (2018) as they outline the value of mixed methods research, where the integration of qualitative and quantitative data offers a more comprehensive understanding than either approach alone. They argue that combining objective (quantitative) and subjective (qualitative) data allows for cross-validation and enhances confidence in the findings, even when qualitative sample sizes are small.

3.4.2. Data Analysis Method

The data analysis will involve both thematic analysis of interview data and statistical analysis of temperature data.

Thematic analysis will be used to analyse the semi-structured interview data. The process will involve familiarisation with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing a final report. This method will allow to identify and articulate key themes related to homeowners' experiences, satisfaction levels, and perceived benefits and challenges of heat pump technology.

The temperature and humidity data collected from sensors will be analysed using statistical methods, such as calculating mean, minimum, and maximum temperatures inside the home. Additionally, the variability in temperatures (standard deviation - STDEV) will be analysed to assess the consistency of thermal comfort provided by the heat pumps. This analysis will help determine whether the systems are performing optimally and whether there are any issues with heat distribution or control.

The qualitative and quantitative data will be integrated to provide a comprehensive understanding of heat pump performance and homeowner satisfaction. For example, if a theme emerges from the interviews indicating that heat pump owners experience uneven heating, this can be cross-referenced with the temperature sensor data to validate or further explore this issue. This integrated approach ensures that the findings are robust and grounded in both subjective and objective evidence.

The mixed-methods approach combining semi-structured interviews and thermal comfort monitoring provides a robust framework for understanding the adoption and performance of heat pumps in the UK. Semi-structured interviews, supported by thematic analysis, will capture homeowners' experiences, motivations, and satisfaction levels, offering deep qualitative insights. Meanwhile, temperature monitoring will provide objective, quantitative data on thermal comfort, enabling a more comprehensive evaluation of heat pump performance. This methodology allows for cross-validation of data, providing a nuanced understanding of the factors influencing heat pump adoption and the extent to which these systems meet homeowners' needs for comfort and energy efficiency. The findings will contribute to the broader knowledge base on heat pump adoption and inform strategies for enhancing user satisfaction and technology uptake.

3.5. Homeowner Survey on Heat Pump Adoption and Heating Preferences in the UK

Despite the UK government’s ambitious target of installing 600,000 heat pump units annually by 2028, the current adoption rates of air source heat pumps (ASHPs) remain low (Lyden et al., 2024). Understanding the reasons behind this gap is crucial for developing strategies to promote heat pump adoption as part of the broader transition to low-carbon heating solutions. Existing literature offers limited insight into the public perception of heat pumps, the factors influencing homeowners' decisions to adopt or reject this technology, and the specific challenges related to heating demand across different house types and insulation levels. To address this gap, this thesis presents the design and implementation of a comprehensive questionnaire distributed among UK homeowners, aiming to gather both quantitative and qualitative data on heating preferences, perceptions of heat pumps, and building characteristics. The survey was distributed among households in the UK via social media platforms such as Reddit, Facebook and heating related forums. Distributing a questionnaire online is suitable because it allows for a broad reach, enabling access to a diverse and geographically dispersed audience, which can enhance the representativeness of the data. They offer convenience for respondents, who can complete the survey at their own pace and on various devices. Additionally, online tools often provide automated data collection and analysis features, improving the efficiency and accuracy of data handling (Regmi et al., 2016).

The literature review conducted earlier in this thesis identified a critical gap: a lack of research on the current adoption rates of heat pumps in the UK, particularly in understanding why homeowners may be hesitant to integrate this technology. Addressing this gap is essential to understand the low installation numbers and why they fall short of government targets. The questionnaire is designed to explore these issues by directly engaging with homeowners to gather data on the following:

- Current Heating Methods: To determine the most popular heating methods in UK homes and the reasons behind these choices.
- Perceptions of Heat Pumps: To explore why some homeowners have adopted heat pumps, while others prefer to continue using gas boilers or other heating systems.
- House Characteristics and Insulation Levels: To assess how different house types (e.g., detached, semi-detached) and insulation levels impact heating demand and the suitability of heat pump technology.
- User Experience of Heat Pump Owners: To understand the satisfaction levels of heat pump owners regarding heating demand, thermal comfort, and energy savings.

The combination of these data points will provide valuable insights into the factors influencing the adoption of heat pumps, potential barriers, and opportunities for targeted interventions to accelerate their uptake.

3.5.1. Data Collection Methodology

The questionnaire will collect both quantitative and qualitative data to provide a comprehensive understanding of homeowner preferences and perceptions:

- Quantitative Data: This will include closed-ended and multiple-choice questions on current heating systems, house types, insulation levels, and demographic information. Quantitative data is essential to identify patterns, correlations, and general trends among different homeowner groups, providing a statistical foundation for understanding the current state of heat pump adoption (Morgan 2014).
- Qualitative Data: Open-ended questions will capture in-depth insights into the reasons behind homeowners' choices, their concerns about heat pumps, and their satisfaction levels. Qualitative data is crucial for uncovering the underlying attitudes, beliefs, and motivations that are not easily quantified, offering a more nuanced perspective on the barriers to heat pump adoption (Morgan 2014).

Collecting both types of data allows for a mixed-methods approach, which provides a richer, more holistic understanding of the research problem. The quantitative data will help in identifying the prevalence and patterns of heating choices, while the qualitative data will provide context and depth to these findings, revealing the personal and contextual factors influencing decisions.

3.5.2. Surveys

This research adopts a mixed-method approach, systematically integrating qualitative and quantitative data to answer the research questions. Building on the literature review and to explore the general public's experience, opinion and awareness in using heat pump technology, a survey was designed. The questionnaire explores the reasons why people in the UK would or would not prefer HPs to heat their homes. It targeted individuals aged 18 and above living in the UK. Random sampling, where participants are chosen based on availability and willingness to respond, was employed (Gravetter & Forzano, 2006; Salim, 2022). The survey included single and multiple-choice questions, and open-ended responses, allowing participants to express their opinions. Quantitative data were gathered from the close-ended questions, while qualitative insights were derived from open-ended responses, shedding light on what makes people to use or not to use heat pump technology in their home.

A survey link with an overview of the research and its purpose was distributed via email and social media to individuals across the UK.

3.5.3. Sample size

In empirical studies like surveys, selecting the appropriate sample size is crucial for drawing reliable conclusions. The confidence interval (CI) quantifies the uncertainty of the collected data. A 95% CI is commonly used, and this study applied a margin of error of 6.5-7.5%. Using normal distribution and z-score values, the sample size was calculated to range between 171 and 228. The survey results, including responses to objective questions, were analysed quantitatively. Open-ended responses were examined qualitatively, with findings relevant to the research questions reported. Collecting data from the targeted sample size was achieved with the questionnaire with 175 responses.

3.5.4. Data Analysis Method

To analyse the collected data, a combination of descriptive statistics, cross-tabulation, and thematic analysis will be employed:

- Descriptive Statistics: This method will be used to summarize the quantitative data, providing a clear picture of the most popular heating methods, types of dwellings, and insulation levels. Measures such as frequencies, percentages, means, and standard deviations will be calculated to describe the sample population and identify overall trends.
- Cross-Tabulation Analysis: Cross-tabulation will be useful in exploring relationships between different variables, such as the correlation between house type or insulation level and the choice of heating system. This method allows for the identification of patterns and potential predictors of heat pump adoption or resistance among different homeowner groups.
- Thematic Analysis: For the qualitative data, thematic analysis will be used to identify, analyse, and report patterns or themes within the responses. This method involves coding the data and grouping similar responses into themes that can help explain homeowners' attitudes toward heat pumps, perceived barriers, and factors influencing their heating choices. Thematic analysis is particularly useful for uncovering the nuanced reasons behind the continued preference for gas boilers or the decision to adopt heat pumps.

The chosen data analysis methods are well-suited for addressing objective 1 of this study. Descriptive statistics and cross-tabulation provide a robust quantitative foundation to understand the general trends and relationships among key variables. Thematic analysis complements these methods by offering a deeper qualitative understanding of the attitudes and perceptions that drive heating choices. This combination of methods ensures a comprehensive analysis that captures both the breadth and depth of homeowner opinions and experiences regarding heat pump technology.

By employing a mixed methods approach through the distribution of a comprehensive questionnaire, this chapter aims to bridge the identified gap in the literature related to the current adoption rates of heat pumps and homeowners' perceptions in the UK. The insights derived from both quantitative and qualitative data will be invaluable for policymakers, energy providers, and other stakeholders seeking to promote the adoption of heat pumps and design effective interventions to overcome the existing barriers. This research not only sheds light on current homeowner preferences but also provides a foundation for understanding how to align these preferences with the UK's broader decarbonisation goals.

3.6. District heating as a competitive technology – Nottingham Ice Centre case study

The methodology in Chapter 8 focuses on a detailed case study of the Nottingham Ice Centre (NIC), focusing on the analysis of heat recovery systems as alternatives to district heating. Currently the centre satisfies the heating demand of the building through district heating. The goal of this case study was to evaluate the feasibility of using heat recovery methods, particularly heat pumps and thermal storages, to reduce energy consumption and minimise reliance on external district heating sources. The research involved a comprehensive assessment of the facility's electricity and heat usage, and recovery mechanisms within the context of a large-scale commercial operation.

3.6.1. Data Collection

- **Energy Data Monitoring**: Electricity usage data were collected from the facility’s refrigeration system, which generates significant waste heat during the process of maintaining ice surfaces. Specifically, electricity and power usage and heat rejection by the building’s chiller system along with the facility’s heating usage was provided by NIC. This waste heat, which would typically be dissipated, was captured and reused within the facility through a heat recovery system. Data were collected on the total amount of heat produced, the proportion recovered, and the energy savings achieved by redirecting this heat for space heating and other thermal needs. Additionally, thermal usage data through the centre’s heat meters was also collected. This was crucial as it would provide the average heat demand through the year and compare it to the heat recovery from heat pumps and thermal storages as alternatives to district heating.
- **System Performance Monitoring**: The performance of the heat recovery system, including the thermal storage units, was continuously monitored. Key performance indicators such as heat recovery efficiency, thermal storage capacity, and overall energy

consumption were tracked over an extended period to evaluate how effectively the system reduced dependence on district heating.

- **Cost and Energy Savings Analysis**: Financial data were also collected to determine the cost savings associated with the use of the heat recovery system compared to conventional district heating methods. The analysis considered both the reduction in energy consumption and the associated reduction in heating costs over time.

3.6.2. Data Analysis

- **Efficiency and Energy Savings Calculation**: The data on energy recovery and consumption were analysed to calculate the efficiency of the heat recovery system. This included determining the ratio of waste heat recovered to the total heat generated by the refrigeration system and the reduction in the facility's reliance on external district heating.

The following equations are the key questions that were used to determine the potential of the proposed heat pumps to deliver heat and if they can satisfy NIC's heating demand, along with the cost effectiveness of using heat pump technology as a thermal energy recovery method:

$$\%Evp_{power} = Heat_{reject} \div \left(\left(HP_{EvpPower} \times 24 \times NoDays\ per\ month \right) \div 1000 \right) \times 100 \qquad \text{(Eq. 5)}$$

Where: ***%EVP**power* is the percentage of the evaporation power of the proposed heat pumps from the cooling tower's ejected heat (%); $\boldsymbol{Heat_{reject}}$ is the rejected heat from the cooling tower (MWh); $\boldsymbol{HP_{EvpPower}}$ is the evaporation power of the proposed heat pumps (kW). Equation 5 allowed to determine the percentage of thermal energy that the proposed heat pumps could utilise as a heat source.

$$HP_{electricity}\left(if\%Evp_{power} < 100\%\right) = HP_{UnitPower}\left(HP_{EvpPower} \div 100\right) \times 24 \times NoDays\ per\ month) \div 1000 \qquad \text{(Eq. 6a)}$$

$$HP_{electricity}\left(if\%Evp_{power} > 100\%\right) = \left(HP_{UnitPower} \times 24 \times NoDays\ per\ month\right) \div 1000 \qquad \text{(Eq. 6b)}$$

Equations 6a and 6b calculate the electricity per month required by each of the proposed heat pumps if $\boldsymbol{\%Evp_{power}}$ is lower or higher than the ejected heat by the cooling tower, respectively. $\boldsymbol{HP_{electricity}}$ is the electricity required by each heat pump per month (MWh); $\boldsymbol{HP_{EvpPower}}$ is the evaporation power of each heat pump (kW); $\boldsymbol{HP_{UnitPower}}$ is the input power rate of each heat pump (kW). It is necessary to divide by 1000 for unit consistency.

$$HP_{heat\ out} = HP_{electricity} \times HP\ COP \qquad \text{(Eq. 7)}$$

Equation 7 calculates the total heat output by each heat pump per month; where: $\boldsymbol{HP_{heat\ out}}$ is the heat output (MWh); ***HP COP*** (unitless) is the estimated coefficient of performance for each heat pump as provided by the supplier (Please see table 8.1 in Chapter 8) (Carrier, 2024).

$\%Difference = 1 - (HP_{heat\ out} \div NIC_{heat\ demand})$ (Eq. 8)

Equation 8 estimates the percentage difference (***%Difference***) between the heat output (calculated using Eq. 7) that can be delivered by each heat pump and the thermal energy demand by NIC per month (***$NIC_{heat\ demand}$***)(MWh).

$HP_{electricity\ cost} = (HP_{electricity} \times 1000 \times Cost\ of\ electricity)$ (Eq. 9)

Equation 9 calculates the energy cost (***$HP_{electricity\ cost}$***)(£/month) to run each of the proposed heat pumps per month. The cost of electricity for NIC as of September 2024 is £0.23/kWh.

It was important to estimate the performance and cost effectiveness of thermal storages as a heat recovery method instead of using heat pumps. As thermal storages alone would not be enough to satisfy NIC's thermal energy demand, district heating would still be necessary to further heat up the water in the thermal storage to 60°C as required by the building. Unlike the heat pump heat recovery system alternative, where the heat pump would completely provide thermal energy to the building instead of district heating. The following equations were used to calculate that:

$DH = (m \times Cp_{water} \times \Delta T) \div 3600$ (Eq. 10)

Equation 10 calculates the rest of the thermal energy required by district heating (***DH***)(kW) to heat up the thermal storage to 60°C; ***m*** is the mass of the thermal storage (kg); ***Cp_{water}*** is the heat capacity of water (4.18 kJ/kg.K); ΔT is the temperature difference between the initial temperature after wasted heat from the NIC's chillers heat up the thermal storage (K) and the required temperature by NIC (60°C = 333.15 K).

$TTE = ((m \times Cp_{water} \times \Delta T) \div (Q \times Cp_{water} \times \Delta T)) \div 60$ (Eq. 11)

Equation 11 estimates the time to heat up the thermal storage (***TTE***)(min) from the initial temperature of the tap water using the ejected heat from NIC's chiller system. ***Q*** is the volumetric flow rate of the tap water (l/s) (Lyon, 2022).

$TTE_{hr} = TTE \div 60$ (Eq. 12)

Equation 12 calculates the time to heat up the thermal storage in hours (***TTE_{hr}***).

$TtC_{day} = TTe_{hr} \times 24$ (Eq. 13)

Equation 13 estimates the times to charge the thermal storage per day (***TtC_{day}***) (unitless).

$TtC_{year} = TtC_{day} \times 365$ (Eq. 14)

Equation 14 calculates the times to charge the thermal storage in a year (***TtC_{year}***) (unitless).

$DHtC_{year} = TtC_{year} \times DH$ (Eq. 15)

Equation 15 estimates the district heating energy required to charge the thermal storage in a year (***$DHtC_{year}$***) (kWh).

- **Comparative Cost Analysis**: The cost of operating the heat recovery system was compared to the costs associated with traditional district heating. As of 2024, NIC's rate of electricity cost is 28 p/kWh and 7p/kWh for heating, data provided by them. This comparison provided insights into the economic feasibility of using heat recovery as a district heating alternative in similar commercial settings. Energy cost reductions, payback periods, and long-term savings were calculated based on the energy performance data.

The case study method was chosen because it allows for an in-depth, real-world examination of a specific energy recovery application within a large commercial facility. The Nottingham Ice Centre, due to its high energy demands for refrigeration and heating, provided a unique opportunity to assess the practical benefits and challenges of heat recovery systems in reducing reliance on district heating. This method also enabled a detailed evaluation of both the technical performance and economic feasibility of heat recovery, offering valuable insights for similar facilities considering alternatives to district heating.

By using real-world performance data, the case study method ensured that the findings were not only theoretically sound but also practically applicable. The extended monitoring period allowed for the capture of seasonal variations in energy demand, providing a robust dataset for analysing the long-term effectiveness of the heat recovery system.

3.7. Profile of the power grid in the UK and the impact by the implementation of electric vehicles.

This stage centres on the grid impact analysis related to the mass adoption of electric vehicles (EVs) in the UK. The aim of this chapter was to evaluate the increased load on the grid caused by large-scale EV adoption as part of the country's decarbonisation strategy. This analysis was conducted using numerical modelling, focusing specifically on how EV adoption would affect grid stability, capacity, and energy demand in line with the UK's Net Zero 2050 ambitions.

3.7.1. Data Collection and Generation

- **Electric Vehicle Penetration Data**: The numerical modelling was informed by forecasts of EV adoption rates in the UK (Milev et al. 2020a). These data were sourced from government reports, industry forecasts, and ongoing national electrification targets for 2030 and 2050. The penetration rates of EVs in the country were a key variable in assessing future grid impacts.
- **National Grid Load Profiles**: Baseline grid load data were obtained from historical records, providing a comprehensive picture of daily and seasonal variations in

electricity demand (Stolworthy, 2022). These profiles helped establish the existing strain on the grid and allowed for the projection of how additional demand from EVs would affect overall grid performance.

- **Energy Demand per Vehicle**: The model incorporated estimates of the energy required to charge a typical EV. This energy demand was based on data about average battery sizes, charging capacities, and usage patterns in the UK. The energy required for EVs was treated as an additional load on top of the existing demand (Milev et al., 2020a).

3.7.2. Numerical Modelling

- **Grid Load Estimation**: The core of the methodology involved calculating the additional load imposed on the grid by EVs. Numerical modelling was used to project how total electricity consumption would rise as EV penetration increased. The model accounted for the energy needs of each EV and aggregated this data based on national EV penetration targets.
- **Peak Demand Stress Testing**: Particular emphasis was placed on estimating how EV-related demand would interact with peak periods of grid load. The model was used to test how the grid would handle peak electricity consumption during high-demand periods, especially in winter, when heating and other residential electricity usage spikes.
- **Grid Infrastructure Analysis**: The model also evaluated the capacity of the current grid infrastructure and its ability to handle the increased electricity load. The analysis involved calculating whether grid reinforcements would be required to prevent overloads as EV adoption rises. It focused on identifying weak points in the distribution network and areas that would need upgrading to accommodate future demand.

3.7.3. Data Analysis

- **Energy Demand Growth Projections**: The numerical model provided detailed projections of how much electricity demand would grow as EV adoption rates increase. The analysis determined both the short-term and long-term increases in demand, with a focus on identifying when grid infrastructure upgrades would be required to prevent overloads.
- **Grid Capacity Utilisation**: The data generated from the model allowed for the calculation of grid utilisation rates, particularly during periods of high demand. By comparing projected EV-related load increases with the grid's capacity, the analysis

was able to highlight critical periods and regions where additional infrastructure investments would be necessary.

- **Potential Overload Scenarios**: One of the key outputs of the modelling exercise was the identification of potential overload scenarios. By stress-testing the grid's ability to meet increased demand, the model was able to predict when and where grid failures could occur if no infrastructure improvements were made.

Numerical modelling was chosen as the primary method for this analysis due to its suitability for estimating future demand scenarios based on real-world data. By using existing load profiles and EV adoption forecasts, this method allowed for the projection of grid performance under various levels of EV penetration. Unlike simulations, which might require complex dynamic interactions, numerical modelling focuses on straightforward calculations of increased load, making it ideal for projecting potential strain on grid infrastructure.

The use of stress testing within the model was justified by the need to identify the grid's ability to handle both the day-to-day demand of EVs and the more severe impacts during peak demand periods. This approach ensures that the findings are directly applicable to policy planning and grid infrastructure development as the UK prepares for a more electrified future

3.8. Enabling Technologies

As part of the case studies and the assessment of the test-rig, infrared thermography was used to investigate heat distribution in the ASHP components or hat leaks in buildings via poor insulation or air infiltration.

3.8.1. Thermal imaging

Visualising a building's thermal characteristics highlights areas of heat loss that might otherwise go unnoticed. To understand how insulation level affects heat losses in houses and the relationship between the climate and thermal energy losses in vehicles, thermal images of a residential building in Brownhills and of a car driven on a cold night were captured in cold climate conditions.

Heat transfer in objects occurs through conduction, convection, and radiation. Conduction refers to heat transfer between solids, while convection involves heat transfer through fluids. Radiation is the transfer of heat via electromagnetic waves emitted by an object. Although heat transfer is invisible to the human eye, infrared radiation, a type of electromagnetic wave, can be detected with an infrared camera. Infrared thermography, which involves using an infrared camera to capture thermal images, allows for the observation of thermal patterns by adjusting for the surface's emissive power at varying temperatures (Salim, 2022). The net heat energy

(q) emitted by an object's surface is calculated using the formula: $q = \mathcal{E}\sigma T^4$, where Ɛ represents the surface emissivity ($0 < \mathcal{E} < 1$), σ is Stefan Boltzmann's constant (5.67×10^{-8} W/m²K⁴), and T is the object's absolute surface temperature in Kelvin. Infrared technology helps identify areas of heat loss in buildings (Salim, 2022).

Thermal images were taken outdoors and indoors. Inside the house images were collected at different locations in case study 2's dwelling to investigate heat distribution in the house and thermal losses through the building elements.

Additionally, the images revealed differences in insulation quality, allowing for comparisons between heat loss through walls, doors, and windows and overall insulation effectiveness. The thermal images were captured using a FLIR T640 thermal camera (FLIR, 2013), and the temperature data was analysed with FLIR software.

3.8.2. Data Loggers

For many stages of this work Omega data loggers (OM-CP-RHTemp101A and OM-CP-TC101A) were used. Their accuracy is described in Chapter 3.3 (Omega Engineering, 2024). The loggers were calibrated through the Omega software provided by the supplier, to ensure accuracy of the captured data.

3.8.3. Power meter

A plug power meter was used in case study 1 to measure the input power and energy consumption by the air-to-air heat pump. The device measures and calculates the energy consumption. It can determine the power consumption of electronic devices. The power consumption of switched-on devices under load is measured (from 2W) which means standby consumption is not measured. The Electronic voltage is 230V AC 50Hz. Maximum current of 16A, and maximum power of 3680W. The power supply for the power meter is 2 LR44 batteries. The measured accuracy of the device is ±2 % (Mecheer, n.d.).

3.9. Summary

This chapter has outlined the methodology used in this thesis. Mixed methods approach was used to address the research questions. To investigate the performance of air-source heat pumps, simulation and validation test-rig was implemented to focus on defrosting cycles and the effects of house types, insulation level, climate, and defrost cycles on heating demand and energy consumption. The integration of experimental validation with simulation modelling are done to comprehensively assess heat pump behaviour under a variety of environmental conditions. Furthermore, the methodology includes a qualitative and quantitative case studies and surveys to explore the user engagement and awareness of heat pumps in a domestic environment through mixed method approach and evaluate the user experience. Additionally, the methodology includes an investigating of investing in heat pumps vs district heating as a competitive heating technology in commercial buildings. And finally, the effect on the grid is analysed if decarbonisation of heating and transportation is implemented.

4. The development of air source heat pump and results

Chapter 4 focuses on the development of an Air Source Heat Pump (ASHP) test rig and presents the results of its operation. The primary goal of this chapter is to describe the construction and setup of a generic ASHP test system, which is crucial for validating simulation models and evaluating various performance enhancement strategies.

The test rig, designed for a standard ASHP with an 8kW rated heating capacity, was constructed to adhere to several British Standards governing heat pump systems, ensuring efficiency, safety, and environmental compliance. These include BS EN 14511, BS EN 14825, BS 7671, and BS EN 378, along with ISO 14001 for environmental management.

Key components of the test rig, such as the ZH21 K4E scroll compressor, a plate heat exchanger for water heating, and a finned tube coil heat exchanger as the evaporator, were carefully selected to optimize performance and cost-effectiveness. Additionally, a sophisticated control system featuring the UVR16x2 universal controller and CAN-I/O45 modules was designed to enable precise monitoring and control of the heat pump’s inputs and outputs, ensuring optimal performance.

This chapter will explore the rig's construction, control system, and various testing setups, providing a detailed overview of the steps taken to ensure that the test rig can serve as an effective platform for studying and improving ASHP performance under different conditions. Through this rig, the simulation model can be validated, and potential improvements in heat pump efficiency can be identified and tested.

4.1. Test rig set-up

The simulation model was built after a heat pump test rig with a rated heating capacity of 8kW at evaporating temperatures of -15°C and condensing temperature of 50°C. At evaporating temperature of 10°C and condensing temperature of 50°C the heating capacity of the unit could reach 14kW (Emmerson 2022). This unit would be suitable for a 3-bedroom house (Cantor, 2011).

One of the key objectives of this PhD research is the construction of an air source heat pump test rig. The setup of this rig, specifically for a standard air source heat pump, involved selecting all components and designing the control system based on recommendations from Gannet Ltd., leveraging their expertise in refrigeration systems. Simon Fanshawe, the director of Gannet Ltd., managed the electrical wiring.

Air source heat pumps in the UK are primarily governed by several British Standards for their design, installation, and testing. Key standards include:

- **BS EN 14511**: This standard specifies the testing methods for the performance of heat pumps, including air source heat pumps. It covers different operating conditions and performance metrics.
- **BS EN 14825**: This standard is used for the evaluation of the seasonal performance of heat pumps and air conditioning equipment.
- **BS 7671**: This is the IET Wiring Regulations, which includes requirements for electrical installations in heat pump systems.
- **BS EN 378**: This standard addresses the safety and environmental aspects of refrigerating systems and heat pumps.
- **ISO 14001**: While not specific to heat pumps, this standard covers environmental management systems, which can be relevant for manufacturers.

These standards ensure that air source heat pumps are efficient, safe, and environmentally friendly.

The main components of the air source heat pump test rig are ZH21 K4E PFJ-524 scroll compressor with a swept volume of 8.04 m^3/h; A condenser plate heat exchanger for water heating; a finned tube coil heat exchanger used as evaporator (model DX SA 33T 2R 12FPI 860L 11N) with aluminium fins, offering a heat transfer area of 0.7151 m^2 and dimensions of 850x842x150 mm; An electronic expansion valve (EX4-I21 / AL800615). The test rig uses a hot gas bypass as a defrost method, which was also simulated in the Simulink model. Please see Appendix I for a full list of components.

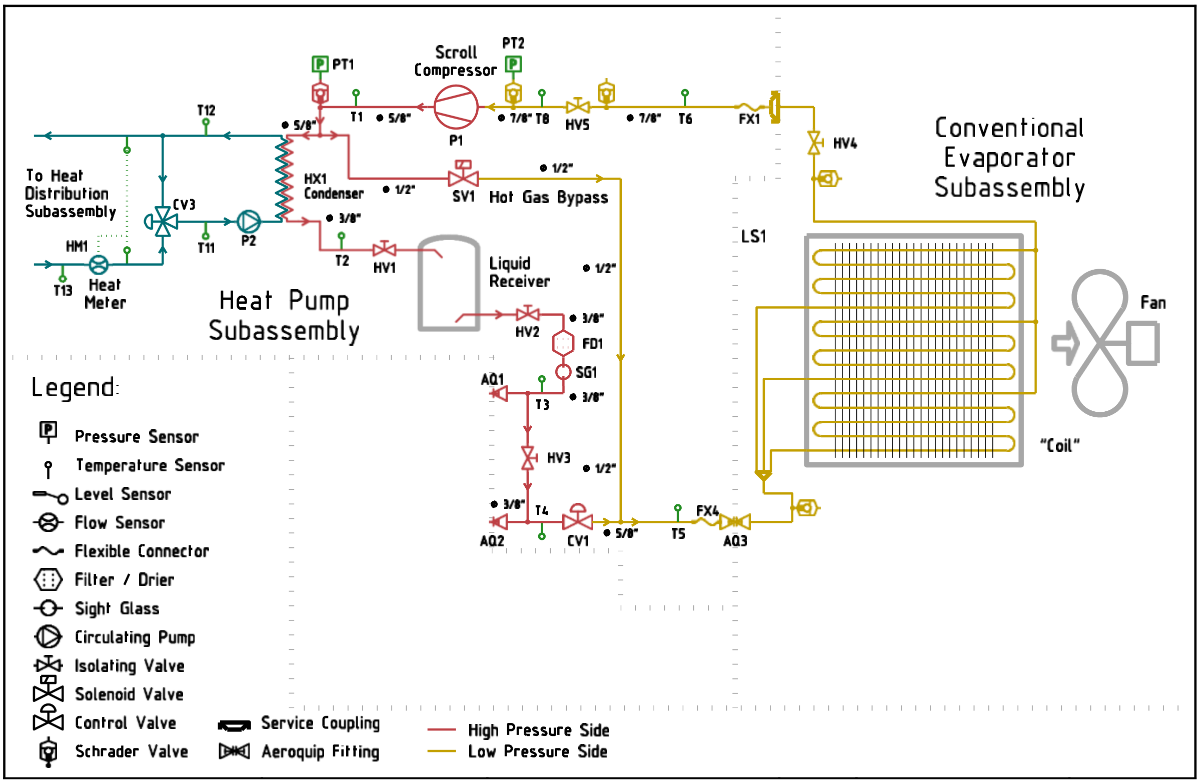


Figure 4. 1 *- Diagram of Conventional Heat Pump Configuration*

Figure 4.1 illustrates the arrangement of components in the air source heat pump. Individual parts were purchased and fabricated prior to assembly. The components, listed in Appendix I, were chosen to minimise costs and delivery times. Ology Services, a certified refrigeration company with experience in brazing and component connection, handled the assembly and brazing tasks.

Evaporator/fan assembly **Test rig of the air source heat pump**

Figure 4. 2 *- Test rig of the air source heat pump*

Figure 4.2-a represents the evaporator and fan assembly. The evaporator was mounted at an angle of 84 degrees to allow the melted frost to be collected at the bottom of the assembly. Figure 4.2-b provides a visual representation of figure 4.1.

4.1.1. Control System

The control system plays a critical role in the heat pump's operation, allowing for programming and monitoring of the heat pump to ensure optimal performance. It primarily tracks the energy input and output. The system's performance was later compared to that of a Simulink model of the standard version, assessing heating output and coefficient of performance (COP). The installed heat meter, part of the control system, measures the thermal energy output from the condenser, providing data such as heating temperature (°C), heat output capacity (kW), and total thermal energy output (kWh). This data enables comparisons between the test rig and simulation model outputs, and helps identify which heat pump version optimizes thermal energy output and overall COP.

The control system assembly began with the UVR16x2 universal controller, which serves as the primary control board for the heat pump. Two CAN-I/O45 modules were connected to this main board to add inputs (e.g., temperature sensors) and outputs (e.g., compressor relays and expansion valves). The CAN-BC2 communication board links the controller to the M-Bus, which includes meters monitoring heating and electrical inputs/outputs. A CMI (Control Monitoring Interface) device, equipped with a 4 GB memory card, serves as a data logger and web interface, storing data from the I/O45 nodes. The CMI is connected to a local computer for setup via the website cmi.ta.co.at, enabling monitoring from any computer or portable device.

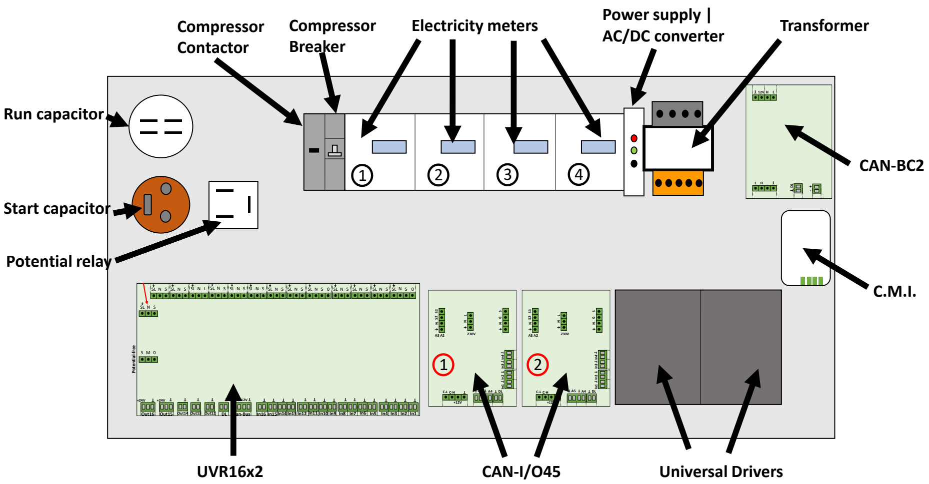


Figure 4. 3 *- Diagram of the control system installed in the heat pump test rig.*

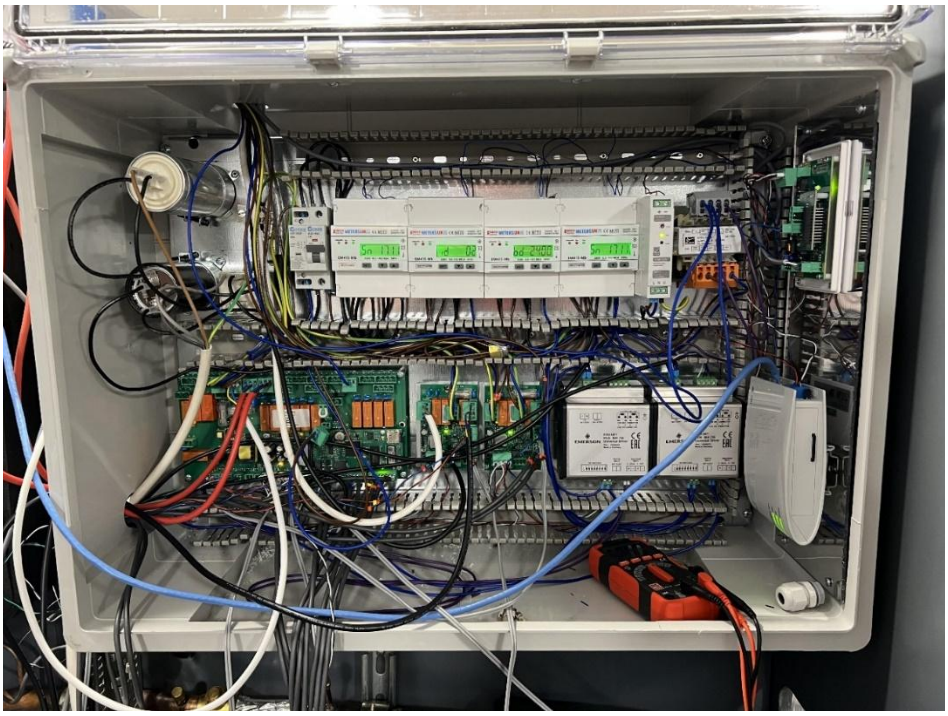


Figure 4. 4 *- Control system of the test rig.*

Both Figures 4.3 and 4.4 showcase the arrangement of the control system components.

Two software packages were installed on both the local PC and workstations: Winsol (version 2.13) for data monitoring and analysis, and Tapps2 (version 1.19.1) for programming and configuring the UVR16x2 main board and other nodes (e.g., I/O45, CAN-BC2). These software packages, recommended by the manufacturer, are compatible with the control system components, support regular updates, and are usable across various operating systems, including Windows, iOS, Mac, and Linux. The web admin feature facilitates downloading and updating Winsol and Tapps2, as well as firmware updates for the control system nodes.

Tapps2 is used to program the units and determine their operation based on input data, such as adjusting evaporator fan power or solenoid valve settings.

Winsol and Tapps2 were used as software because they are specifically designed to interface with the control units of the heat pump system, including the UVR16x2 controller and CAN modules. Winsol is utilised for data monitoring and analysis, allowing for real-time tracking and comprehensive evaluation of the system's performance, while Tapps2 is used for programming and configuring the control units, ensuring precise operation of the heat pump's components.

These software packages were chosen because they are recommended by the manufacturer of the control system components, ensuring compatibility and reliable performance. Additionally, they are regularly updated, supported by the manufacturer, and can operate across various operating systems, including Windows, iOS, Mac, and Linux. The use of these specific software ensures seamless integration, optimal functionality, and easier troubleshooting, which may not be as effectively achieved with other generic or less compatible software tools.

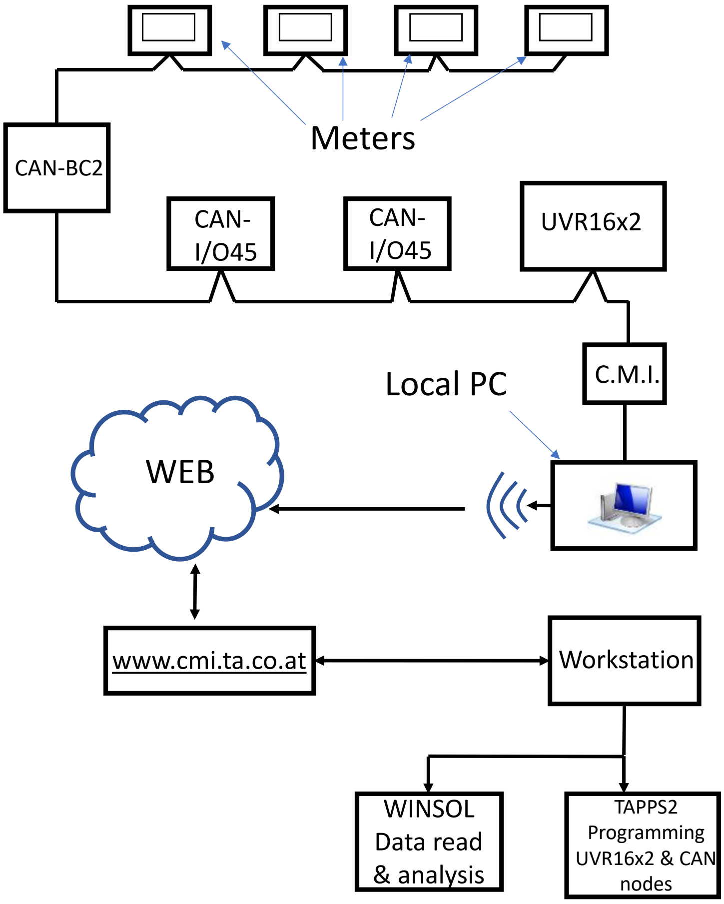


***Figure 4. 5** - Diagram of the Heat Pump Control System Working Principle*

Figure 4.5 outlines the working principle of the heat pump control system. The system allows any computer device to log in via the web, enabling adjustments to the control system and monitoring of inputs and outputs. The data logging interval was set to 2 seconds to capture detailed operational data for both heat pump systems. The temperature utilised for the test rig were connected to the UVR16x2 board. The sensors are PT1000 with an accuracy of ±0.3 °C (Instrumentation, 2023).

4.1.1.1. Start Capacitor

Compressors in heat pump systems often require significant power during startup, known as inrush current, which can exceed the motor's capacity, potentially causing startup failure or circuit breaker trips (AirCompressorHelp 2019). To address this, start capacitors are included in the electrical and control systems to storage and release energy as needed during startup.

4.1.1.2. Run Capacitor

Once the compressor is running, the run capacitor provides the additional charge needed to sustain operation (CapeFear Air Conditioning 2019).

4.1.1.3. Potential Relay

The potential relay disconnects the start capacitor once the compressor motor reaches the necessary speed, triggered by voltage changes in the start winding (Mars Tech 2022).

4.1.1.4. Power Supply – AC to DC Converter

The power supply converts mains alternating current (AC) to a 15V direct current (DC) to power the UVR16x2 board, CAN-BC2, and I/O45 modules.

4.1.1.5. Transformer

A transformer regulates the voltage from the mains power supply, providing 24V to the universal drivers.

4.1.1.6. Universal Drivers

Each expansion valve requires a universal driver to control its operation, adjusting the valve’s opening to maintain pressure levels as dictated by the Tapps2 program. In the conventional heat pump configuration, one expansion valve is sufficient; however, a second valve is needed for the novel system to control the thermal storage's temperature.

4.1.1.7. Universal Controller UVR16x2

This programmable controller offers numerous options for heating and building management. It interfaces with the I/O45 modules and a CAN-bus module, enabling communication between all linked devices within the control system (Please see Figure A10 – Appendix X).

The UVR controller has nine temperature, and two pressure sensors attached as inputs. Outputs are also connected to specific slots to prevent interference and allow for future upgrades or reconfiguration. Outputs 15 and 16 are reserved for the universal drivers of the expansion valves, which require 24V slots.

The UVR controller is powered through a 230V AC mains input, which supplies all connected units. Expansion valve drivers, however, need a separate transformer to convert 230V AC to 0-15V DC.

4.1.1.8. Inputs and Outputs

The control system includes 14 temperature sensors and 2 pressure sensors, some of which are connected to CAN I/O45 nodes for differentiation. Each input controls specific outputs based on programmed functions via Tapps2.

There are 17 programmed outputs, including the solenoid valve for hot gas bypass, which redirects compressor discharge directly to the evaporator for defrost cycles.

Table 4. 1 *- Nodes and the corresponding inputs attached to them.*

Controller Inputs			
Control Area Description	ID	Controller ID	Units
UVR16x2 - MAIN CONTROLLER	**Node 1**	**N1**	
Compressor discharge temperature	T1	N1/IN1	°C
Condenser ref outlet temperature	T2	N1/IN2	°C
Refrigerant temp into thermal storage	T3	N1/IN3	°C
Refrigerant temp out of thermal storage	T4	N1/IN4	°C
Expansion outlet temperature	T5	N1/IN5	°C
Evaporator outlet temperature	T6	N1/IN6	°C
Compressor discharge pressure	PT1	N1/IN7	Bar
Compressor suction pressure	PT2	N1/IN8	Bar
Compressor suction temperature	T8	N1/IN10	°C
Evaporator air inlet temperature	T9	N1/IN11	°C
Evaporator air outlet temperature	T10	N1/IN12	°C
Hot gas bypass status	SV1	N1/DI1	On/Off
NODE 10 – CAN-I/O45		**N10**	
Humidifier inlet temperature	T23	N10/IN3	°C
Humidifier outlet temperature	T24	N10/IN4	°C
Hot gas bypass request		N10/DI1	On/Off
NODE 11 – CAN-I/O45		**N11**	
Condenser water inlet temperature	T11	N11/IN1	°C
Condenser water outlet temperature	T12	N11/IN2	°C
Return temperature from heat output unit	T13	N11/IN3	°C
Compressor power pulse output	KWHM1	N11/IN4	Dimensionless

Table 4. 2 *- Nodes and the corresponding outputs attached to them.*

Controller Outputs				
Control Area Description	ID	Type	Controller ID	Units
UVR16x2 - MAIN CONTROLLER	**Node 1**	**UVR16x2**	**Node 1**	
Compressor contactor	P1 / K1	Contactor	N1/AUS1	On/Off (0/1)
Heat output fan		Fan	N1/AUS6	%
Hot unit vent damper supply		Damper	N1/AUS7	%
Hot to cold unit damper supply		Damper	N1/AUS8	%
Hot unit vent control		0 – 10 V	N1/AUS13	Volts (V)
Heat unit to cold unit control		0 – 10 V	N1/AUS14	Volts (V)
Expansion valve control	CV1	0 - 10V	N1/AUS15	Volts (V)
Hot gas bypass request		On/Off	N1/DO9	On/Off (0/1)
Evaporator fan power request		0 – 100%	N1/DO11	%
Condenser circulator request		On/Off	N1/DO13	On/Off (0/1)
Evaporator fan speed request		0 - 100%	N1/AO9	%
NODE 10		**CAN-IO45**	**N10**	
Hot gas bypass solenoid valve	SV1	Solenoid Valve	N10/A1	Dimensionless
Evaporator fan power	FAN	VS Fan	N10/A3	kW
Evaporator fan control	FAN	0 - 10V	N10/A4	V
NODE 11		**CAN-IO45**	**N11**	
Condenser heat transfer circulator	P2		N11/A1	kWh
Heat output move to recirc.	CV3		N1/A2	kWh
Heat output move to heat.	CV3		N1/A3	kWh

Tables 4.1 and 4.2 list the inputs and outputs, detailing their allocation within the control system nodes.

4.1.1.9. CAN-BC2

The CAN-BC2 (Controller Network Area) enables communication between the UVR16x2 controller, I/O45 units, and the host computer. It supplies 12V power to the CAN I/O units. (Please see Figure A 11 – Appendix X).

4.1.1.10. CAN I/O45

This module serves as an input/output extension. For the heat pump control system, it mainly functions as additional input space, as the UVR controller has limited input slots. Two CAN I/O45 modules are used to simplify the differentiation of inputs and outputs and allow room for future expansions. (Please see Figure A 12 – Appendix X).

4.1.1.11. Electricity Meters

Four electricity meters monitor the energy consumption of the heat pump components. Table 4.3 outlines the components connected to each meter.

Table 4. 3 *- Node/component allocation to the electricity meters.*

Meter	1	2	3	4
Node/component	Compressor	CAN I/O45 2	CAN I/O45 1	UVR16x2

4.1.1.12. Heat Meter

The heat meter includes a display module connected to a flow meter and temperature sensors, which measure the temperature difference between the heated and cooled water, flow rate, heat capacity, and total heat output. This setup allows for detailed monitoring of thermal performance.

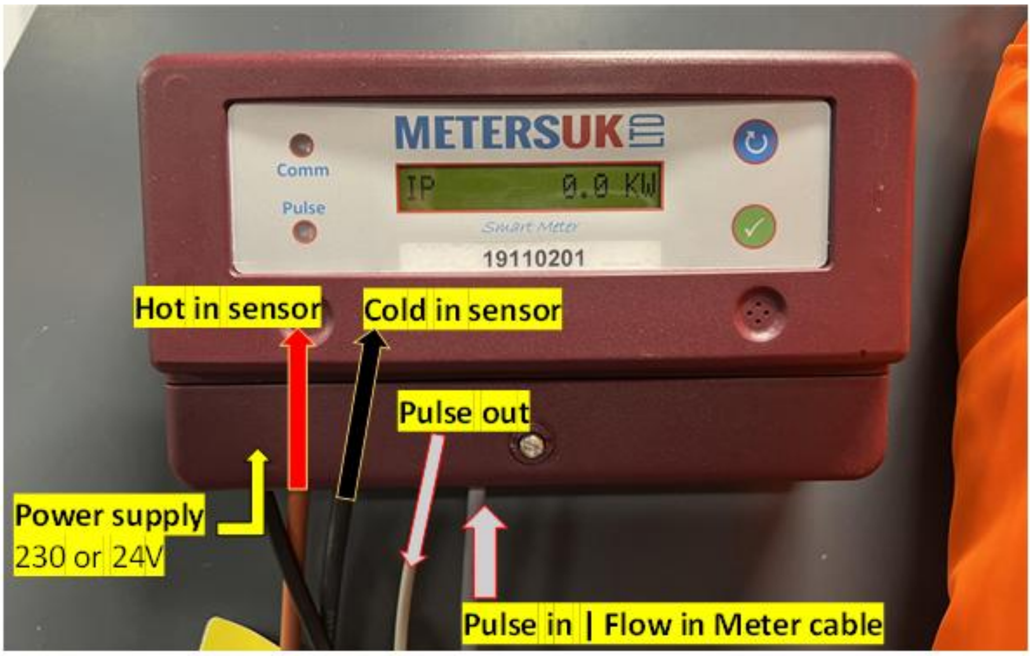


Figure 4. 6 *- Diagram of the heat meter.*

4.1.1.13. Data Collection and Performance Analysis

Energy consumption data is recorded by the CMI node, providing insights into how much energy each component consumes. The Winsol software facilitates data analysis, allowing total energy consumption calculations. By comparing power consumption and heat output, the performance of the heat pump, including COP, can be graphically represented.

4.1.1.14. Humidity Sensors

Two temperature and humidity loggers were placed near the evaporator and fan area, and one is positioned near the hot end of the condenser. These loggers collect temperature and humidity data, which helps assess the relationship between humidity levels and frost formation. The frost amount is measured post-defrost in its liquid state. The chosen loggers were OM-CP-RHTemp101A with accuracy of ±0.5°C for temperature and ±3.0% RH for humidity.

4.1.2. Heat recycling/environmental chamber

A heat recycling chamber was designed to function as an environmental chamber, simulating cold climate conditions. The system comprises two main components: a hot box and a cold box, each containing a heat exchanger. The hot box heat exchanger is filled with water heated by the hot refrigerant circulating through the condenser. This water is then monitored by flow and heat meters to measure the heat produced by the heat pump. The heated water can either be circulated within the hot box, passed through a humidity box, or delivered to the lab interior where testing occurs.

In standard air source heat pump setups, a fan typically draws air through an evaporator (an outdoor fin coil heat exchanger) and expels it outside. This expelled air is generally cooler than the incoming air due to the heat exchange between the ambient air and the refrigerant in the evaporator coils. In the cold box, this recirculated air can cause temperatures to drop, potentially shutting down the system if it falls below -25°C—the minimum operational temperature for the R134a refrigerant (Alton, 2017). To manage this, the cold box is connected to the hot box via five air ducts: two ducts at the bottom draw cold air from the cold box into the hot box, while three ducts at the top supply warm, humid air from the humidity box back to the cold box. A vent controlled by the system manages the bottom ducts, while the top ducts are manually controlled by paddles, which can either recycle the hot air within the hot box or expel it outside through another vent.

The system’s humidity is managed by a peristaltic pump, which delivers water through humidifier filter cassettes in the humidity box. As hot air from the hot box passes through these wet cassettes, its humidity increases, and it is then directed into the cold box, promoting frost build-up on the heat exchanger. Temperature sensors in the humidity box monitor both incoming and outgoing hot, humid air, while sensors in the cold box measure the temperature of air from the evaporator fan and the air passing through the evaporator. Humidity sensors are strategically placed to monitor the relative humidity both in the humidity box and near the evaporator/fan area.

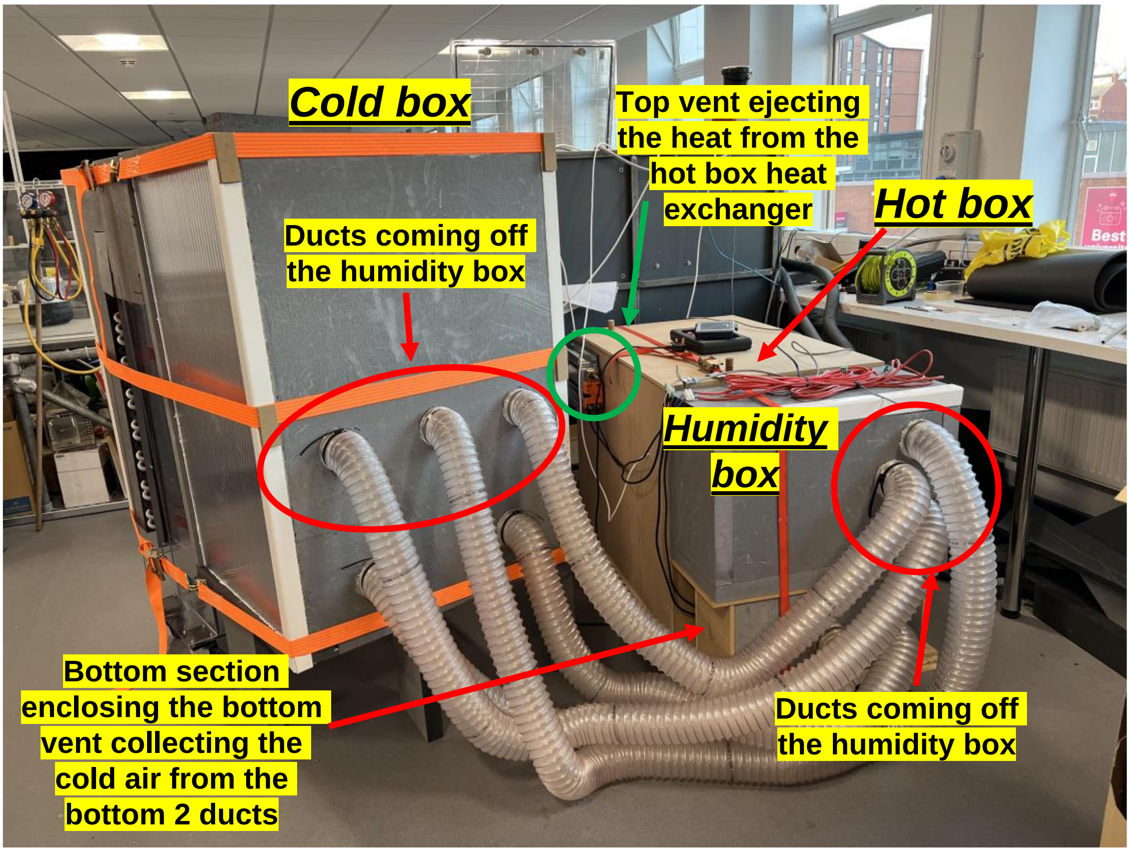


Figure 4. 7 *- Cold end box of the environmental/heat recycling chamber.*

Figure 4.10 illustrates the environmental/heat recycling chamber, where the top three ducts supply warm, humid air to the cold box, while the bottom vent collects cold air from the cold box and directs it through the hot box heat exchanger for reheating.

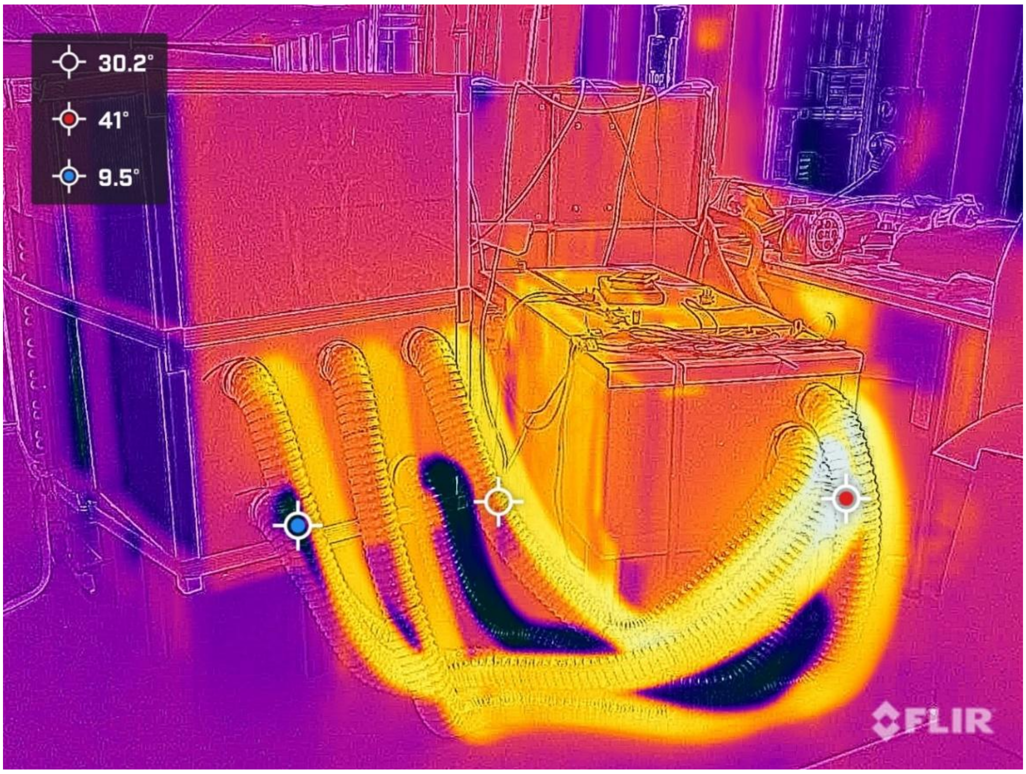


Figure 4. 8 *- Infrared thermography of the heat recycling chamber at operation.*

Figure 4.11 presents a thermal image of the heat recycling box at operation (please see Figure 4.10). The image showcases that the device is working as expected. The top 3 ducts delivered warmer humid air to the cold box (on the left), which promoted frosting conditions for the evaporator.

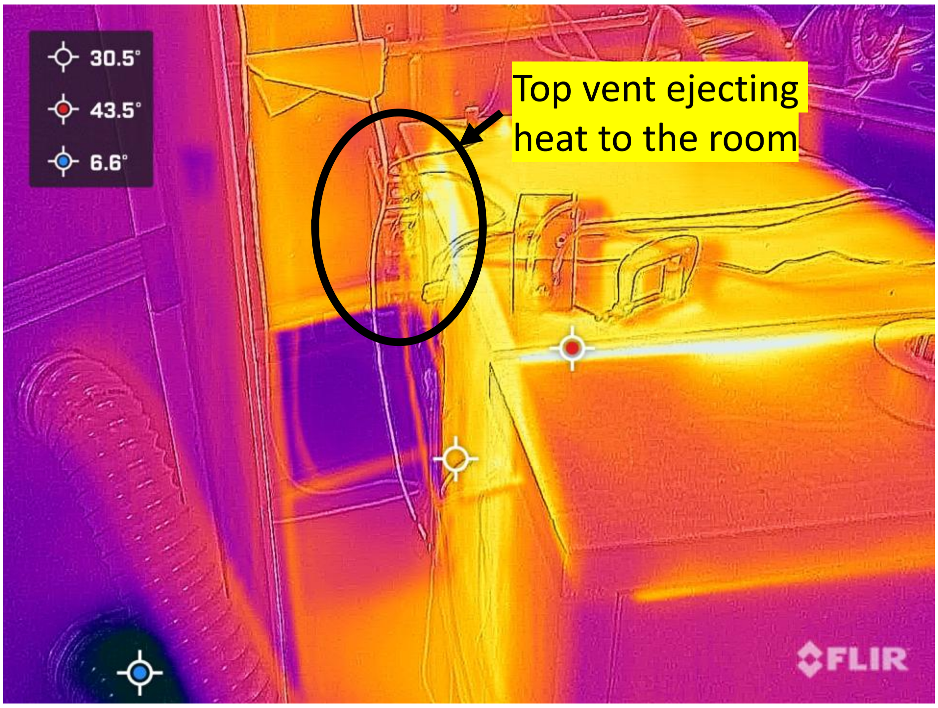


Figure 4. 9 *- Infrared thermography of the hot-end box of the heat recycling chamber at operation.*

Figure 4.12 showcases a thermal image of how heat is distributed from the hot-end box to the room. The box was much warmer as this thermal energy was transferred from the heat pump's condenser.

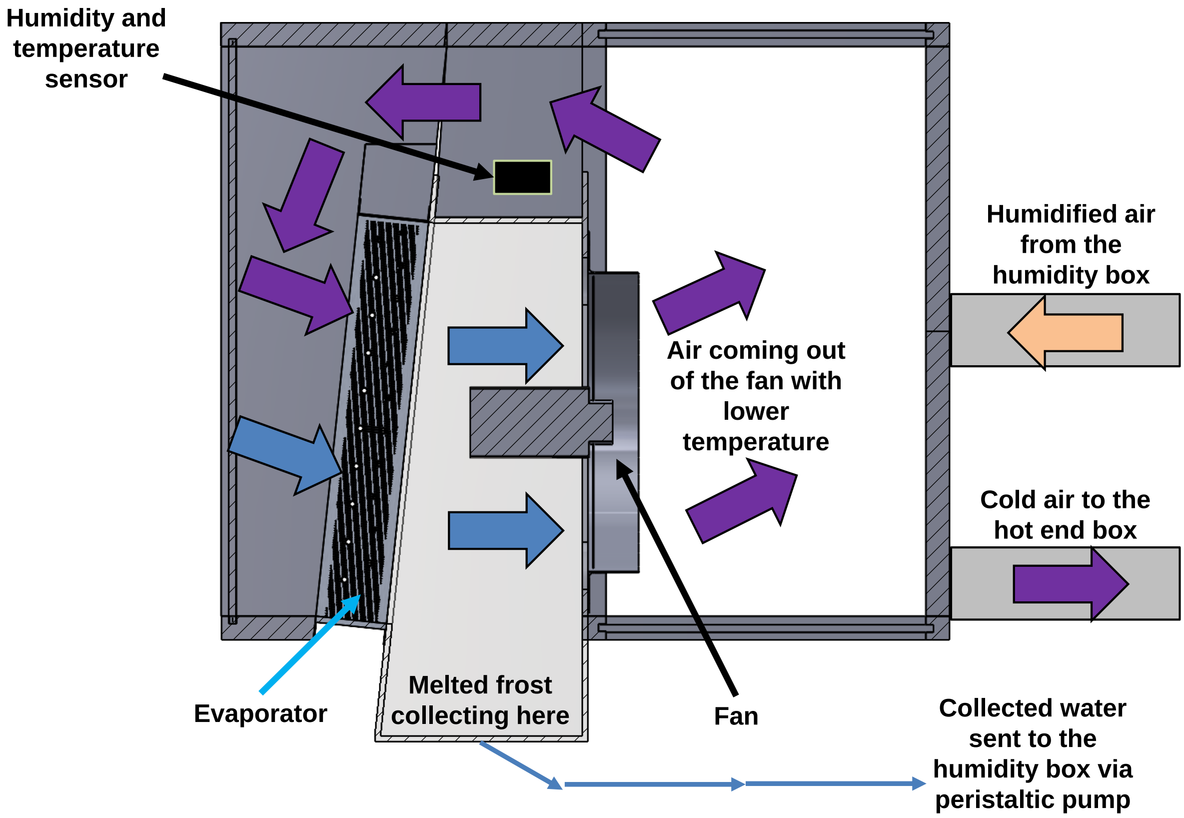


Figure 4. 10 *- Diagram of the cold end box of the environmental/heat recycling chamber.*

Figure 4.13 depicts the cold side box's operational diagram, highlighting how the air temperature further decreases as it circulates within the cold box, necessitating the supply of warmer air from the hot box for temperature and humidity control.

Throughout the study, temperatures at the evaporator were often referred to as "ambient temperature," reflecting efforts to replicate cold climate conditions. During defrost cycles, the ambient temperature around the evaporator sometimes increased significantly due to refrigerant bypassing the condenser and flowing directly from the compressor through the evaporator and expansion valve (CV1, Figure 4.1, Chapter 4.1).

Technical drawings of the evaporator-fan frame and assembly are provided in Figures D and E in Appendix VI and VII, respectively.

Figure 4.13 provides a different view of the cold-end box, showing its construction with transparent triple-walled polycarbonate sheets on the fan-side area, allowing observation of frost build-up and melting.

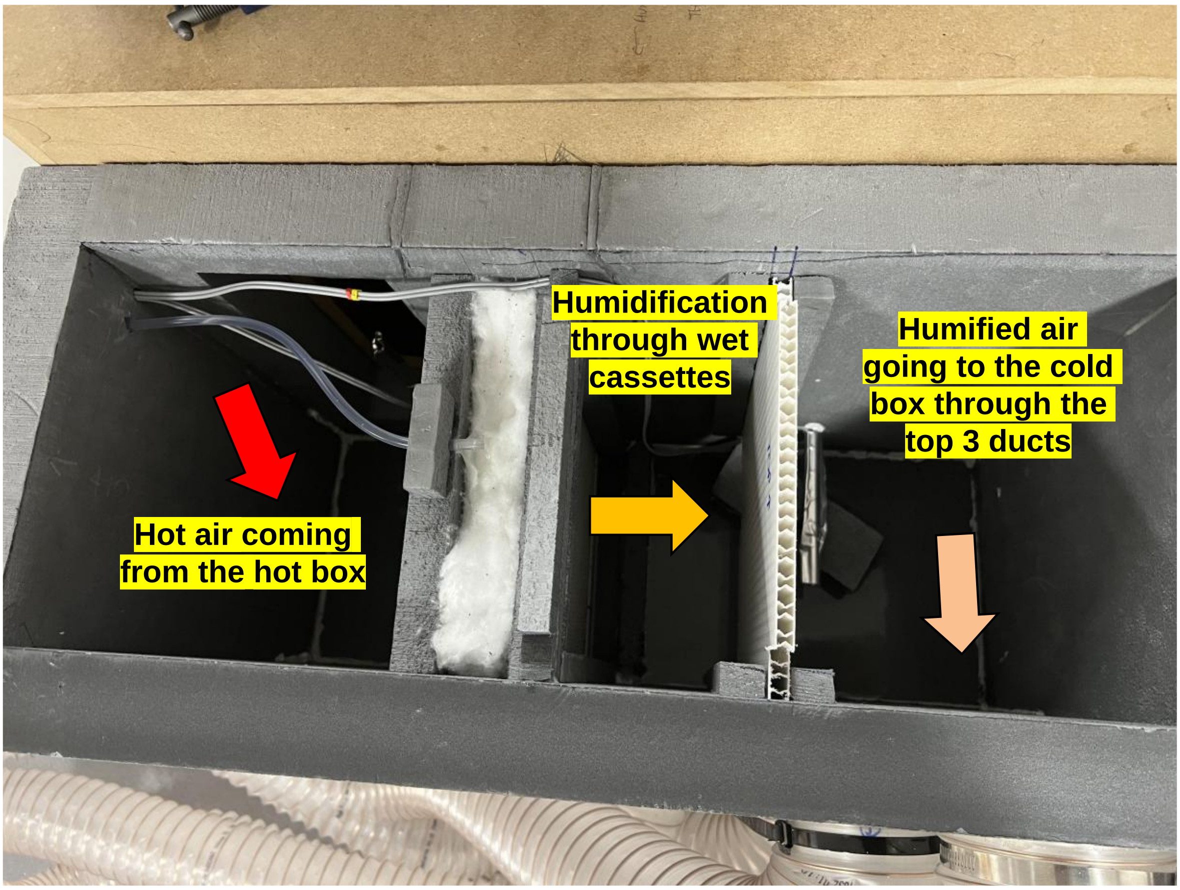


Figure 4. 11 - *Cold end box of the environmental/heat recycling chamber.*

Figure 4.14 shows the humidity box mounted on the hot box, where hot air passes through wet filter cassettes for humidification before being directed into the cold box to encourage frosting on the evaporator. Water collected from defrost cycles is stored and reused by a peristaltic pump to further humidify the air in the cold box.

***Figure 4. 12** - Infrared thermography of the humidity box.*

Figure 4.15 presents a thermal image of the working humidification box (please see Figure 4.14). The hot air from the hot-end box passes through the wet cassettes where the air is cooled down and humidified. After that the humid air goes to the cold-end box where to promote frosting conditions at the evaporator.

The environmental/heat recycling chamber was built to simulate cold climate conditions and study the performance of heat pumps in such environments. Its primary purpose is to control and maintain specific temperature and humidity levels around the heat pump's evaporator to replicate the challenges faced in cold climates, such as frost build-up. Existing environmental chambers were not suitable because they lacked the precise control over heat and humidity recycling necessary to simulate extreme cold conditions with the desired accuracy. This custom chamber was designed with interconnected hot and cold boxes, along with multiple ducts and control systems, allowing for a tailored approach to managing temperature, humidity, and airflow. This design ensures the flexibility to precisely replicate cold weather scenarios and monitor the heat pump's performance under those conditions, which was not achievable with conventional chambers.

After a defrost cycle the melted frost was collected in a 1000 mL graduated cylinder for each test. The accuracy of the cylinder was of 50mL subdivision.

4.2. Summary

This chapter has described the developed ASHP test rig. The ASHP test rig, designed for a standard 8kW heat pump, was assembled following British Standards (BS EN 14511, BS EN 14825, BS 7671, and BS EN 378) and ISO 14001 for environmental compliance. Components, including a scroll compressor, plate heat exchanger, evaporator, and electronic expansion valve, were chosen for cost-efficiency. The control system, featuring a UVR16x2 universal controller and CAN-I/O45 modules, monitors and controls the heat pump's performance. Software tools Winsol and Tapps2 were used for data logging and system programming, ensuring precise control of energy input, thermal output, and overall system efficiency. The system also incorporates start and run capacitors, potential relays, and universal drivers to manage the heat pump's electrical needs. An environmental chamber was designed to simulate cold climates, promoting frost formation on the evaporator for testing defrost cycles. The chamber consists of interconnected hot and cold boxes, ductwork, and humidity control systems, allowing precise management of temperature and airflow. Thermography images and humidity sensors tracked the performance of the heat recycling chamber, ensuring accurate frost buildup and defrosting operations. Energy consumption and performance data were gathered using the control system's sensors, including temperature and humidity loggers, to evaluate the coefficient of performance (COP). The test rig's performance and frost accumulation were used to validate the simulation model (Chapter 5).

5. The simulation of air source heat pumps and defrost cycles with validation

This chapter includes a description of the simulation model that was developed and its validation using the test-rig system.

The performance of air source heat pumps (ASHPs) in residential buildings is highly dependent on a variety of factors, including house type, insulation level, and the external climate. While ASHPs are seen as a crucial technology for the UK's decarbonisation efforts, their effectiveness can vary significantly across different housing archetypes, especially given the diverse and aging building stock in the country. Understanding these variations is critical for ensuring that the widespread adoption of ASHPs delivers the anticipated reductions in energy consumption and carbon emissions.

This chapter focuses on the detailed analysis of ASHP energy performance across various house types and insulation standards using simulation modelling. By incorporating a wide range of building archetypes—from poorly insulated older homes to modern, energy-efficient constructions—this analysis provides insights into how the efficiency and energy savings associated with ASHPs vary based on the characteristics of the dwelling.

The chapter also examines how improvements in insulation can influence ASHP performance and the overall energy demand of the household. Given that many UK homes are older and not adequately insulated, this analysis is vital for informing retrofitting strategies that can complement ASHP installations. The findings presented here are essential for policymakers, energy providers, and homeowners alike, as they highlight the need for integrated approaches that consider both the heating technology and the energy efficiency of the building envelope to maximize the benefits of ASHP adoption.

The chapter's results are derived from simulations that model ASHP performance under a range of scenarios, reflecting the diversity of housing in the UK. The analysis contributes to a more nuanced understanding of how ASHPs can be deployed effectively across different building types, offering practical recommendations for optimising their performance in both well-insulated and poorly insulated homes. The system developed by the researcher in this chapter offers significant advantages over other systems identified in the literature, specifically in terms of simulation model precision, the range of housing archetypes considered, and the integration of insulation improvements with ASHP performance. Many existing simulation models of heat pumps either focus on specific housing types or idealised conditions without capturing the full diversity of the building stock. For example, Guo et al., (2024) focus on high, medium and low

U-values in their simulation, which does not indicate clearly the wall types and insulation level of the dwelling in their research. Additionally, ready-to-use provided simulation models from Matlab do not allow the flexibility to adjust details such as the building element's values which could enrich the captured data and outcomes from the simulation.

5.1. Simulation model

A custom simulation model of the heat pump test rig was developed to accurately capture the specific conditions and parameters relevant to this study, including the detailed dynamics of frost build-up and defrost cycles, which are often not fully addressed in existing models. While there are pre-existing simulation models of air-source heat pumps and building thermal performance, they typically do not account for the precise experimental configuration and environmental variables specific to this research (Guo et al., 2024; MathWorks, 2023) , such as the correlation between ambient temperature, relative humidity, and frost accumulation on the heat exchanger.

Simulink was chosen for its versatility and robust integration capabilities, allowing for a modular approach to model complex systems with dynamic interactions between components. Unlike other models, Simulink provides a flexible environment where custom sub-modules, such as the frost build-up model, can be easily implemented and validated against experimental data, ensuring a higher accuracy representation of the test rig's performance under varying conditions. This level of customisation and the ability to directly compare simulation outputs with experimental results justify the need for a custom simulation model tailored to the specific research objectives of this study.

The Simulink model replicates the operation of the test rig and extends the analysis across a broader range of conditions. It incorporates environmental parameters such as ambient temperature and relative humidity, along with a frost build-up sub-module that predicts frost accumulation and the necessity for defrost cycles. The model also integrates a switch mechanism to activate auxiliary heating when the ambient temperature drops below -17°C, reflecting real-world operational strategies. One of the critical challenges in the study was the integration of an accurate numerical model for frost build-up into the simulation framework. Frost build-up on the heat pump's outdoor unit can significantly reduce its efficiency and increase energy consumption. Existing models often lack the ability to account for dynamic environmental conditions, such as varying humidity levels, which play a crucial role in frost formation. To overcome this limitation, a novel frost build-up model was developed, incorporating factors such as relative humidity, air velocity, and heat exchanger surface temperature.

5.1.1. Module 1.2 - building energy simulation

In order to simulate the energy demand needed for a heat pump in a household, there will be a need to simulate the dynamic performance of the house itself where the heat pump is used; as the demand for heating will depend on the level of insulation and the dimensions/architype of the house. In this research, a detailed model of energy building insulation and heating demand was analysed for typical average houses in the UK (see Table 3.1). Additionally, in this section, models of a houses in 10 countries are created in Simulink, see Fig. 5.1. The same methodology can be conducted for any other city or country as suitable.

Module 1.2: Contribution to heat losses coefficient from building elements

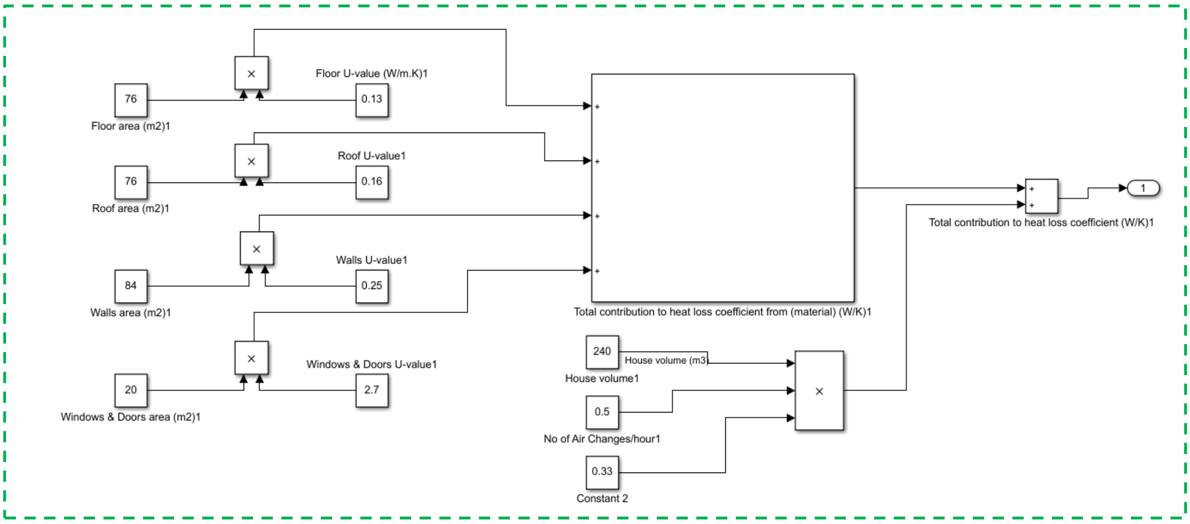


Figure 5. 1 - Modules of the building heat transfer simulation model

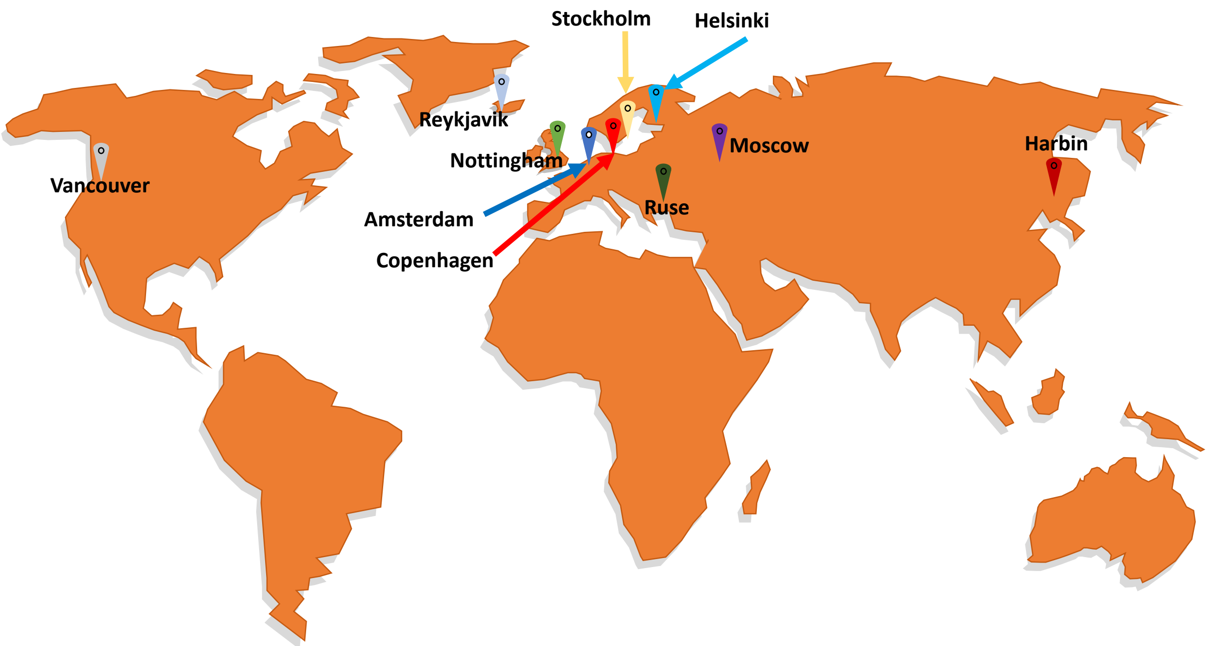


Figure 5. 2 *- Map of the world with the investigated cities.*

The aim of this model is to showcase the losses of heat in the dwelling and the daily heating demand which is also driven by the ambient temperature. This to allow the accurate simulation of the heating demand required by the heat pump. Fig. 5.1 presents the contribution to heat losses coefficient from the house elements, which include windows, floor, roof, and walls. The purpose of this research is to use average house size and thermal specifications to predict the heating demand for each country.

5.1.2. Module 2

Module 2 in the simulation model is built through a series of switch blocks which monitor the ambient temperature, and when it reaches −17 °C the heat pump switches off and a back-up electrical resistant heater with a capacity of 3 kW switches on. It has been estimated that at an ambient temperature of around −17 and −20 °C air source heat pumps tend to suffer and do not operate properly (Konrad & MacDonald, 2023). At -17°C, the simulation model incorporates a switch to auxiliary heating elements, such as electric resistance heaters, to provide the necessary heat output. As ambient temperatures approach -17°C, the efficiency of air-source heat pumps drops significantly. This is due to the reduced heat extraction capability from the ambient air and increased energy required for defrost cycles. At these low temperatures, the coefficient of performance (COP) of the heat pump may fall below 1, meaning that the heat pump is consuming more energy than it is providing in useful heat. This renders the heat pump less effective and less economical compared to direct electric heating. At temperatures around -17°C and below, the likelihood of mechanical and operational issues with the heat pump increases, including compressor failure or freeze-ups in the refrigerant cycle. Manufacturers often recommend shutting down the heat pump at these low temperatures to prevent damage to the system and ensure longevity. Therefore, switching to an auxiliary heating element is a preventative measure that ensures continued heating reliability without risking system integrity.

Module 2: Auxiliary heating

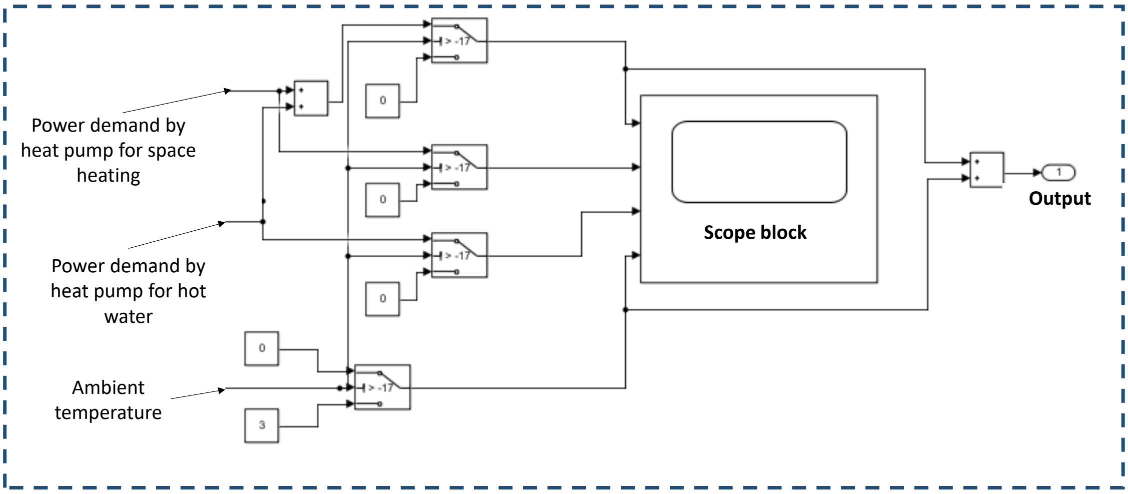


Figure 5. 3 *- Module 2 of the simulation model*

Fig. 5.3 shows how module 2 of the simulation model was built. When the ambient temperature drops below −17 °C, a back-up electrical resistant heater switches on and provides the thermal energy needed to satisfy the demand for space heating and hot water. Note that a typical restarting temperature is −12.2 °C for the residential heat pump; so that the difference between −17 °C and −12.2 °C creates the needed hysteresis to efficiently control the heat pump; and reduce wear and tear. However, in this case it has been assumed in the simulation that the control system does not include hysteresis and assumed ideal control process for this purpose at −12.2 °C.

After validation of the Simulink ASHP, the simulation considered heat pump power demand, maximum heat output, and used typical weather data from typical housing stock in the UK. Another simulation included 10 global cities to analyse heat pump performance provides a diverse set of climate conditions, capturing variations in temperature, humidity, and weather patterns across different geographical regions. This approach allows for a comprehensive assessment of how the heat pump operates under various environmental conditions, ensuring that the simulation results are robust and applicable to a wide range of real-world scenarios. Additionally, it helps identify the impact of local climate on heat pump efficiency and defrost cycles, providing valuable insights into the adaptability and performance of the heat pump in different climates. The Simulink model determined when defrost mode was triggered and the associated power demand. Figures 5.4, 5.5, and 5.6 and subsequent sections elaborate on the Simulink block diagram and the equations used.

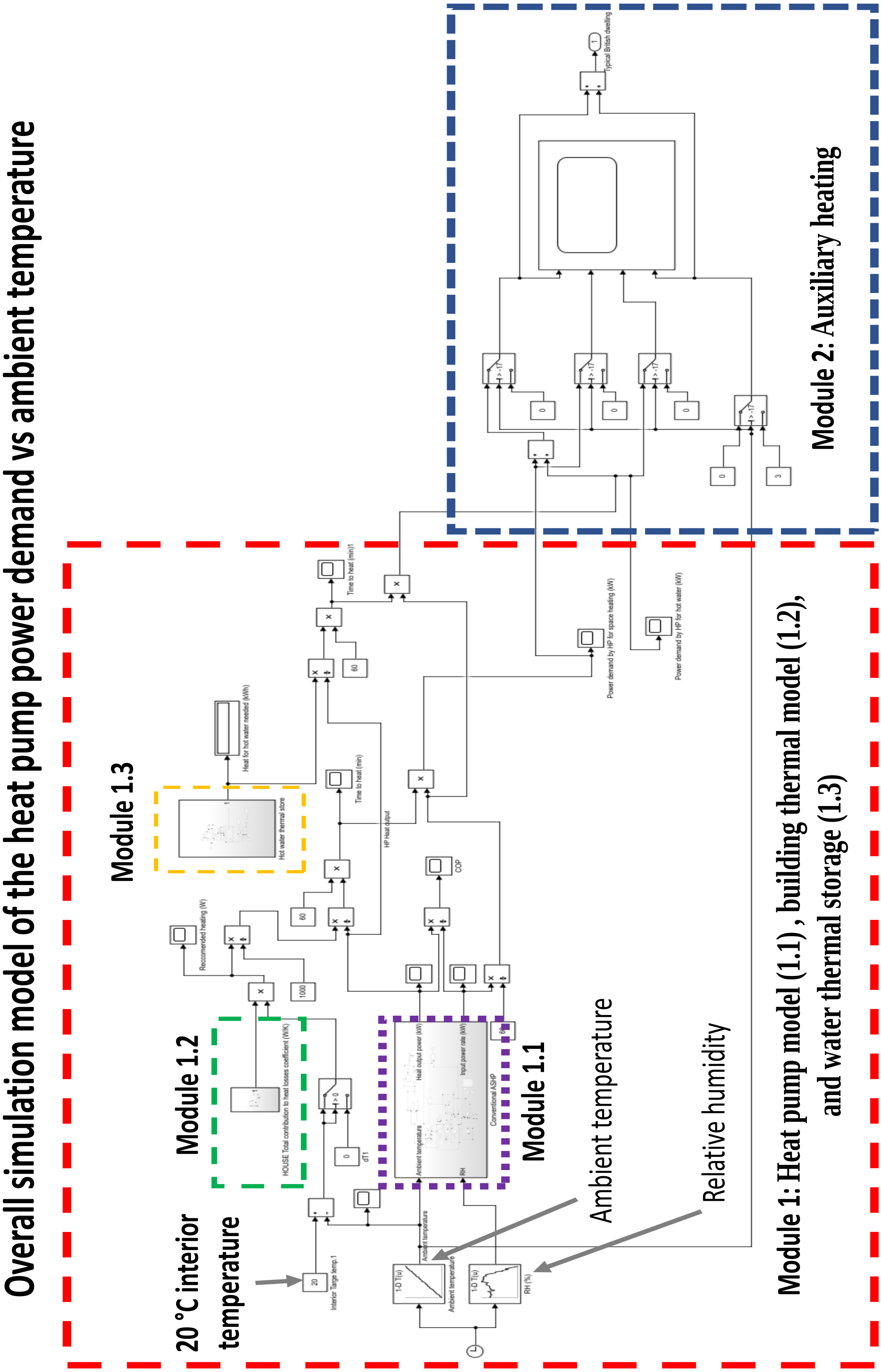


Figure 5. 4 *- Main modules of the heat pump demand vs ambient temperature.*

5.1.3. Module 1: Heat pump model, building thermal model, and water thermal storage

Module 1 included models for the air source heat pump, building heat loss contributions, and water thermal storage.

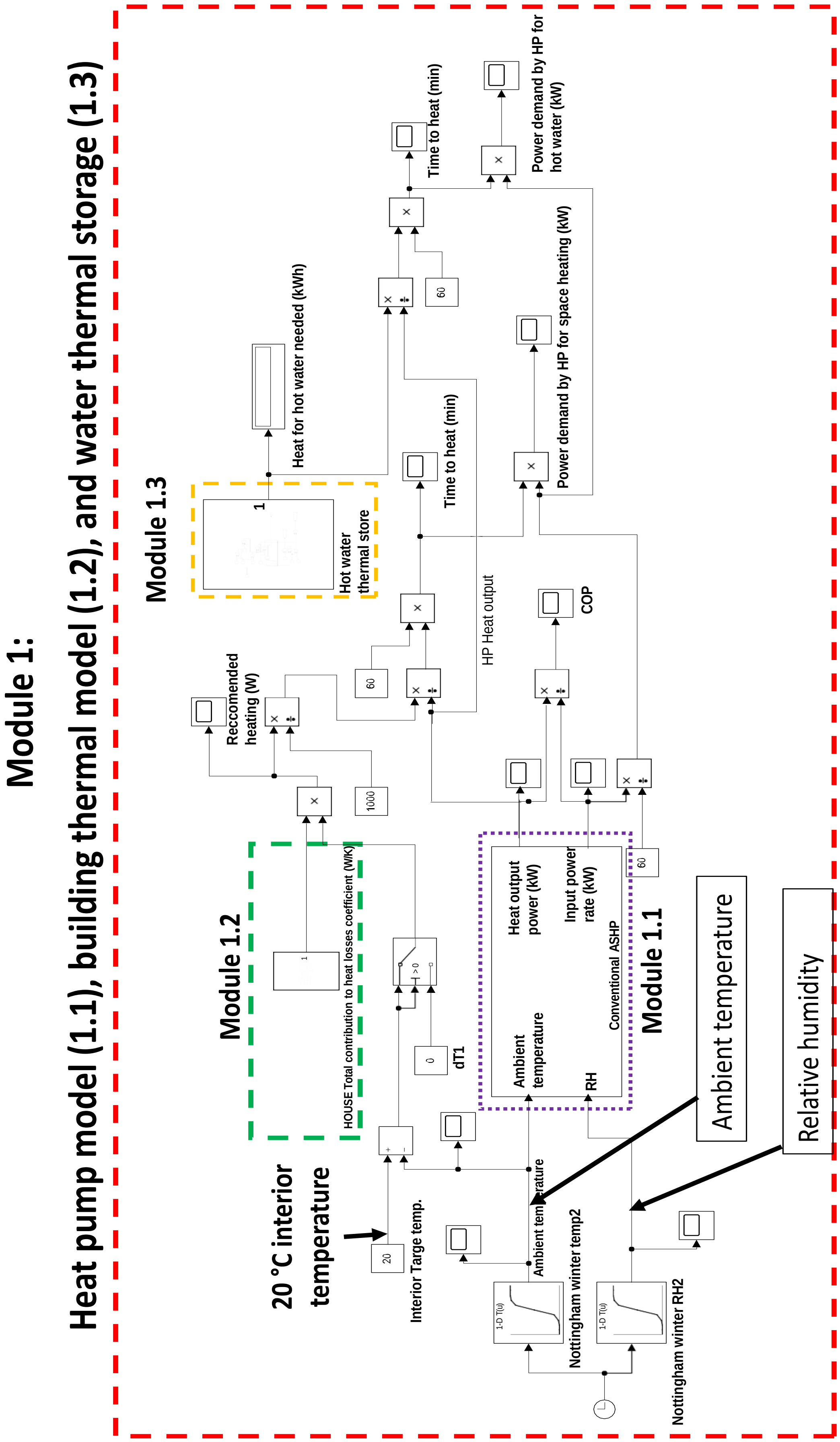


Figure 5. 5 - Module 1 of the simulation model

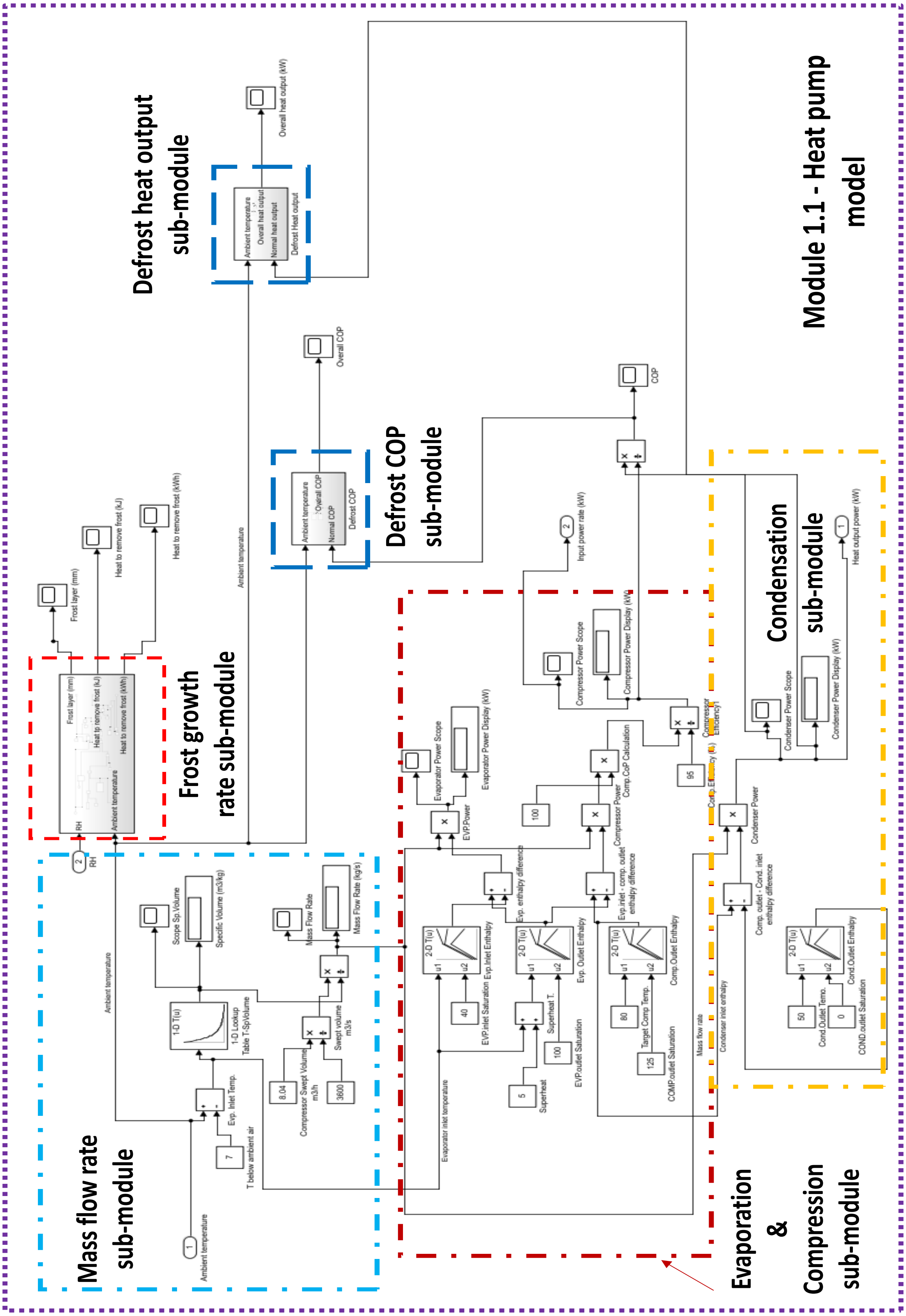


Figure 5. 6 - The suggested air source heat pump model (Module 1.1).

Figure 5.5 provides further details about Module 1 including building element heat loss contributions (floor, roof, windows, walls), and hot water thermal storage. While Figure 5.6 shows the heat pump configuration. Each sub-module is detailed in the following sections.

5.1.4. Module 1.1: Air source heat pump model

Figure 7 illustrates the configuration of the heat pump, including frost growth rate, compressor power input, and evaporator and condenser power. Key parameters monitored were power consumption, heat output, and the coefficient of performance (COP).

The Mass Flow Rate sub-module calculates system mass flow rate based on the compressor's swept volume (manufacturer-specified) and specific volume, extrapolated using R134a refrigerant's enthalpy-pressure (P-h) diagram. The compressor's swept volume per second ($\boldsymbol{V_{Sw1}}$) is given by:

$$V_{Sw1} = V_{Sw} \div 3600 \qquad \text{(Eq. 16)}$$

where $\boldsymbol{V_{Sw}}$ is the compressor swept volume (m^3/h) and $\boldsymbol{V_{Sw1}}$ is the swept volume per second (m^3/s) (Byrne et al., 2014).

The mass flow rate ($\dot{m}$) is calculated as:

$$\dot{m} = V_{Sw1} \div V_{sp} \qquad \text{(Eq. 17)}$$

where $\boldsymbol{\dot{m}}$ is the refrigerant mass flow rate (kg/s), and $\boldsymbol{V_{sp}}$ is the refrigerant specific volume (m^3/kg), extrapolated from the P-h diagram of R134a (Byrne et al., 2014; Evans, 2019).

Module 2 calculates the evaporator heat capacity using a 2-D look-up table of the P-h diagram in Simulink, which extrapolates enthalpy values and multiplies them by the mass flow rate.

- **a) Evaporation and Compression Sub-module**

The evaporator heat capacity ($\boldsymbol{Q_{ev}}$) is given by:

$$Q_{ev} = \dot{m} \times (h_2 - h_1) \qquad \text{(Eq. 18)}$$

where $\boldsymbol{Q_{ev}}$ is the evaporator heat capacity (kW), $\boldsymbol{h_2}$ is the outlet enthalpy, and $\boldsymbol{h_1}$ is the inlet enthalpy of the evaporator (kJ/kg), derived from the R134a P-h diagram (Evans, 2019).

Compressor power rating ($\boldsymbol{P_{com}}$) is calculated as:

$$P_{com} = \dot{m} \times (h_3 - h_2) \qquad \text{(Eq. 19)}$$

where $\boldsymbol{P_{com}}$ is compressor power (kW), $\boldsymbol{h_3}$ is the outlet enthalpy, and $\boldsymbol{h_2}$ is the evaporator outlet enthalpy (Byrne et al., 2014; Evans, 2019).

After determining the compressor efficiency, refrigerant reaches the target temperature of 50°C, passing through the condenser in the evaporation and compression sub-module where heating capacity is calculated based on enthalpy differences multiplied by the mass flow rate.

The condenser inlet temperature may vary slightly due to interactions with multiple components.

- **b) Condensation Sub-module – Condenser Heating Capacity**

Condenser heating capacity ($\boldsymbol{Q_c}$) is given by:

$$Q_c = \dot{m} \times (h_3 - h_4) \quad \text{(Eq. 20)}$$

where $\boldsymbol{Q_c}$ is condenser heating capacity (kW), and $\boldsymbol{h_4}$ is the condenser outlet enthalpy (kJ/kg) from the R134a P-h diagram (Byrne et al., 2014; Evans, 2019).

- **c) Frost Growth Rate Sub-module**

This sub-module models frost build-up on the outdoor unit (evaporator). A numerical model was developed to predict frost accumulation on the outdoor heat exchanger (δ_{ice})(m^3).

The model includes relative humidity, which significantly affects frost growth. The model is validated experimentally and can be expressed as:

$$\delta_{ice} = \frac{\{((V_{hx} \times S_a) \times t) \times \rho_{air}\} \times HR}{A_{evp}} \quad \text{(Eq. 21)}$$

where $\boldsymbol{V_{hx}}$ is outdoor heat exchanger volume (m^3), $\boldsymbol{S_a}$ is evaporator air velocity (m/s), $\boldsymbol{t}$ is time of frost accumulation (s), $\boldsymbol{\rho_{air}}$ is air density (kg/m^3), $\boldsymbol{HR}$ is humidity ratio (kg/kg), and $\boldsymbol{A_{evp}}$ is heat exchanger area (m^2).

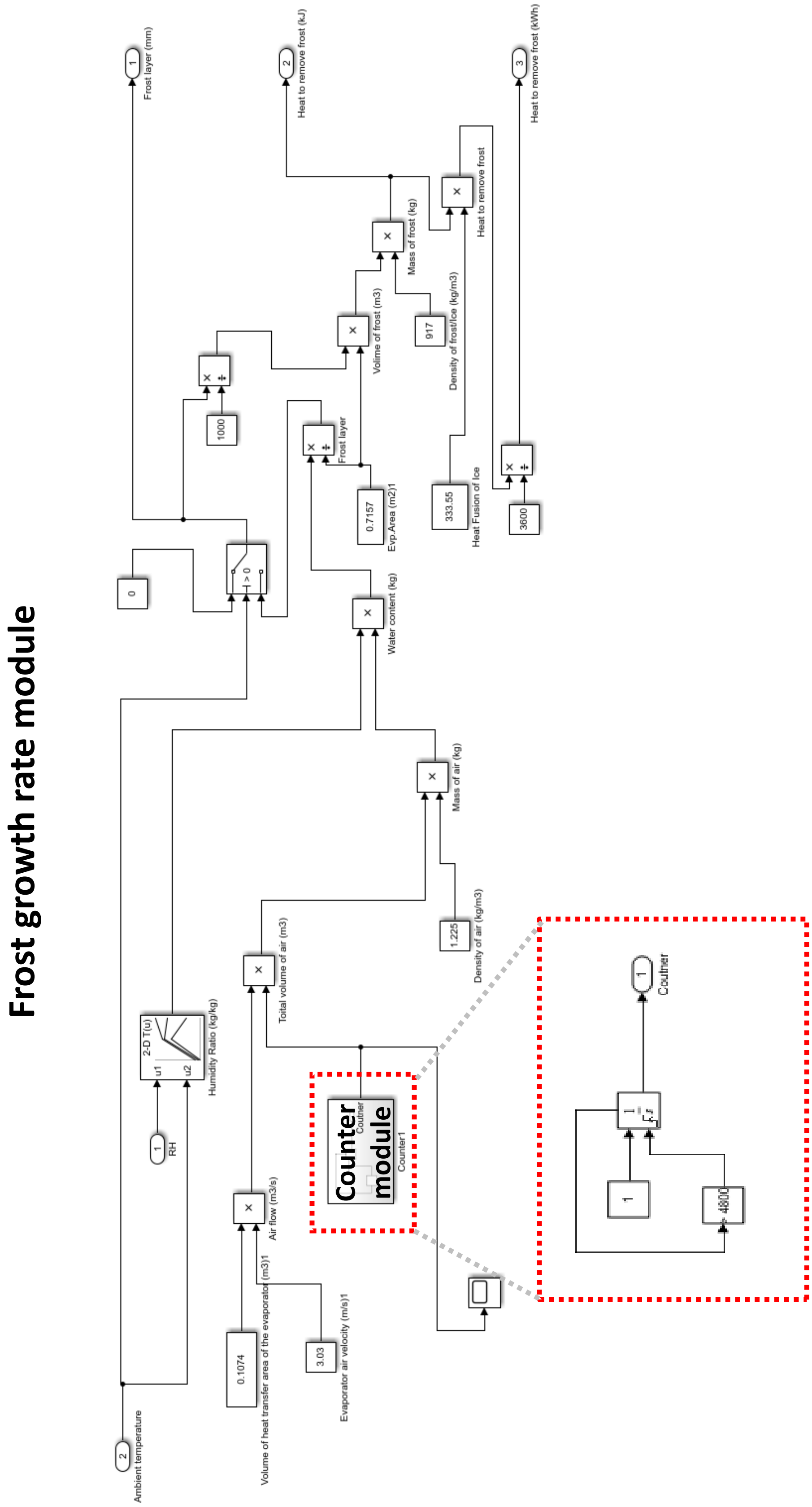


__Figure 5. 7__ - Frost growth rate sub-module.

Figure 5.7 presents how the frost growth rate was implemented in Simulink. The sub-module also includes a counter of defrost cycles. There is a switch block which uses the ambient temperature as a threshold, if it drops below 0°C, ice starts forming on the evaporator. The frost layer thickness is monitored. From there the model calculates the energy needed to remove the frost build-up. The mass of the ice layer accumulated is calculated as:

$$m_{ice} = V_{ice} \times \rho_{ice} \qquad \text{(Eq. 22)}$$

where $\boldsymbol{m_{ice}}$ is the mass of the ice layer accumulated on the outdoor unit (kg); $\boldsymbol{V_{ice}}$ is the volume of the ice layer (m^3); $\boldsymbol{\rho_{ice}}$ is the density of the ice layer (kg/m^3).

The heat needed to remove the ice build-up can be expressed as:

$$Q_{removeIce} = m_{frost} \times 333.55 \qquad \text{(Eq. 23)}$$

where $\boldsymbol{Q_{removeIce}}$ is the heat needed to remove the ice build-up on the outdoor unit (kJ); 333.55 is the heat fusion of ice (kJ/kg).

The heat needed to remove the ice deposition on the outdoor unit is expressed as:

$$Q_{ice-rem} = Q_{removeIce} \div 3600 \qquad \text{(Eq. 24)}$$

where $\boldsymbol{Q_{ice-rem}}$ is the heat needed to remove the ice deposition on the outdoor unit (kWh); $\boldsymbol{Q_{removeIce}}$ was divided by 3600 to convert from kJ to kWh.

- **d) Defrost COP Sub-module**

This sub-module calculates system performance by dividing heating capacity by compressor power:

$$COP = Q_c \div P_{com} \qquad \text{(Eq. 25)}$$

During defrost, the COP is zero as the hot gas bypass method does not deliver heat to the condenser.

- **e) Defrost Heat Output Sub-module**

This sub-module tracks condenser heat output, accounting for defrost cycles where no heat is delivered. Figure 5.8 illustrates the defrost heat output sub-module in Simulink, with counters monitoring defrost timing.

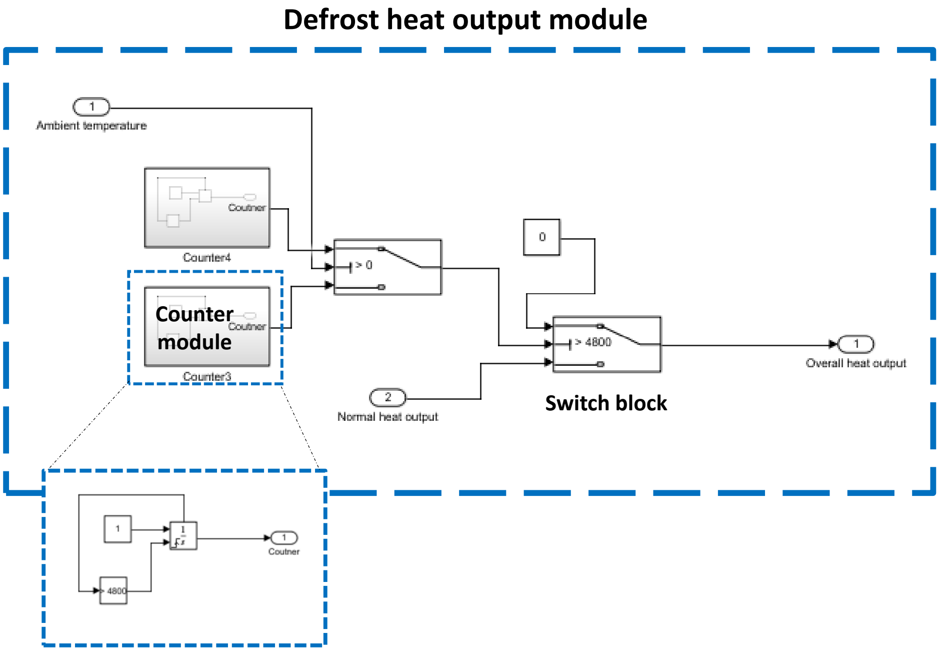


Figure 5. 8 - *Defrost heat output sub-module in Simulink.*

The defrost COP model follows similar construction but with system COP connected to the switch block. It assumes defrost cycles are triggered before frost significantly degrades heat transfer, validated experimentally.

5.1.5. Module 1.2: Building Energy Simulation

To simulate heat pump energy demand in a household, the dynamic performance of the house itself was modelled. This involved simulating heat losses influenced by insulation level and house dimensions/architecture.

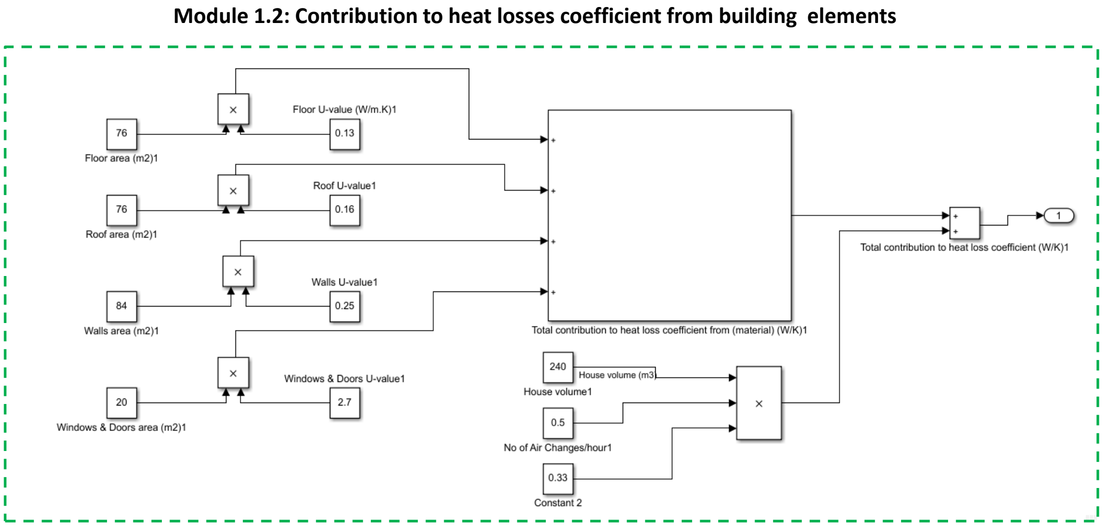


Figure 5. 9 - *Modules of the building heat transfer simulation model*

For each of the 10 cities and the house types in the UK, a model of a typical house was created in Simulink (Figure 5.9), showcasing heat losses and daily heating demand driven by ambient temperature. This allowed accurate simulation of heating demand. The heat loss contribution from house elements (windows, floor, roof, walls) was calculated (Figure 5.9). The area and U-values for each of the building element were adjusted according to the wall type and the typical size and values for each country.

The total contribution to heat loss coefficient (***C_{hlc}***) (W) is given by (Moss, 2007):

$$C_{hlc} = (0.33 \times ACH \times V_h) + \{(A_1 \times U_1) + (A_n \times U_n) \ldots\} \quad \text{(Eq. 26)}$$

where ***C_{hlc}*** is the heat loss coefficient (W/m²K), ***ACH*** is air change rate per hour, and ***V_h*** is house volume (m³). Coefficients (U_1, U_2, etc.) reflect heat loss elements and areas (A_1, A_2, etc.) of heat loss coefficients (W/m²K) from various elements like windows, walls, etc. Heat losses are calculated from external heat transfer coefficients in Table 5.1.

5.1.6. Module 1.2 - Building Energy Simulation

To estimate the energy demand required for a heat pump in a household, it is necessary to simulate the dynamic performance of the house where the heat pump is installed. The heating demand is influenced by the house's level of insulation, size, and architectural type. This study analyses a detailed model of building insulation and heating demand for a typical average house types in the UK and in each of 10 cities. The same approach can be applied to any other city or country as needed. In this section, a house model for each house type for the UK as well as of the 10 countries is created using Simulink. The model aims to demonstrate heat losses in the dwelling and the daily heating demand, which is also influenced by the ambient temperature. This approach allows for an accurate simulation of the heating demand required by the heat pump. Figure 5.9 illustrates the contribution to the heat loss coefficient from various house components, including windows, floors, roofs, and walls. The goal of this research is to use average house sizes and thermal properties to estimate the heating demand for each country. A more precise simulation could be achieved with a more specific house design, including detailed location and orientation information. However, the intention here was to provide a reasonable estimate of heating demand. Solar heating is not considered, especially since defrosting cycles generally occur at night when there is no solar radiation.

Module 1.2 calculates the space heating demand of the house and further estimates the power demand of the heat pump. Tables 3.1 and 5.1 includes data on dwelling size and the heat transfer coefficients for building elements such as windows, walls, roof, and floor.

Additionally, the data for the global cities analysis was gathered from various energy efficiency requirements and policies specific to each country, as shown in Table 5.1.

***Table 5. 1** - Typical characteristics of building elements of dwellings in each country (Milev et al., 2023).*

Country	A_{house}	U_{walls}	U_{floor}	U_{roof}	U_{window}	ACH	A_{wall}	A_{window}	V_{house}
Bulgaria	67.6	0.28	0.28	0.28	0.7	0.23	82	19	170
Canada	177	0.21	0.14	0.14	1.6	0.6	122	27	407
China	60	3.8	4	3.5	2.5	0.25	84	5.25	162
Denmark	98.8	0.3	0.2	0.2	1.8	0.23	99	15	247
Finland	75.8	0.17	0.16	0.09	1	0.2	87	8	189
Iceland	119	0.25	0.2	0.15	1.7	0.23	109	12	296
Netherlands	116	0.29	0.29	0.25	1.65	0.24	112	23	301
Russia	67	2.4	2.9	3.4	1.2	0.23	82	5.25	168
Sweden	90	1	1	1	1	0.22	95	20	225
UK	76	0.25	0.13	0.16	2.7	0.33	84	20	240

The values from Tables 3.1 (Chapter 3.2) and 5.1 are used to simulate the heat pump's power demand over a three-month winter period. Additionally, a look-up chart was developed using Simulink and the data from Tables 3.1 and 3.5 to estimate the air source heat pump's demand based on ambient temperature.

The heat pump's power demand can be calculated by:

$$P_{sh} = \left[\left(\frac{(C_{hlc} \times \Delta T) \div 1000}{Q_{HPout}}\right) \times 60\right] \times P_{comp} \quad \text{(Eq. 27)}$$

where P_{sh} is the power demand for space heating (kW); Q_{HPout} is the heat output capacity of the heat pump (kW); and P_{comp} is the compressor power rating (kW).

This simulation not only determines the time required to meet the space heating demand but also calculates the heat pump's power demand to satisfy this heating requirement. Equation (27) can also be applied to estimate the heat pump's power demand for hot water needs by substituting the total heat loss coefficient C_{hcl} with the hot water thermal storage capacity, which is determined by Equations (28) and (29), along with Module 1.3 as outlined in the subsequent section.

5.1.7. Module 1.3 – Thermal Storage

Figure 5.10 shows how Module 1.3 was developed in Simulink.

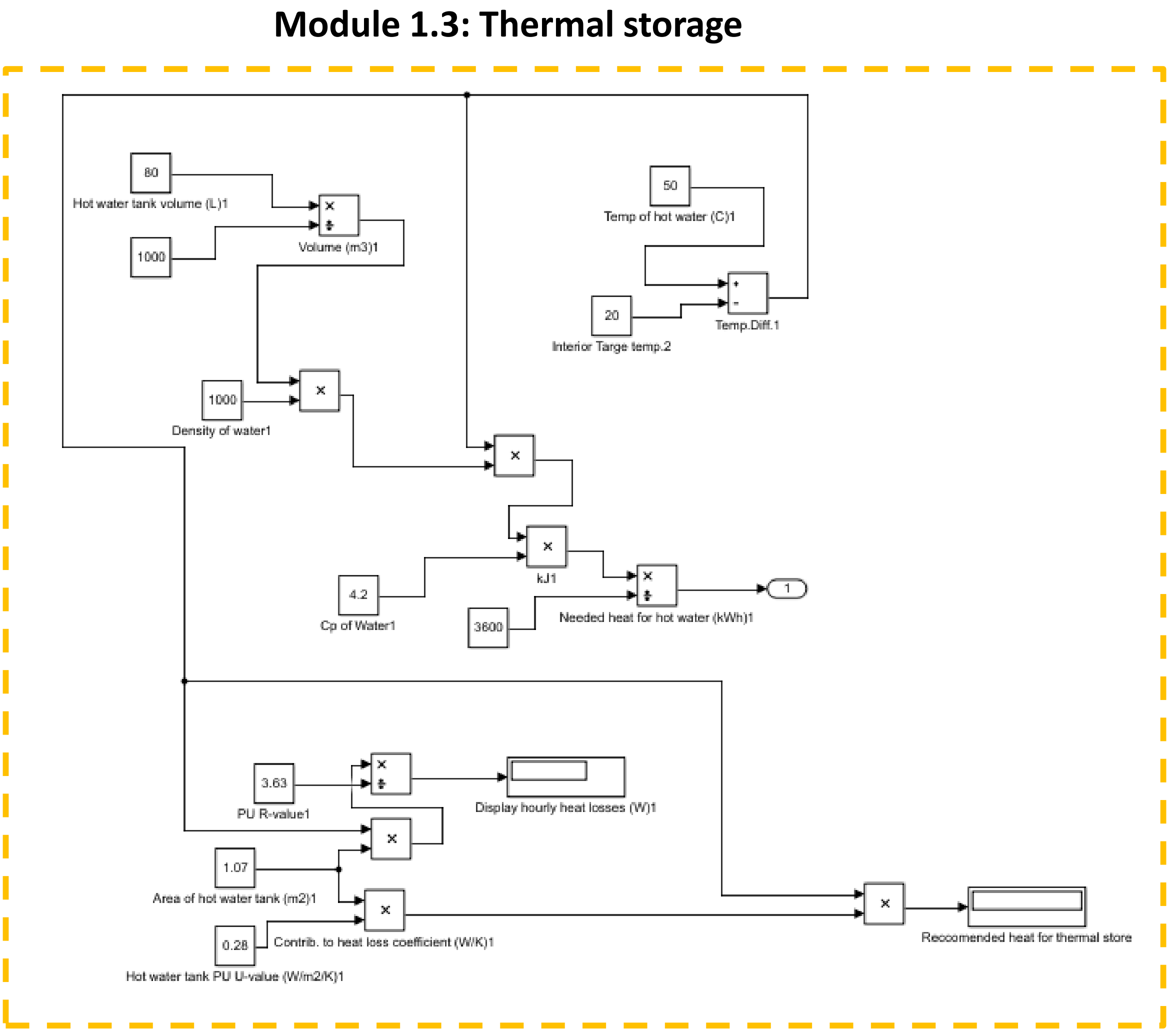


Figure 5. 10 *- Module 1.3: Thermal storage model in Simulink.*

This module tracks the household's hot water demand and includes it in the overall power demand of the heat pump.

The required heat for hot water can be expressed as:

$$Q_{hw} = (V_{ts} \times \rho_w) \times Cp_w \times \Delta T \quad \text{(Eq. 28)}$$

where Q_{hw} is the heat required for the hot water in thermal storage (kWh); V_{ts} is the volume of the thermal storage (m^3); ρ_w is the density of water (kg/m^3); Cp_w is the specific heat capacity of water (kJ/kg·K); and ΔT is the temperature difference between the hot water tank and the house interior (K).

The recommended heat capacity for the hot water tank can be expressed as:

$$Q_r = (A_{ts} \times U_{ts}) \times \Delta T \quad \text{(Eq. 29)}$$

where Q_r is the recommended hot water tank thermal capacity (kW); A_{ts} is the area of the thermal storage (m^2); and U_{ts} is the U-value of the thermal storage, typically composed of polyurethane insulation (0.28 W/m^2·K).

5.1.8. Module 2

Module 2 in the simulation is constructed using a series of switch blocks that monitor the ambient temperature. When the temperature reaches -17°C, the heat pump shuts off, and a backup electric resistance heater with a 3 kW capacity is activated. It has been found that air source heat pumps generally struggle and do not operate effectively at ambient temperatures between -17°C and -20°C (Konrad & MacDonald, 2023).

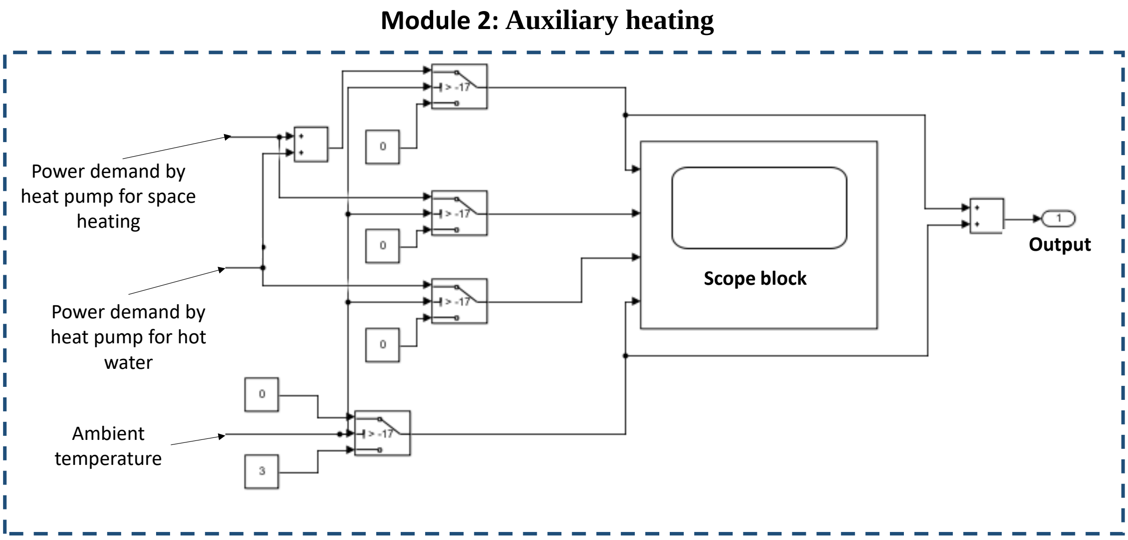


Figure 5. 11 *- Module 2 of the simulation model*

Figure 5.11 illustrates the construction of Module 2 in the simulation. When the temperature drops below -17°C, the backup electric resistance heater activates to provide the necessary thermal energy for space heating and hot water. Typically, the heat pump restarts at -12.2°C; this difference between -17°C and -12.2°C introduces hysteresis, allowing efficient control of the heat pump and reducing wear and tear. However, for the purposes of this paper, the simulation assumes an ideal control process without hysteresis, with a set point of -12.2°C.

The methodology outlined in this chapter provides a comprehensive approach to understanding the performance of air-source heat pumps under varying environmental conditions and insulation standards. By integrating experimental validation with advanced simulation techniques, the study addresses a critical gap identified in the literature concerning the impact of frost cycles on heat pump efficiency and energy demand. The chosen research design, data collection methods, and analytical techniques were all selected to ensure that the findings are robust, reliable, and applicable to real-world scenarios. The novel frost build-up model and the detailed look-up table for heat pump performance across different house types and climates represent significant contributions.

The same method described in Chapter 5.1 was followed for both analysis of the house types typical in the UK and the global 10 cities (Chapter 5.2).

5.2. Global cities analysis – cold season analysis

After estimating the power consumption of the ASHP across various house types in the UK, the approach outlined in chapter 3.4 was similarly applied to analyse 10 global cities (please see Table 3.5). This approach not only helps in assessing how local climates influence heat pump power demand but also reveals how insulation practices in each country affect the device's power requirements. Subsequently, a similar look-up chart to that explained in chapter 3.4 was developed to relate heat pump power demand to ambient temperature, considering the local climate and housing insulation for the 10 cities. This chart enables researchers to use the model to simulate grid demand in any of the 10 cities using the proposed simulation methodology. These cities were likely selected to provide a representative sample of the wide range of climatic and housing insulation conditions around the globe. The cities chosen to represent a wide spectrum of climates, which is crucial for studying the performance of ASHPs, particularly because heat pump efficiency is strongly affected by ambient temperatures and humidity. For example, Harbin (China), Moscow (Russia), and Helsinki (Finland) represent very cold climates with long, harsh winters; Reykjavik (Iceland), Stockholm (Sweden), and Copenhagen (Denmark) have cold, but relatively milder winters compared to the aforementioned cities; Vancouver (Canada), Nottingham (UK), and Amsterdam (Netherlands) offer more temperate maritime climates with milder winter temperatures; Ruse (Bulgaria) provides an example of a transitional climate between continental and temperate zones. This climatic variety allows the analysis to cover different temperature ranges and evaluate the effects of defrost cycles in varying environmental conditions, making the results more globally applicable. The selected cities can be effectively classified using the Köppen climate classification, which categorizes climates based on temperature, precipitation, and seasonal patterns (Domroes, 2003). Harbin (China), Moscow (Russia), and Helsinki (Finland) fall under the Dfc classification (subarctic or boreal climates) due to their long, cold winters and relatively short summers. Reykjavik (Iceland), Stockholm (Sweden), and Copenhagen (Denmark) align with the Cfc classification (marine west coast climate), characterized by milder winters and cool summers (Peel et al., 2007). Vancouver (Canada), Nottingham (UK), and Amsterdam (Netherlands) are representative of Cfb climates (temperate oceanic climates), which have moderate temperatures and precipitation throughout the year. Ruse (Bulgaria), situated at the transition between continental and temperate zones, aligns with the Dfb classification (humid continental climate) due to its warm summers and cold winters (Peel et al., 2007). The Köppen climate classification provides a robust framework for justifying the city selection because it ensures a scientifically grounded representation of diverse climatic zones. This alignment supports the validity of the findings by systematically capturing variations in ambient temperature and humidity, which significantly impact ASHP performance (Chen and Chen, 2013). Such a classification method ensures the analysis is both comprehensive and transferable across regions with similar climate profiles, thus enhancing the global applicability of the research (Chen and Chen, 2013). All ten cities are located in the northern hemisphere, which aligns with the study's focus on heat pump performance during the cold season (December 1 to February 28). This period corresponds to winter in these cities, making them relevant for studying heating demand and the behaviour of ASHP systems under cold-weather conditions. The choice of northern hemisphere cities ensures that the study captures real-world heating demand during the months when temperatures are typically low, enabling accurate analysis of power consumption and defrost cycle impact. The chosen cities also represent different building and insulation practices, which are critical to understanding how local construction norms influence ASHP power consumption. Northern European countries (e.g., Sweden, Finland, Denmark) typically have higher insulation standards due to stringent energy efficiency regulations (Milev et al., 2023), while other cities may have varying standards depending on regional policies or economic conditions. By including cities with varying insulation standards, the study can assess how housing characteristics (e.g., insulation levels) affect the heating demand, giving insights into the interaction between building design and heat pump efficiency.

Further analysis for the ten global cities was conducted, to estimate the effect of defrost cycles for each city over three-month winter period, focusing on the coldest days of the season to evaluate how these cycles affect power demand and heat output. The results highlight the anticipated impact on electricity demand due to heat pumps and their defrost cycles.

For the house type and insulation level and heating demand relationship analysis methods please see Chapter 3.4. typically, duration simulation ran for three months during the cold season (December 1 to February 28) when temperatures in the northern hemisphere are typically low (Internet Geography, 2021). It assumed continuous operation of the heat pump for space and water heating. When outdoor temperatures dropped below 0 °C, the defrost cycle activated 80–90 minutes later and lasted approximately 5 minutes. It was estimated that air source heat pumps can operate for 80–90 minutes with accumulated frost on the outdoor heat exchanger (Chung et al., 2021) and typically, 5 to 10 minutes are sufficient for defrosting (Payne and O'Neal, 1995). After frost removal, normal operation resumed.

The simulation used weather data from the PVGIS tool (European Commission, 2021), which provided ambient temperature and relative humidity for the 10 cities studied. The Photovoltaic Geographical Information System (PVGIS), developed by the European Commission, is a reliable source of meteorological data, particularly suited for energy assessments, including those related to air source heat pumps (ASHPs). It provides high-resolution, long-term climate data, including solar radiation, temperature, and humidity, crucial for evaluating energy system performance. The data is derived from a combination of satellite observations and ground station measurements, ensuring credibility and accuracy. The degree days method is a commonly used approach to estimate heating and cooling energy demand by measuring how much daily temperatures deviate from a base temperature (Sauer & Howell, 1991). While this method is simple and useful for long-term trends, the PVGIS tool is more suitable for the simulation and the chosen 10 cities in this case. The PVGIS tool is more suitable than the degree days method for simulating air source heat pump performance in the chosen 10 cities due to its high-resolution, hourly data on temperature and humidity, which are crucial for accurately modelling ASHP operations and defrost cycles. Unlike the degree days method, which aggregates daily temperature deviations and lacks humidity data, PVGIS provides detailed, city-specific meteorological inputs essential for capturing short-term temperature fluctuations and frost formation. This makes PVGIS particularly well-suited for analysing ASHP efficiency and energy demand in varying climates, offering more precision for the simulation. This data was interpolated into the model and fed into the heat pump simulation to calculate heating capacity of the evaporator and condenser, as well as compressor input power. A target inlet temperature for the condenser was set to 50 °C. Relative humidity data was essential as it influences frost growth on the outdoor heat exchanger. The simulation model comprised several sub-modules, detailed in the following sections.

5.3. Simulink Simulation Analysis

This section presents the analysis of Air Source Heat Pump (ASHP) performance using Simulink simulations. The simulations were validated against real-world data from test rigs and used to evaluate the impact of various factors, such as house types, insulation levels, and ambient temperatures on heating demand and energy consumption. Additionally, this chapter explores the implications of widespread ASHP adoption on the power grid, with a focus on different scenarios and the associated energy demands.

5.3.1. Model Validation: Comparison Between Test Rig and Simulation Model of the Heat Pump

To ensure the reliability of the Simulink model, 20 comparative tests were conducted between the model outputs and data obtained from a test rig setup, as indicated in Table 5.2. The validation process included a correlation analysis and a paired t-test to assess the accuracy and reliability of the simulation model.

***Table 5. 2** – Test rig tests and outcomes*

Test No	Running time (min)	Defrost time (min)	Total running time (min)	Total heat output (kWh)	Total electricity input (kWh)
1	106	6	112	8.5	3
2	114	8	122	9.2	3.3
3	140	4	144	9.2	3.7
4	176	2	178	11.8	4.9
5	187	3	190	12.2	5.2
6	203	2	205	14.2	5.9
7	173	2	175	12.4	5.1
8	185	2	187	14	5.8
9	216	2	218	16	5.6
10	205	3	208	15	5.6
11	232	4	236	15.1	6
12	205	3	208	11.7	5.1
13	187	4	191	10	4.3
14	155	4	159	9.4	3.7
15	163	4	167	9.6	3.9
16	189	7	196	11.9	4.6
17	189	6	195	11.6	4.5
18	185	6	191	11.6	4.5
19	152	7	159	10.2	3.9
20	212	7	219	13.4	5.2

Along with the temperature and humidity data that were fed into the simulation model, the running and defrost time were also replicated in Simulink. The tests included various running times, defrost cycles, total heat output, and electricity consumption metrics. For example, the defrost time ranged from 2 to 8 minutes across tests, with total running times between 112 and 236 minutes. The corresponding heat outputs varied from 8.5 kWh to 16 kWh, while the total electricity inputs ranged from 3 kWh to 6 kWh.

5.3.2. Correlation Analysis Results

A high correlation coefficient of 0.97 (Figure 5.12) for total input energy and 0.99 (Figure 5.13) for total heat output was found between the test rig data and the Simulink model outputs. These results indicate a strong positive correlation, suggesting that the simulation model accurately reflects the performance characteristics of the ASHP observed in real-world conditions.

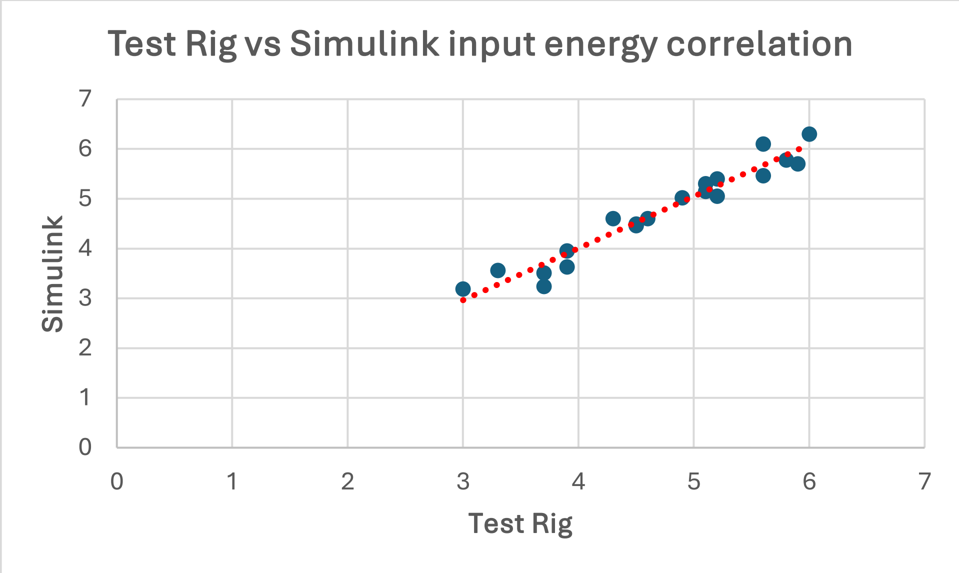


Figure 5. 12 *– Test Rig vs Simulink input energy correlation*

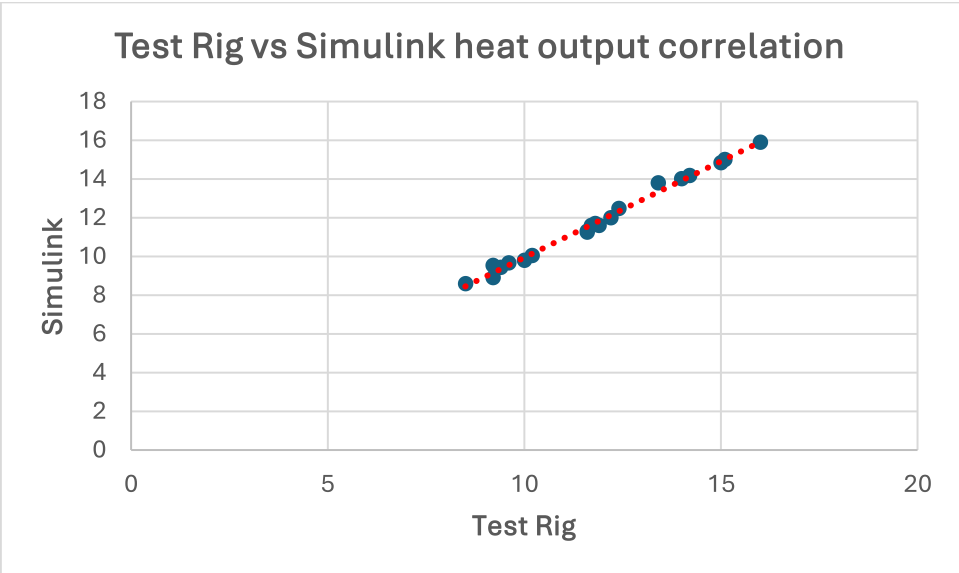


Figure 5. 13 *– Test Rig vs Simulink input energy correlation*

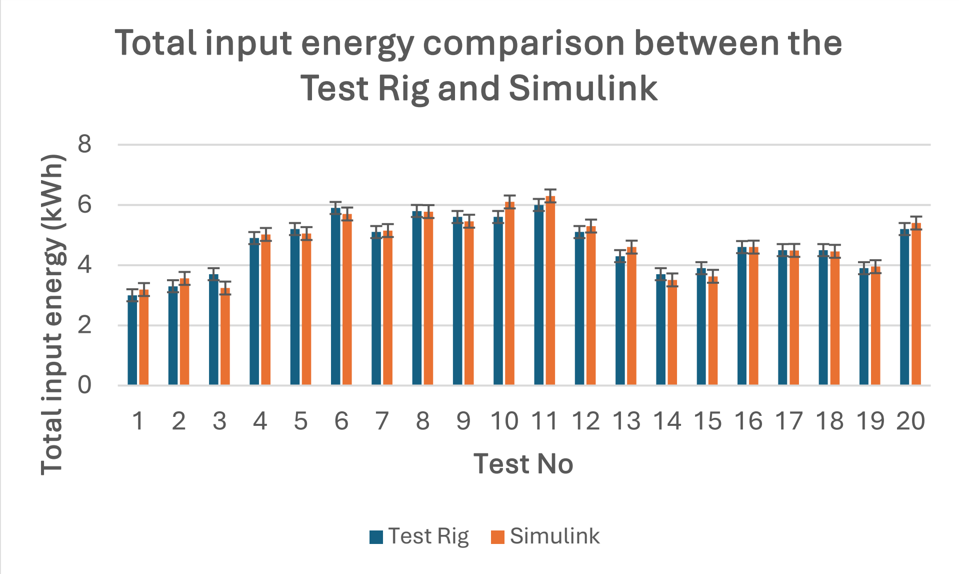


Figure 5. 14 *– Test Rig vs Simulink total input energy comparison*

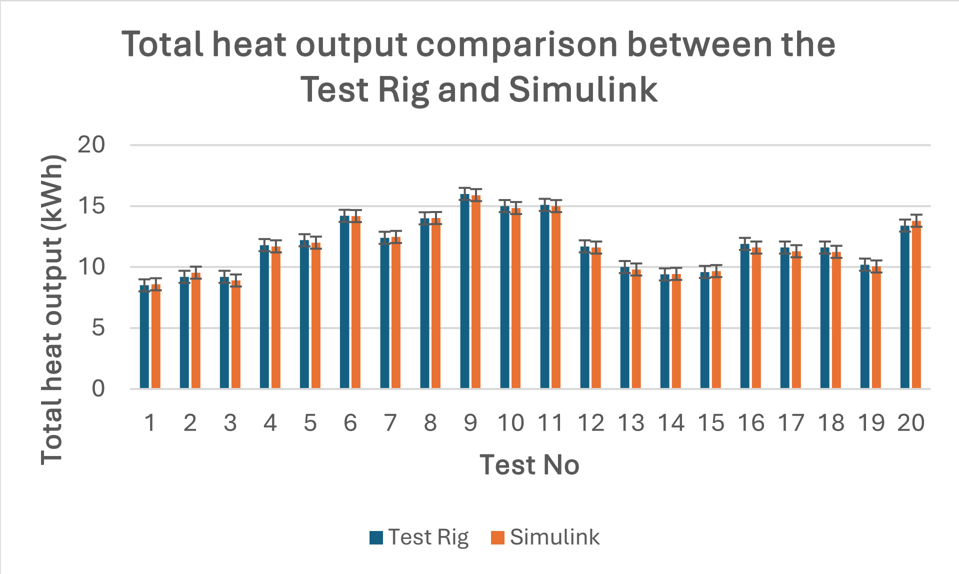


Figure 5. 15 *– Test Rig vs Simulink total heat output comparison*

Both Figures 5.14 and 5.15 compare the total input energy consumption and total heat output, respectively, between the test rig and the Simulink model, highlighting minor discrepancies that are within acceptable error margins.

***Table 5. 3** – Test rig vs Simulink frost accumulation comparison*

Test №	*Test Rig*	*Simulink*	*Standard deviation*
1	0.97	1.02	0.033
2	1.79	1.88	0.06
3	0.15	0.16	0.005
4	0.21	0.22	0.007
5	0.28	0.29	0.009
6	0.27	0.28	0.009
7	0.39	0.41	0.013
8	0.27	0.23	0.029
9	0.49	0.58	0.068
10	0.37	0.33	0.025
11	0.63	0.57	0.043
12	0.34	0.33	0.003
13	0.46	0.45	0.005
14	0.17	0.23	0.039
15	0.27	0.26	0.003
16	0.94	0.92	0.01
17	0.60	0.59	0.0067
18	0.57	0.56	0.0064
19	1.04	1.02	0.011
20	1.18	1.16	0.013

Table 5.3 showcases the comparison between the measurements of water content after defrost cycles from each test rig test and the results from the simulation model.

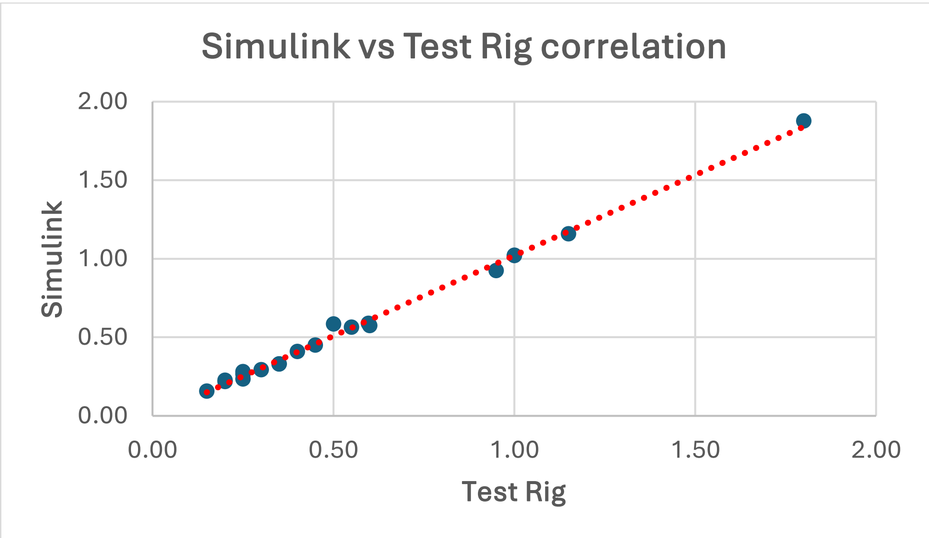


***Figure 5. 16** – Frost accumulation correlation between the test rig and the simulation model.*

The correlation coefficient between the measured water content from the test rig and the simulation model is 0.99 (Figure 5.16). Figure 5.17 represents graphically the frost volume comparison between the test rig and the simulation model for each of the 20 tests.

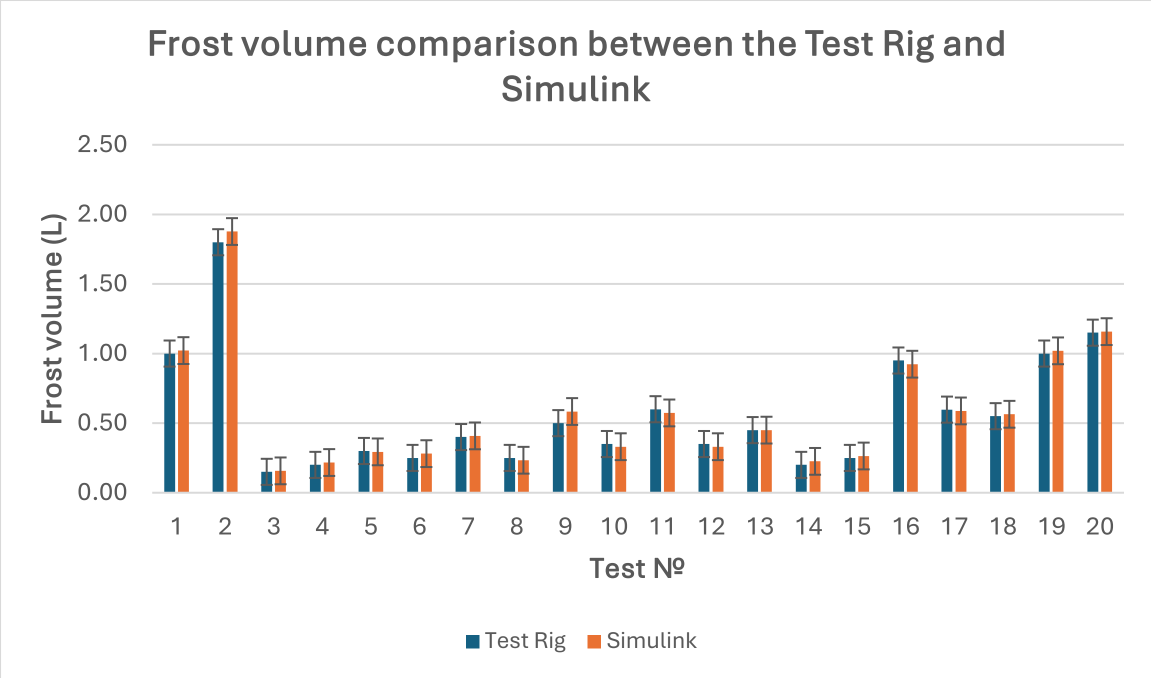


***Figure 5. 17** – Frost accumulation comparison between the test rig and the simulation model.*

5.3.3. Paired t-Test Results

Based on the paired t-test results (Please see Table 5.4) for both "Total Heat Output" and "Total Input Energy," there is no evidence to suggest a statistically significant difference between Variable 1 and Variable 2 in either dataset. For the Total Heat Output, the calculated t-statistic (1.504) is smaller than the critical value (2.093), and the p-value (0.149) exceeds the common significance level of 0.05, indicating that any observed difference between the variables is not statistically significant. Similarly, for the Total Input Energy, the t-statistic (-0.668) is also less than the critical value (2.093), with a p-value of 0.512, far above the 0.05 threshold.

***Table 5. 4** - t-Test: Paired Two Sample for Means results*

	Total input energy		*Total heat output*	
	Variable 1	*Variable 2*	*Variable 1*	*Variable 2*
Mean	4.69	4.7245	11.85	11.7825
Variance	0.79989474	0.92031026	4.911053	4.894757
Observations	20	20	20	20
Pearson Correlation	0.97135543		0.995893	
Hypothesized Mean Difference	0		0	
df	19		19	
t Stat	-0.6678387		1.504037	
P(T<=t) one-tail	0.25513397		0.074507	
t Critical one-tail	1.72913281		1.729133	
P(T<=t) two-tail	0.51226795		0.149013	
t Critical two-tail	2.09302405		2.093024	

***Table 5. 5** – t-Test: Paired Two Samples for Means (Frost accumulation) results*

	Variable 1	*Variable 2*
Mean	0.564858764	0.574911464
Variance	0.175805782	0.185249373
Observations	20	20
Pearson Correlation	0.997905274	
Hypothesized Mean Difference	0	
df	19	
t Stat	-1.515867569	
P(T<=t) one-tail	0.07300689	
t Critical one-tail	1.729132812	
P(T<=t) two-tail	0.146013781	
t Critical two-tail	2.093024054	

The t Stat (-1.51587) is the calculated t-value for the paired t-test (Table 5.5).

The t Critical two-tail (2.09302) is the critical value of t for a two-tailed test with 19 degrees of freedom (df = 19). For the difference to be significant at the 0.05 level, the absolute value of the t-statistic would need to be greater than the critical value (2.09302). Since t Stat is less than t Critical two-tail, the t-statistic does not exceed the critical value. The p-value for the two-tailed test P(T<=t) two-tail is 0.146, which is greater than the common significance level of 0.05. A p-value greater than 0.05 indicates that the difference between the means is not statistically significant, hence the experimentally measured and simulated frost are not significantly different.

5.3.4. Validation Summary

Based on the correlation analysis and t-Test results, the Simulink model was found to adequately replicate the performance characteristics of the heat pump observed in the test rig. The key areas of agreement include high correlation for total heat output, while discrepancies were noted in the total input energy consumed. These findings provide a basis for confidence in the model's predictions for subsequent analyses.

5.4. Impact of House Types and Insulation Levels on Heating Demand

Following the validation, the Simulink model was used to estimate the heating demand of various UK house types under different ambient temperatures. The results highlight the variability in heating demand based on house type and insulation level, which are crucial factors influencing the effectiveness of ASHPs.

5.4.1. UK house types

The simulation results indicated significant differences in heating demand across various UK house types, particularly when comparing older, uninsulated homes to modern, well-insulated dwellings.

5.4.1.1. Heating Demand Variability

The simulation found that traditional small British houses with adequate insulation had significantly lower heating demands compared to older homes with solid, uninsulated walls. For instance, a very old house with uninsulated solid walls had a heating demand of approximately 18.38 kWh at -20°C, which decreased to 0 kWh at 20°C as temperatures increased. In contrast, a well-insulated house with filled cavity walls required much less energy, showcasing the critical role of insulation in reducing heating demands.

Table 5.1 (Chapter 5.1.6) showcase the U-values of the building elements for each UK house used in the simulation.

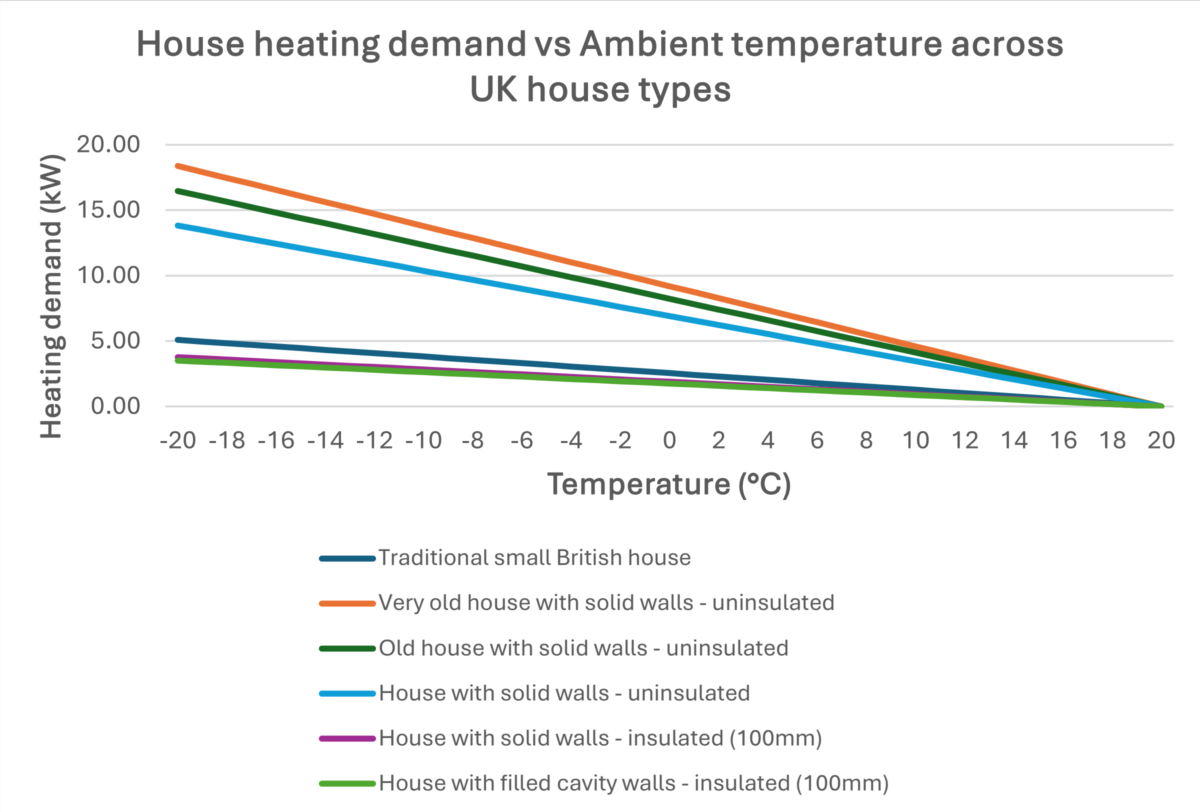


Figure 5. 18 *– House heating demand vs Ambient temperature across UK house types*

Figure 5.18 illustrates the relationship between ambient temperature and heating demand for different house types. As shown, the better the insulation (e.g., filled cavity walls with 100mm insulation), the lower the heating demand at lower ambient temperatures. This graph underscores the potential energy savings achievable through improved insulation.

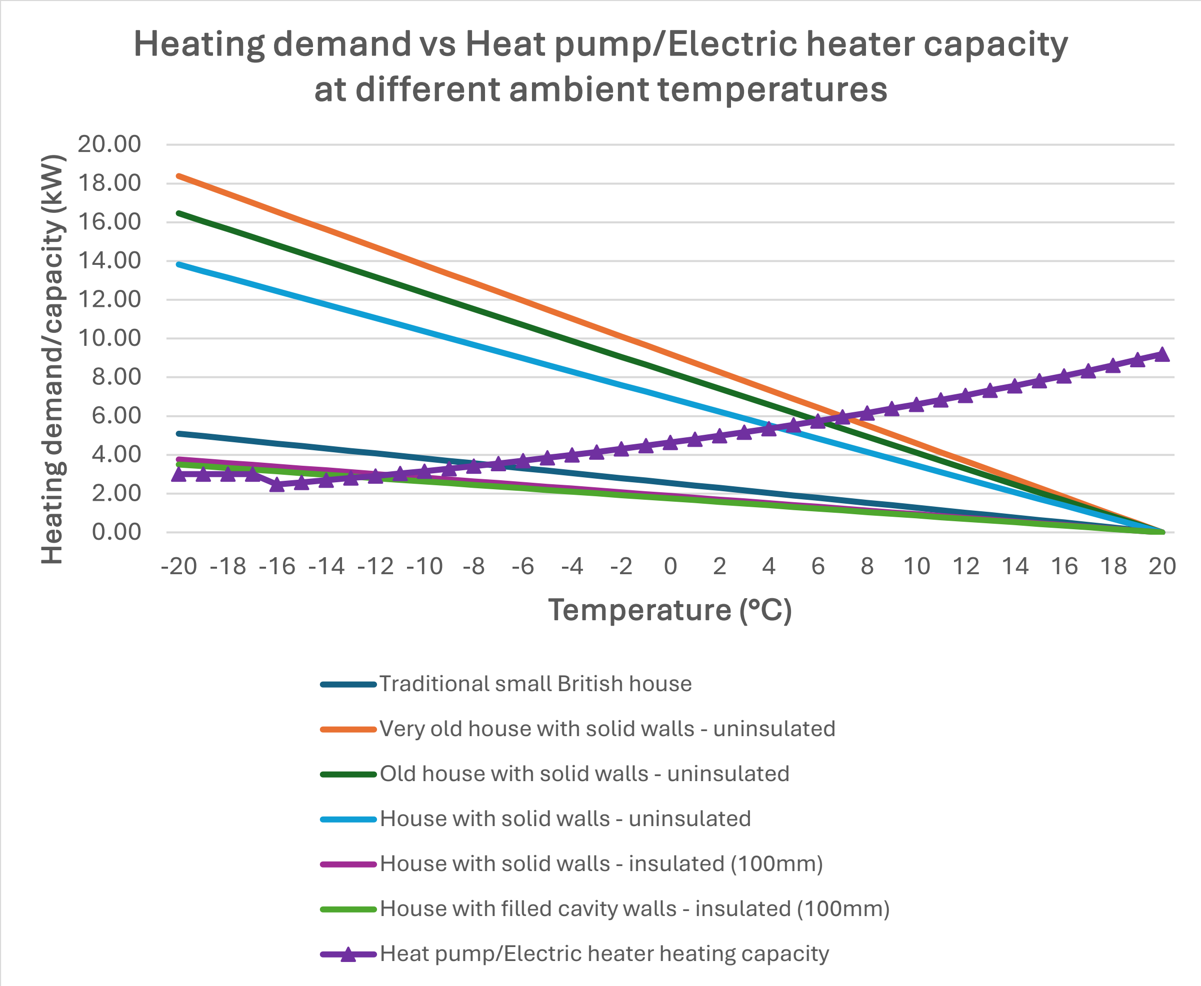


***Figure 5. 19** – Heating demand vs Heat pump/electric heater capacity at different ambient temperatures.*

Figure 5.19 above indicated the ability of the heat pump and electric heater (at -17°C and below) to satisfy the heating demand of different house types in the UK. It is evident that with better insulation, the HP would be able to satisfy the heating demand of the dwelling at around -12°C ambient temperature. The back-up electric heater would be able to satisfy to a certain extent the demand of houses with filled cavity wall and 100mm insulation in place.

5.4.1.2. Power demand

The power demand of the heat pump also varied significantly with house type and insulation level. The simulation showed that well-insulated homes had much lower power demands, which not only enhances the efficiency of ASHPs but also reduces the strain on the power grid.

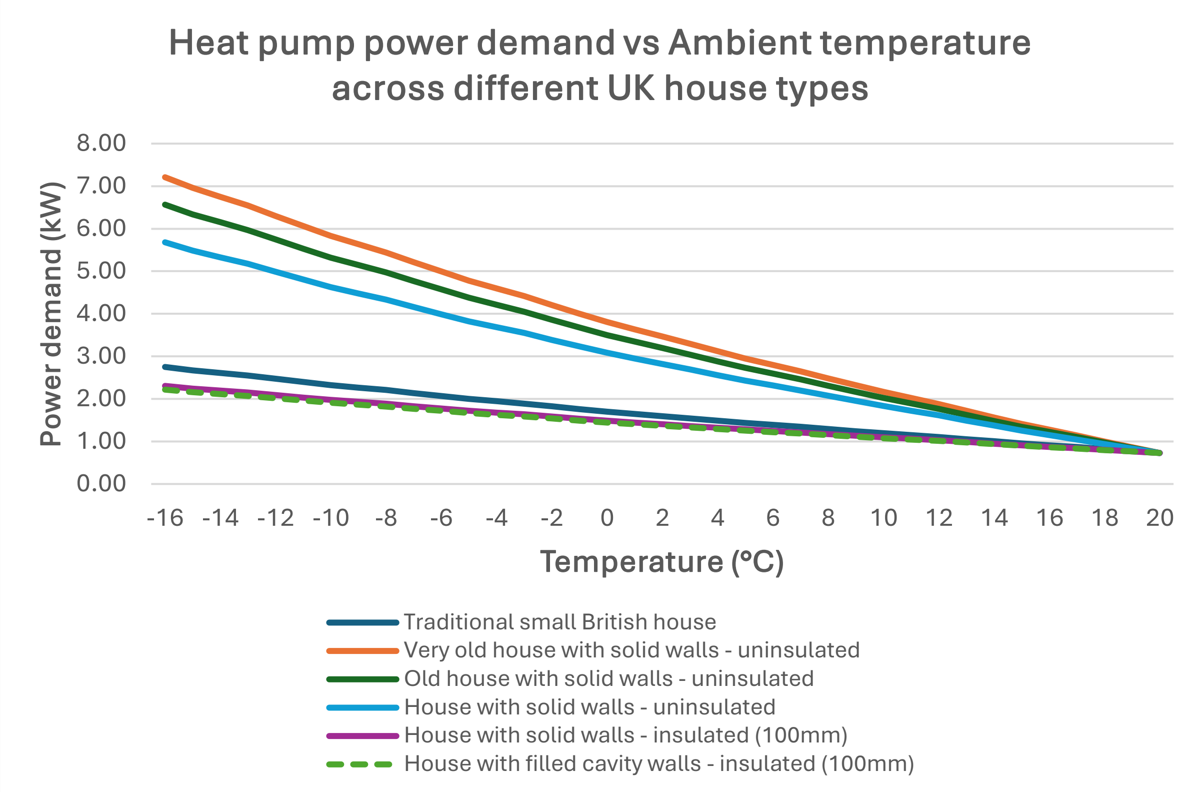


***Figure 5. 20** – Heat pump power demand vs Ambient temperature across different UK house types.*

Figure 5.20 shows the heat pump power demand across different UK house types, emphasizing that houses with better insulation can maintain thermal comfort with significantly less energy. This data suggests that upgrading insulation in older homes could be a critical step in optimizing ASHP performance and reducing overall energy consumption.

5.4.2. Global cities house types

The study extended the simulation analysis to 10 global cities with varying climatic conditions and insulation standards, offering insights into how ASHP performance might differ internationally. Similar look-up charts (Fig. 5.18, 5.19, and 5.20) have been created, as shown in Figures 5.21, 5.22, and 5.23, to display the power and heating demand in kW for an average household in each of the 10 selected cities, based on ambient temperatures ranging from -20°C to +20°C, for both air source heat pumps and resistive electric heaters.

This section presents the simulation results of different house types and insulation levels on heating demand when using ASHPs. The findings indicate that:

5.4.2.1. Heating Demand Variability

The analysis across 10 global cities demonstrated that insulation standards dramatically affect heating demands. For example, Finnish homes, which are typically well-insulated, showed up to 90% lower heating demand compared to uninsulated buildings in China. This discrepancy highlights the importance of building codes and insulation requirements in determining the feasibility and efficiency of ASHPs.

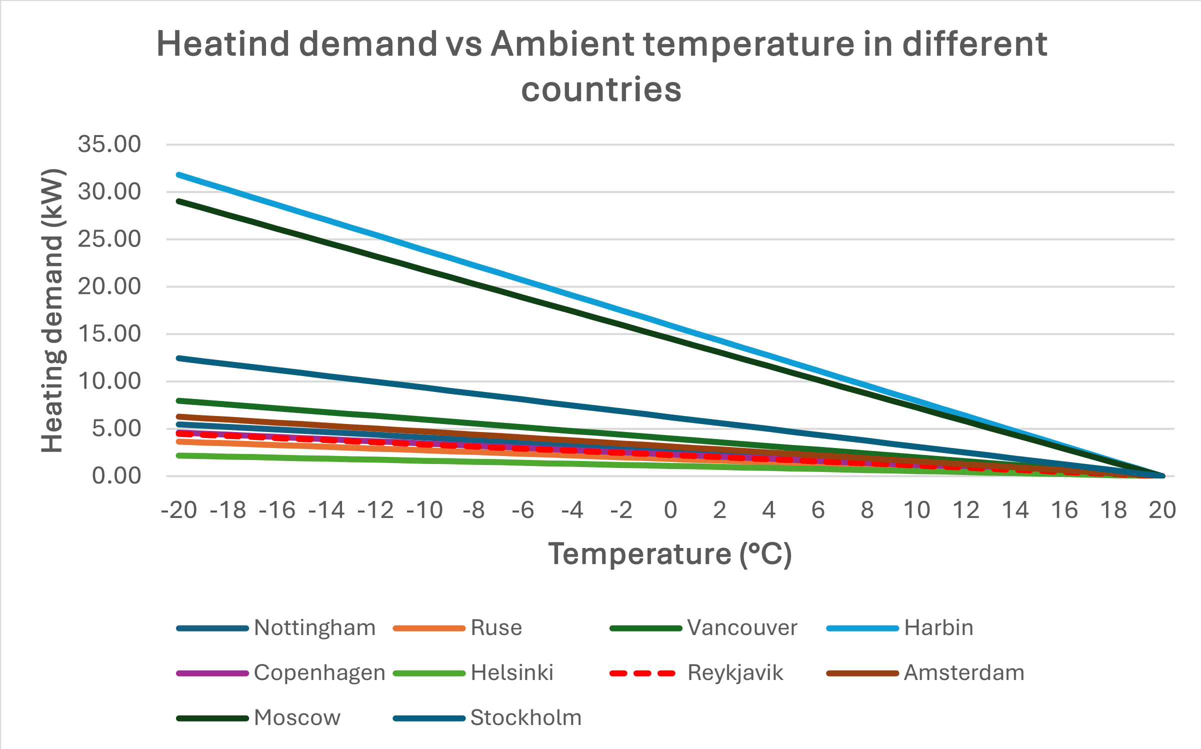


Figure 5. 21 *– Heating demand vs Ambient temperature in different countries.*

Figure 5.21 compares the heating demand vs. ambient temperature in different countries. Finnish homes showed a sharp decrease in heating demand as temperatures rose, demonstrating how insulation effectively reduces the need for supplementary heating even in extremely cold conditions.

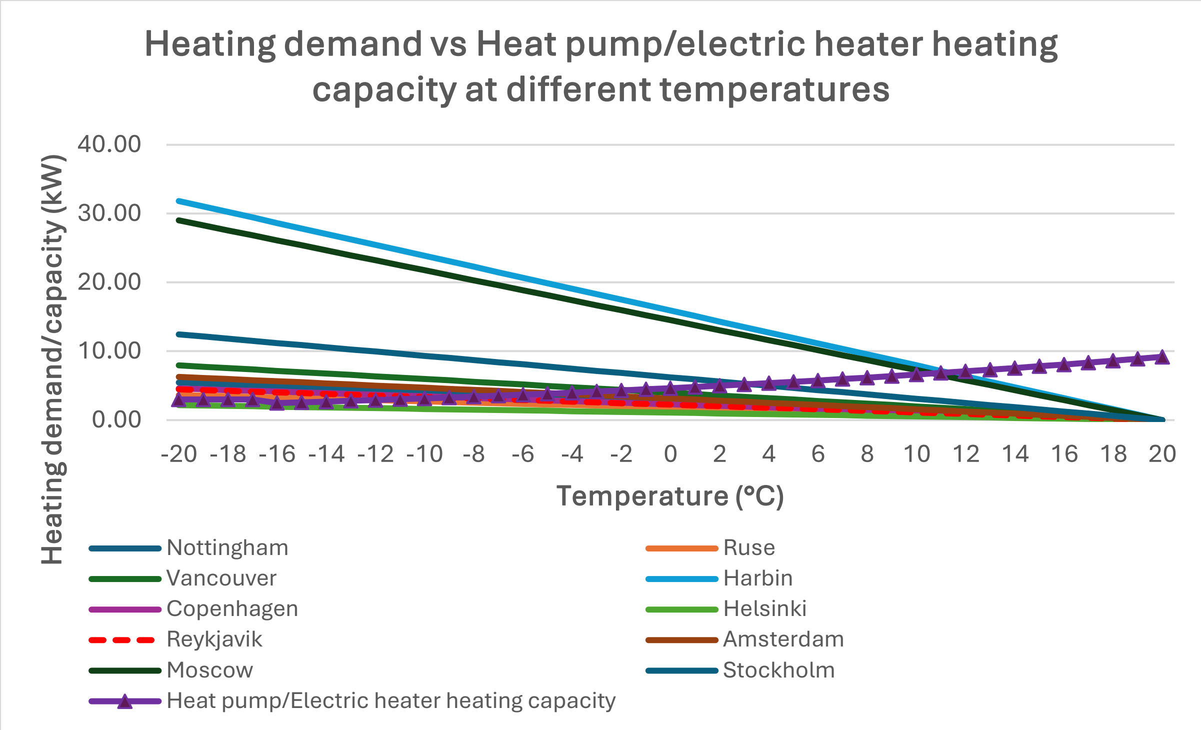


***Figure 5. 22** – Heating demand vs Heat pump/electric heater heating capacity at different temperatures.*

Figure 5.22 showcases the ability of both the heat pump and the back-up electric heater to satisfy the heating demand in typical Finish dwellings. The reason is the high insulation level of the houses in Finland (Table 5.5, Chapter 5.1.6). Whereas with low insulation levels in Moscow and Harbin, the heat pump could satisfy the demand until 10-12°C. Below this ambient temperature, their thermal comfort wound not be satisfied by the heat pump.

5.4.2.2. Power demand

The power demand for heat pumps in these cities showed a similar trend, where cities with better-insulated housing, like Helsinki and Reykjavik, had significantly lower power demands compared to less insulated regions like Moscow or Harbin. The simulations also indicated that at very low temperatures, heat pumps would switch to resistive heating, increasing the power demand sharply.

Figure 5.23 illustrates heat pump power demand vs. ambient temperature across different countries, providing a lookup table for expected power demand based on typical ambient conditions in each city.

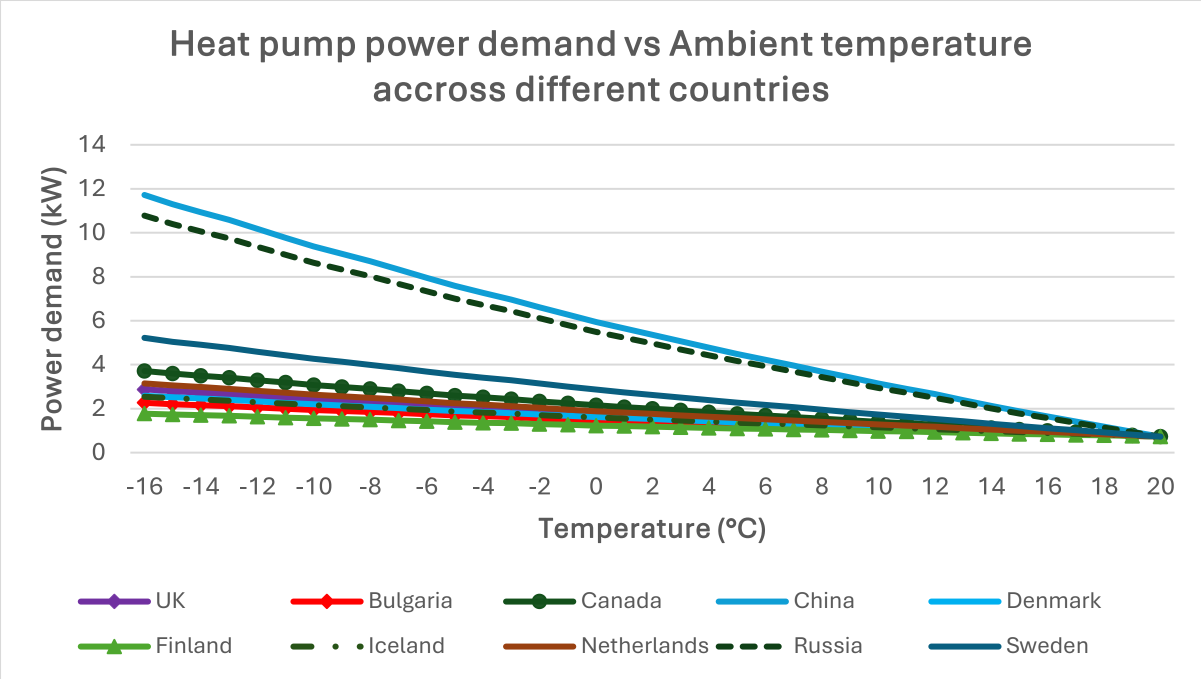


Figure 5. 23 *– Heat pump power demand vs Ambient temperature across different countries.*

The results presented in Figure 5.23 also take into account the average dwelling size in each city and the U-values of building components like windows, walls, roofs, and floors. This graph can be used as a look-up table for each of the analysed cities, providing an approximate prediction of the power demand for air source heat pumps for space and hot water heating based on ambient temperature. Figure 5.23 further highlights the significance of improved insulation in dwellings. For example, countries like Finland and Bulgaria, which typically have better-insulated building elements, show lower heat pump power demand compared to countries like Russia and China, where insufficient insulation leads to higher power demand.

5.4.3. Energy Consumption Scenarios with ASHP Deployment

This section explores the potential impact of widespread ASHP deployment on energy consumption and the power grid, focusing on scenarios where ASHPs are used extensively across the UK and in various global cities.

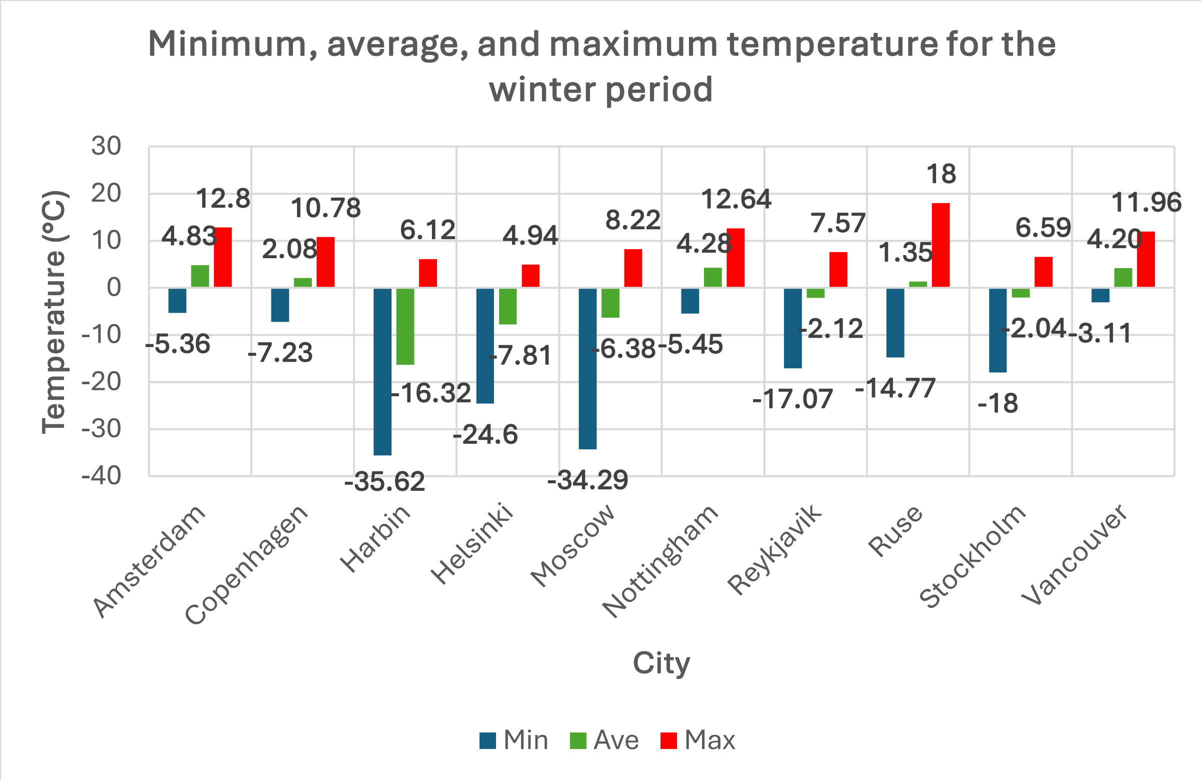


***Figure 5. 24** – Minimum, average, and maximum temperatures for the winter period in the 10 cities.*

Figure 5.24 showcases the minimum, average, and maximum temperatures for the winter period in the selected 10 cities. It can be noted that the overall winter temperature in Harbin, Moscow, and Finland are considerably lower compared to cities such as Amsterdam and Copenhagen.

5.4.3.1. Seasonal simulation in global cities

An analysis was conducted to determine the number of defrost cycles for air source heat pumps in various cities worldwide. Figure 5.25 shows the simulation results for the 3-month winter season across the 10 cities studied. It is clear from Figure 5.25 that ambient temperature significantly affects the power demand of heat pumps. For instance, when temperatures drop to around -17°C, backup heating systems are activated, as seen in Helsinki. Figure 5.26 summarizes the number of defrost cycles for the 10 global cities, highlighting that locations like Helsinki and Harbin experience a significant number of defrost cycles.

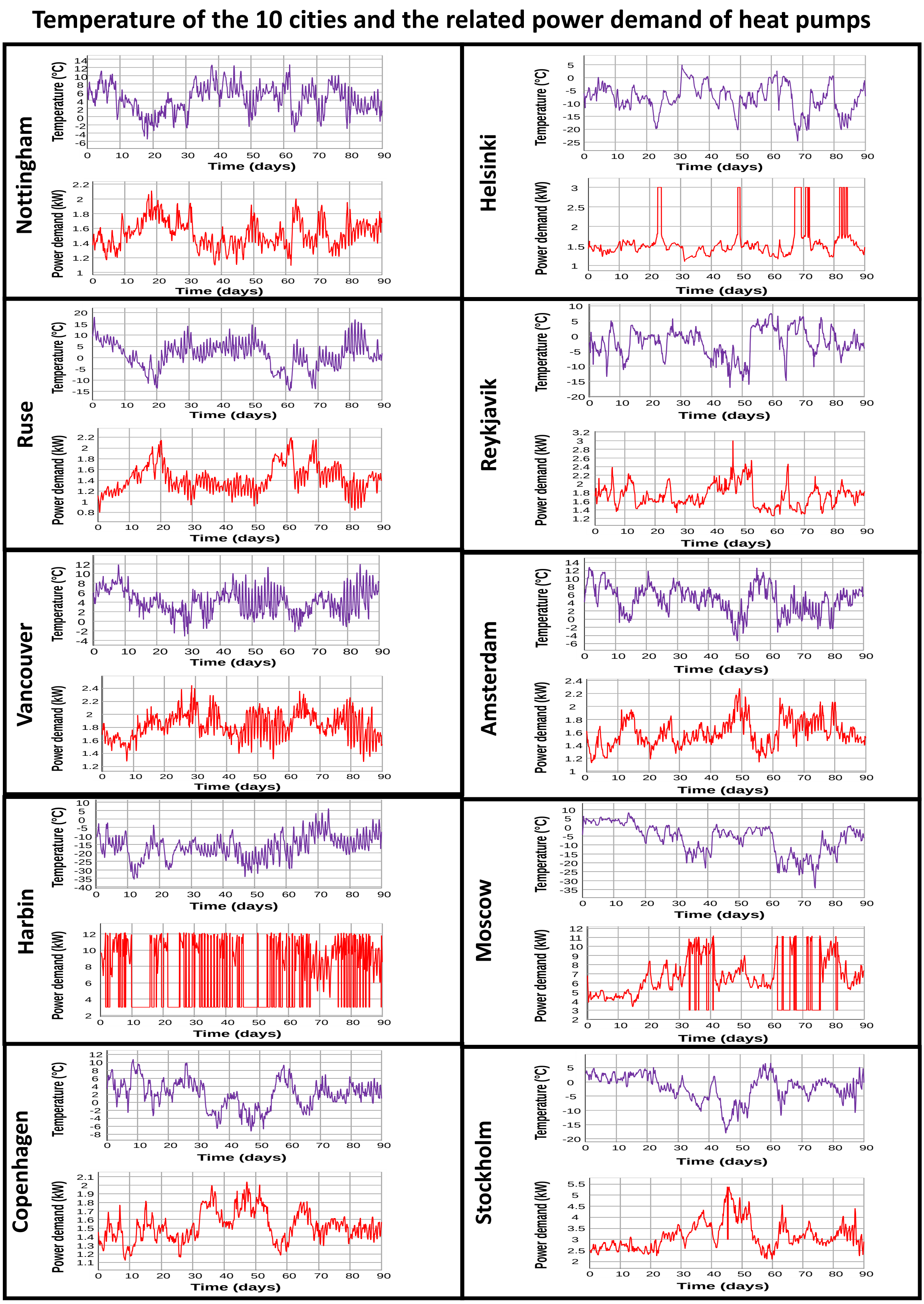


Figure 5. 25 *- Temperature of the 10 cities and the related performance of the heat pump.*

Figure 5.25 presents the relationship between ambient temperature and the number of defrost cycles. A strong negative correlation was observed, indicating that as temperatures drop, defrost cycles increase, which can lead to higher energy consumption and potential grid strain during peak periods.

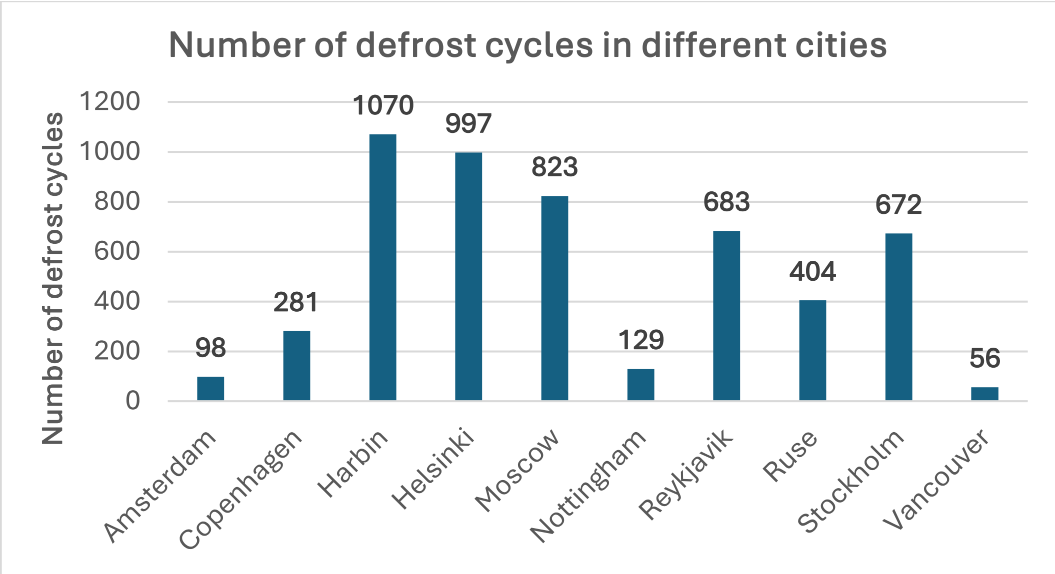


Figure 5. 26 *- Number of defrost cycles in various cities during the cold season.*

As shown in Figure 5.26, colder regions undergo more defrost cycles, with cities like Helsinki and Harbin experiencing harsher winters compared to places like Vancouver or Amsterdam. In colder areas, multiple heat pump units may perform defrost operations simultaneously, or their cycles may overlap, potentially causing a significant and sudden load on the grid.

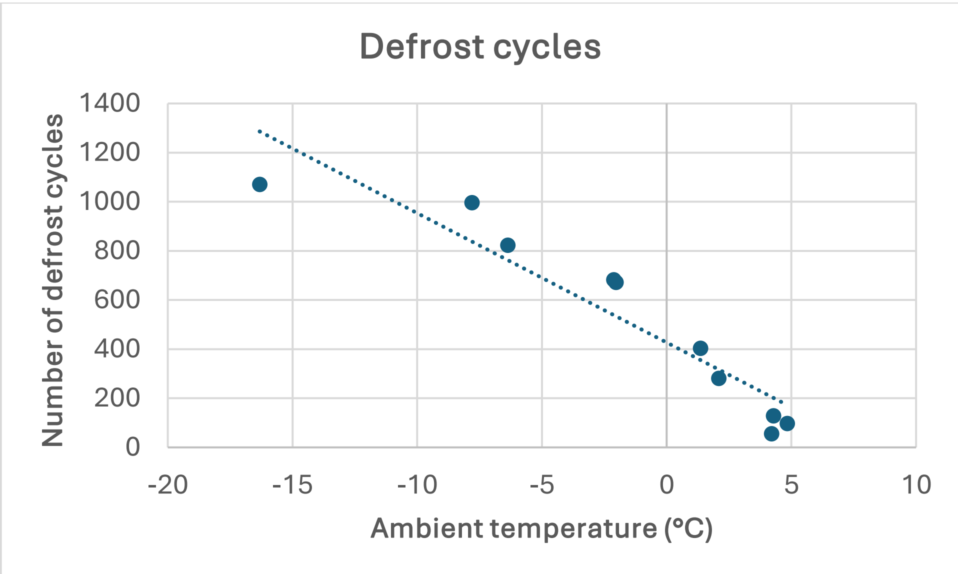


Figure 5. 27 *- Correlation between number of defrost cycles and ambient temperature.*

Figure 5.27 demonstrates a strong correlation between the number of defrost cycles and ambient temperature, with a correlation coefficient of -0.94, indicating that lower temperatures lead to more frequent frost removal operations by heat pumps.

Simulations were conducted to assess the number of defrost cycles for ASHPs in various global cities during a typical three-month winter season (Figure 5.26). The findings showed that colder cities like Helsinki and Harbin experienced a significantly higher number of defrost cycles, impacting the overall efficiency and power demand of the heat pumps.

Although the winter temperatures in both Helsinki and Harbin are very low, Finnish housing have lower heating and power demand compared to Chinese dwellings. The main reason for this could be the higher insulation level of houses in Finland.

5.4.3.2. ASHP adoption in the UK

Building on these findings, along with equations and Figure 4.16, the UK electricity grid is examined in detail as a case study to analyse how heat pump usage and defrost cycles impact the grid. The UK is chosen for this detailed analysis for simplicity, though the approach can be generalized to any country or city. To begin analysing the demand curve, the daily electricity consumption on a typical cold day (with temperatures between -1°C to -3°C) was assessed, as shown in Figure 5.28 (Stolworthy, 2021).

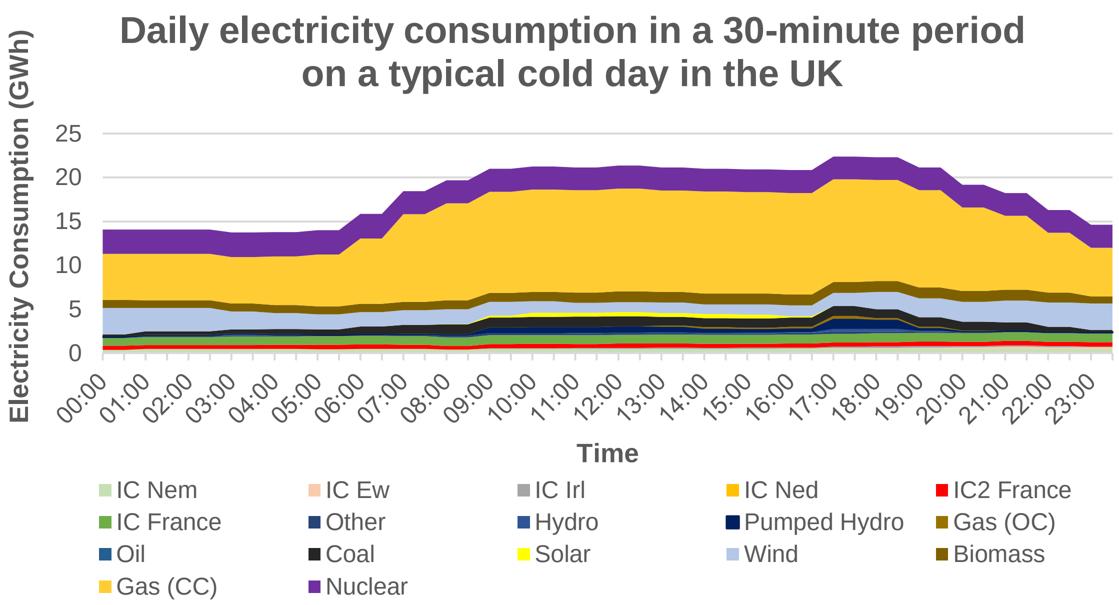


Figure 5. 28 *- A typical current daily winter electricity consumption in a 30-minute period in the UK (based on data from Gridwatch (Stolworthy, 2021)).*

The data was collected using Gridwatch (Stolworthy, 2021), which provided hourly values for electricity consumption and the sources of energy, including international grid connections (Figure 5.28). Currently, the UK grid mix includes the following energy sources: Gas (40.6%), Wind and Solar (23.8%), Nuclear (17.3%), Coal (2.1%), Oil and other fuels (2.8%), Hydro (1.8%), and other renewables (11.5%). Approximately 40% of electricity is produced using combined cycle gas turbines. In recent years (2018-2020), wind and solar capacities have significantly increased (Department for Business, Energy & Industrial Strategy, 2019) while coal-fired power station capacity has decreased. The UK has reduced its reliance on fossil fuels and shifted towards more sustainable energy solutions.

This section explores the impact of heat pumps, assuming that Nottingham's weather conditions, representative of the Midlands, are an average for the entire UK. The analysis covers the daily power demand during the UK cold season over three months.

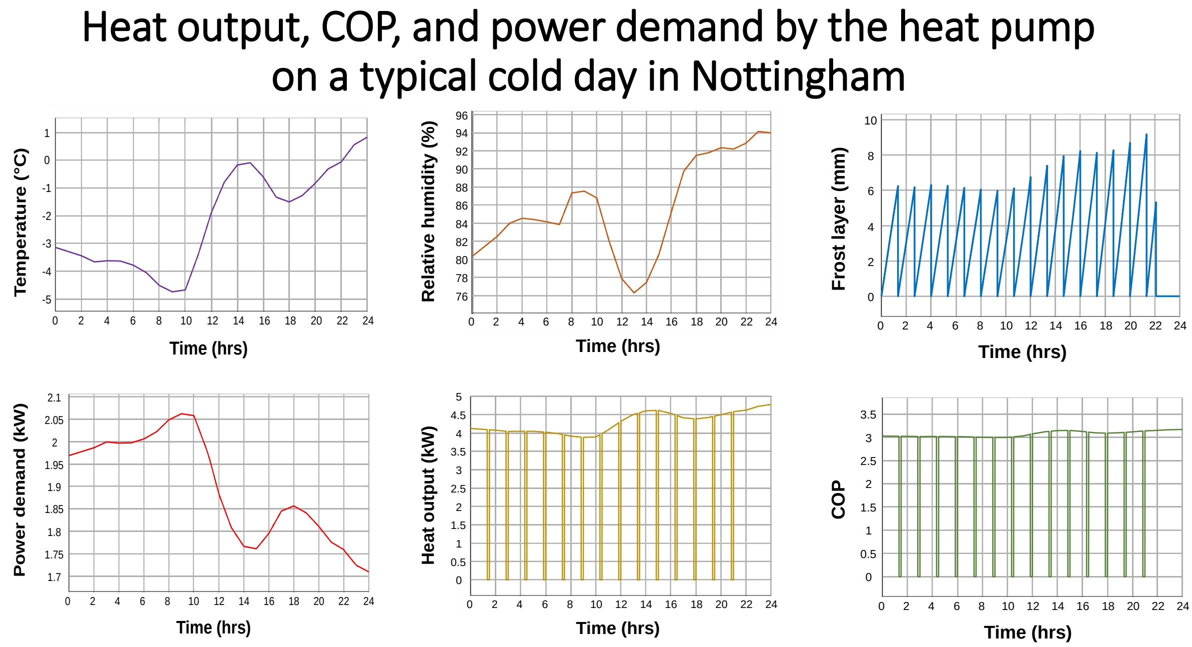


Figure 5. 29 *- Heat output, COP, and power demand by the heat pump in Nottingham.*

Figure 5.29 graphically displays the heat output, Coefficient of Performance (COP), and power demand of a heat pump on a typical cold day in Nottingham, UK, along with charts for ambient temperature, relative humidity, and frost layer thickness on the outdoor heat exchanger. The power demand reflects the heating needs of dwellings, considering the U-values of building elements. It is observed that frost accumulation on the heat exchanger is influenced by air humidity, with higher humidity leading to a thicker frost layer. Drops in heat output and COP indicate defrost cycles, during which the heat output and performance drop to zero, as no heat is delivered to the condenser.

This research analysed the impact of ASHP adoption in the UK, specifically assessing daily electricity consumption on typical cold days and projecting this across the cold season. The findings suggest that if all 27.8 million UK households were to adopt ASHPs, the daily electricity consumption could rise by approximately 144%, posing significant challenges for grid stability and capacity.

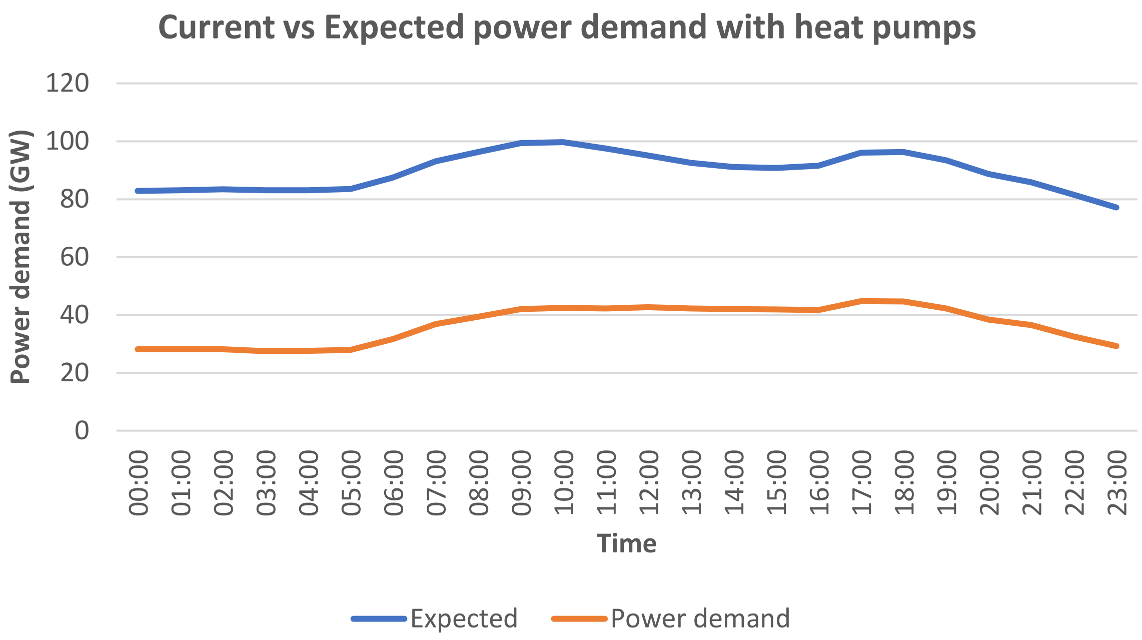


***Figure 5. 30** - Analysis of one day energy demand comparison in the UK with current demand and the heat pumps.*

Figure 5.30 compares current UK electricity demand with the projected demand assuming widespread ASHP adoption, illustrating potential disruptions to the grid. The need for increased capacity, smart grid technologies, and better integration of renewable energy sources is highlighted to manage the expected rise in energy consumption.

Electricity demand peaks are more common in winter, particularly between 7:00-11:00 and 17:00-19:00 when many people heat their homes and water upon returning from work. This indicates that UK power stations would need to increase their capacity to meet the heightened demand.

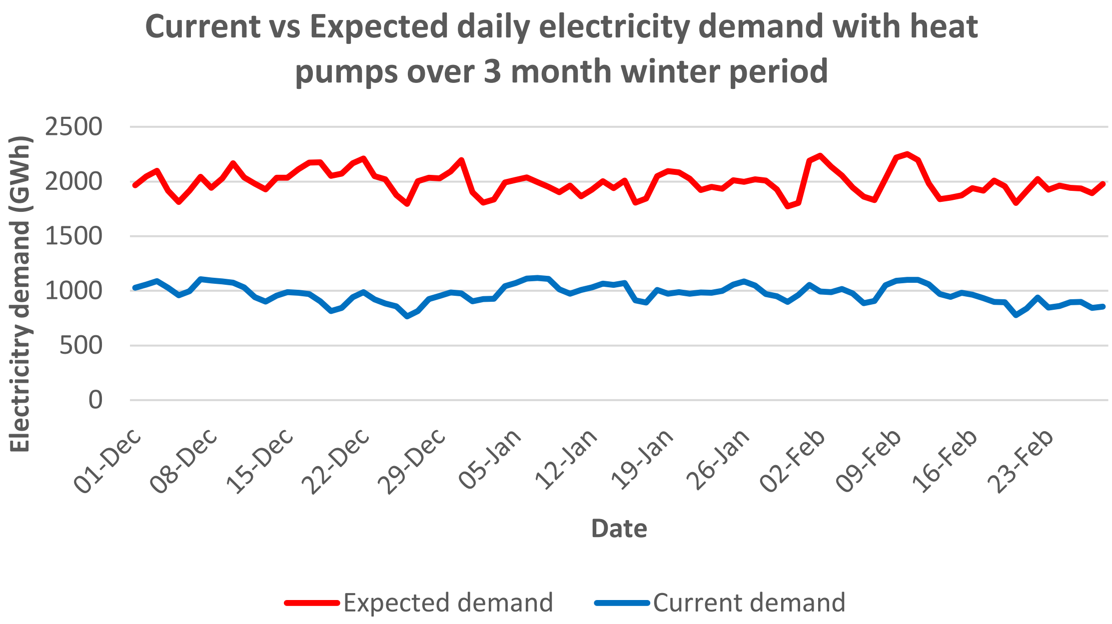


Figure 5. 31 *- The electricity demand comparison for the period between 1st December – 28th February between current use and expected demands using heat pumps.*

Figure 5.31 further explores the implications of ASHP deployment by showing the expected demand increase over the three-month winter period. The simulation predicts that average daily energy consumption could increase by approximately 106%, underscoring the need for strategic planning and infrastructure upgrades to support this transition.

5.5. Summary

The Simulink simulation analysis provided critical insights into the performance and implications of ASHP deployment across different house types, insulation levels, and geographical locations. The model validation confirmed the reliability of the simulations, which revealed that insulation significantly impacts heating and power demands. The study also highlighted the substantial grid impact of widespread ASHP adoption, suggesting that while ASHPs offer a viable low-carbon heating solution, careful planning and investment in grid infrastructure are necessary to accommodate the increased energy demands.

6. User experience in using heat pumps – Two case studies

6.1. Introduction

This chapter will highlight two case studies of two households using air source heat pumps as the main source of heat in winter (Figure 6.1). The two case studies will investigate experimentally as well as via discussion and interviews with the households the benefit of the heat pumps the energy savings or carbon savings, cost, and dissatisfaction of heating process in winter. The decision to employ different monitoring periods and timescales for Participant A and Participant B can be justified by the fact that these are two separate case studies with distinct goals: one focusing on the operational performance of an ASHP under extreme winter conditions, and the other concentrating on thermal comfort in a house during a transitional weather period. De Rear and Brager (2001), suggest that the use of different timescales and periods for monitoring supports the idea that thermal comfort data must be gathered over time to capture adaptive responses to changing environmental conditions.

Figure 6. 1 *– Case study 1 and case study 2 dwellings (exact address is kept anonymous).*

6.2. Case Study 1 (Participant A): ASHP Performance in Semi-Detached Housing

This section details the findings from the first case study, focusing on a semi-detached house (Figure 6.2) equipped with an air-to-air heat pump, located in Nottingham. The sensors monitored indoor and outdoor temperature (Figure 6.3).

Figure 6. 2 *- Case study 1 – Participant's house*

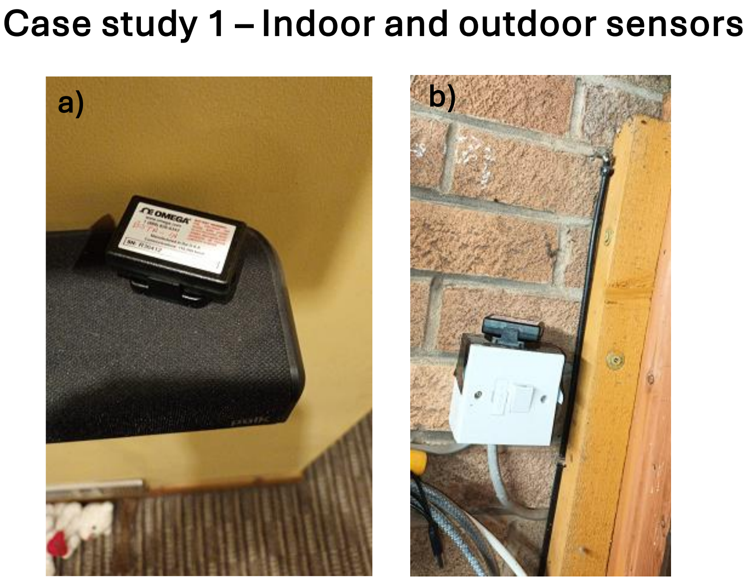


Figure 6. 3 *– Indoor (a) and outdoor (b) temperature sensor, respectively*

6.2.1. System Performance

Participant-A has an air-to-air heat pump which is part of the heating system but still uses gas. When the ambient temperature drop below 0°C they shut off the HP and rely solely on their gas boiler for heating (please see Table 6.2 and Chapter 6.3). After retrieving the measurements from the power meter, the maximum and minimum power usage by the heat pump was revealed along with the total electricity usage for the period of 1st December 2023 and 2nd February 2024 (Please see Table 6.1 and Figure 6.2). The power meter also revealed that the total operation of the heat pump was 26 days (Figure 6.4), suggesting that the unit was not use throughout the time. Hence, indicating some limitations in using the ASHP in winter for this type of house.

Table 6. 1 *- Power meter measurements from Participant A's heat pump.*

Measurement	**Value**
Minimum power usage	0.9 W
Maximum power usage	1583 W
Total electricity consumed	291 kWh

Figure 6. 4 *– Participant A's heat pump power measurements.*

6.2.2. Thermal comfort

The total monitoring period of the thermal comfort of Participant A's house was between 1st December 2023 and 2nd February 2024. Chapter 3.3 describes the details of how data was collected. Figure 6.6 reveals the temperature fluctuation of Participant A's house throughout the monitoring period.

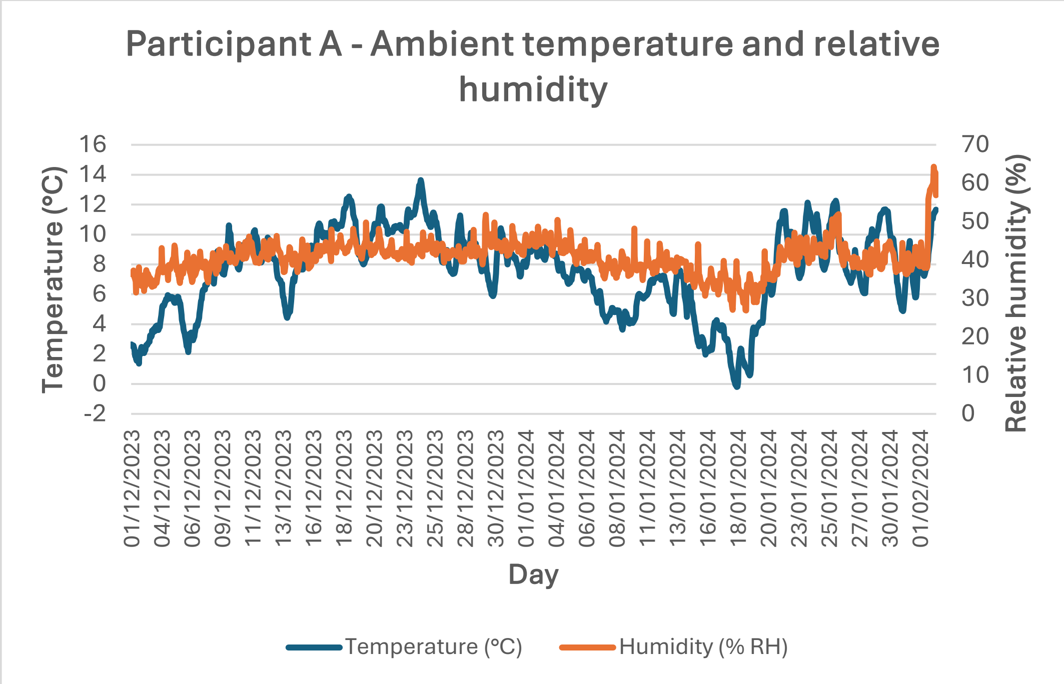


Figure 6. 5 *– Temperature fluctuation at Participant A's house.*

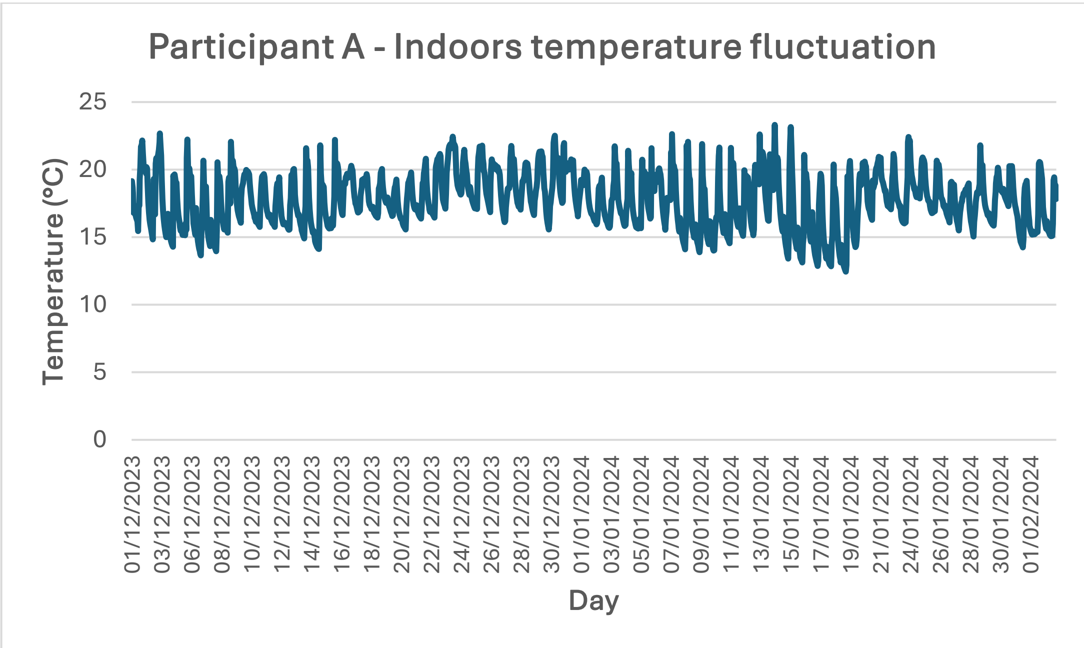


Figure 6. 6 *– Temperature fluctuation at Participant A's house.*

Figures 6.5 and 6.6 showcase temperature fluctuation at Participant A's household (both indoors and outdoors) throughout the monitoring period. It can be noted that the temperature has been relatively stable even though the heat pump was not operational throughout the time. This data suggests and confirms A's experience that they use their gas boiler when it gets cold so they can maintain their thermal comfort at their house.

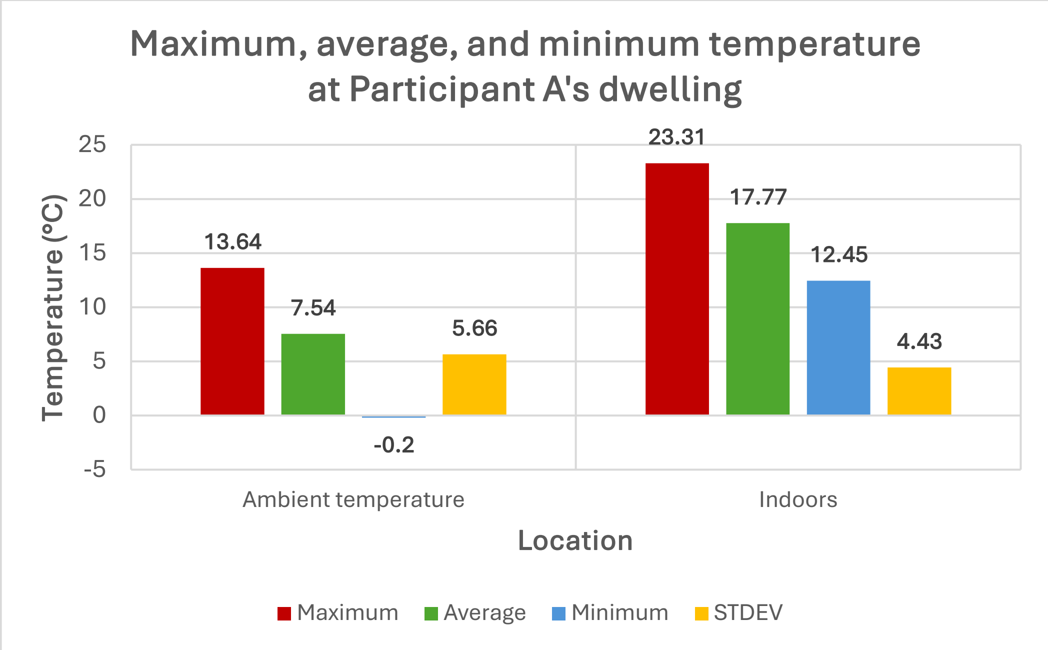


Figure 6. 7 *– Maximum, average, and minimum temperature at Participant A's dwelling.*

The ambient temperature (Figure 6.7) shows a standard deviation of 5.66, indicating a fairly high variability in temperature readings. The temperatures range from -0.2°C to 13.64°C could account for that high variability. This variability is expected in an outdoor or less controlled environment and does not directly impact indoor comfort. However, high variability in ambient temperature suggests that the heating system may have to work harder to maintain stable indoor conditions, especially during colder periods when the temperature drops below freezing.

From Figure 6.6 it can be noted that inside the house has a standard deviation of 4.43, with temperatures ranging from 12.45°C to 23.31°C and an average of 17.77°C. A standard deviation of 4.43 indicates moderate variability. This suggests that while the lounge maintains a generally comfortable average temperature, there are fluctuations that may occasionally move outside the optimal comfort range. The variability could lead to times when the lounge feels too cool or slightly too warm, affecting the consistency of thermal comfort.

The lounge has a moderate level of variability (4.43), which suggests it may occasionally experience conditions that are not ideal for comfort but overall maintains a reasonably steady thermal environment. To improve thermal comfort, reducing variability in areas with higher standard deviations, such as near the indoor heat exchanger, would be beneficial. This could involve better control mechanisms, adjustments to heat distribution, or insulating these areas more effectively to buffer against rapid temperature changes. The period between 1st December 2023 and 2nd February 2024 was chosen to assess how the ASHP performs in the coldest part of the winter, where external temperatures drop significantly, especially below 0°C. This allows researchers to investigate the limitations of ASHP technology in such conditions, particularly its efficiency and operational characteristics when temperatures fall to levels that might reduce its performance, necessitating a switch to the gas boiler.

6.3 Case Study 2 (Participant B): ASHP Performance in Detached Housing

The second case study involves a detached house located in Brownhills, equipped with an air-to-water heat pump (Figure 6.8).

Figure 6. 8 *– Case study 2, Participant's house*

6.3.1. Energy Consumption and Heating Output

Participant B shared in the interview that their winter heat output by the heat pump averages between 600 and 1000 kWh/month. According to the energy consumption details and their energy consumption is around 400 and 750 kWh/month.

***Figure 6. 9** – Participant B's energy consumption and heat output throughout the monitoring period.*

Figure 6.9 showcases Participant B's energy consumption and heat usage during the monitoring period (between 15th February and 31st March 2024).

6.3.2. Thermal comfort

The total monitoring period of the thermal comfort of Participant B's house was between 15th February 2024 and 20th March 2024. Chapter 3.3 describes the details of how data was collected. Figure 6.10 showcases the ambient temperature and humidity fluctuation throughout the monitoring period for the case study of house B. Figure 6.11 reveals the temperature fluctuation of Participant B's house throughout the monitoring period.

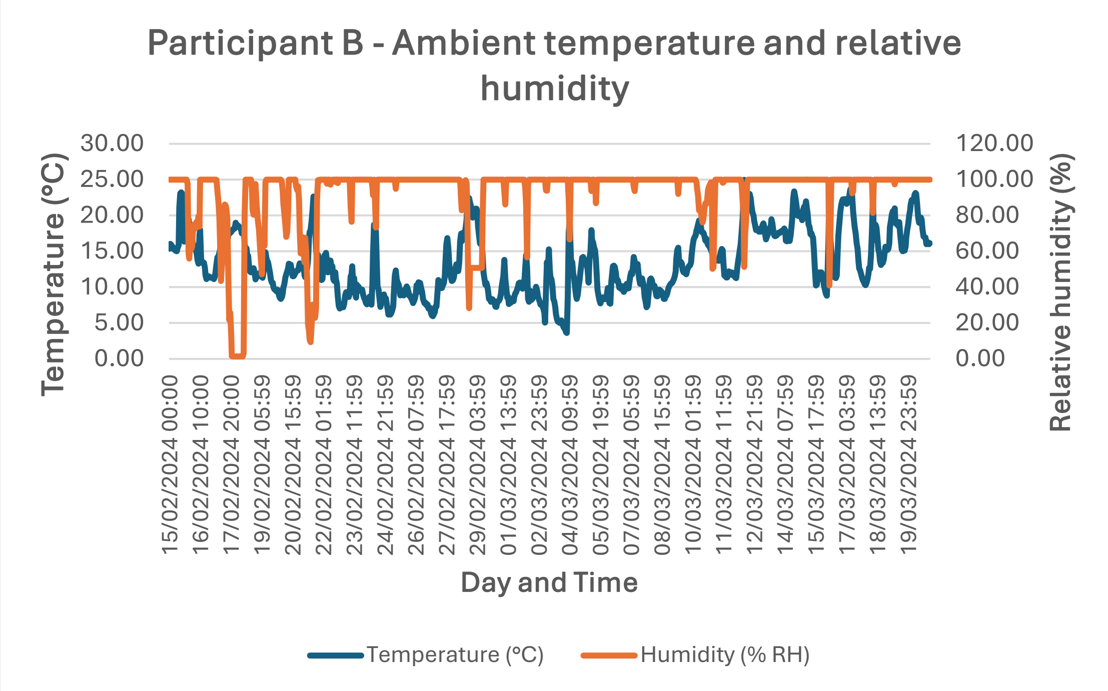


***Figure 6. 10** – Temperature fluctuation at Participant B's house* (outdoors).

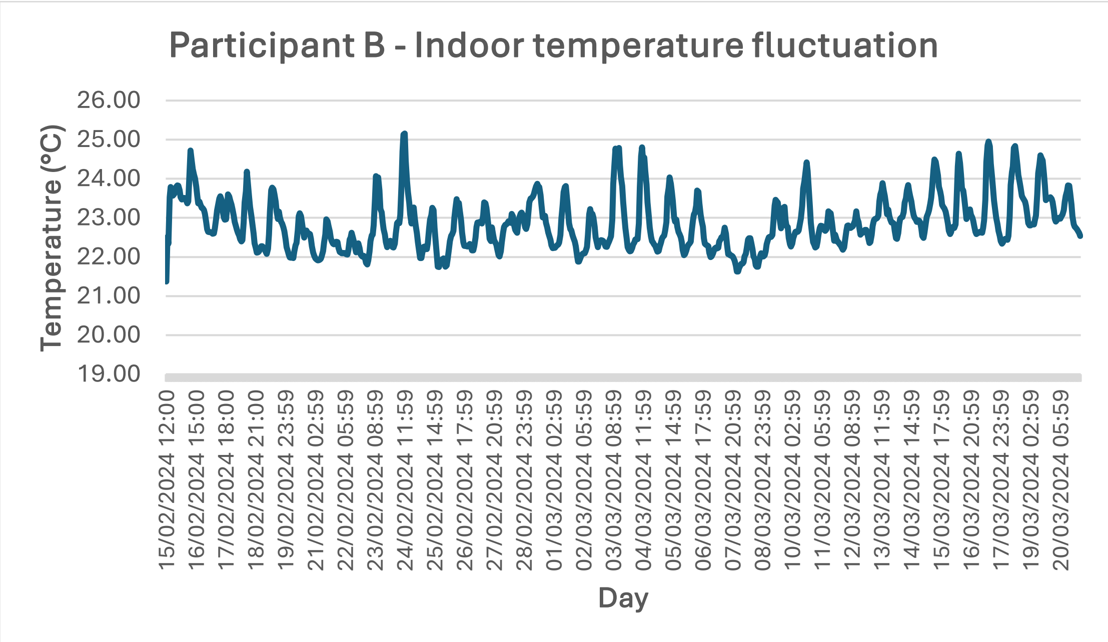


***Figure 6. 11** – Temperature fluctuation at Participant B's house* (indoors).

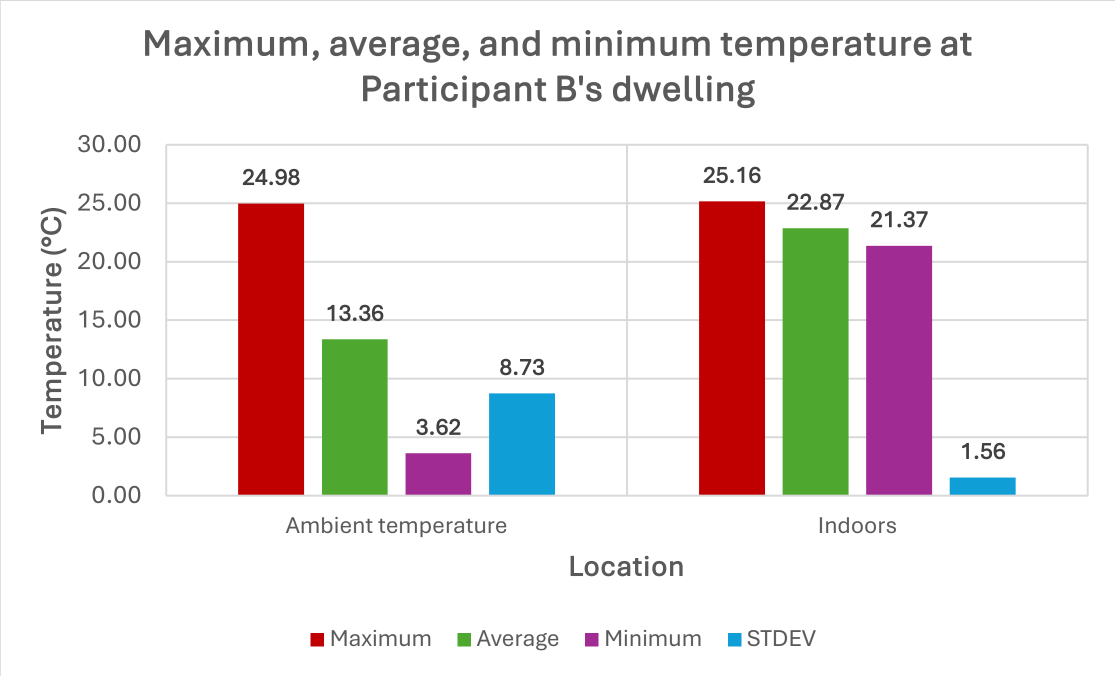


***Figure 6. 12** – Maximum, average, and minimum temperature at Participant A's dwelling.*

The ambient temperature sensor (Figure 6.12) has the highest standard deviation of 8.73, which indicates a large variability in temperature readings. This suggests that the ambient temperature outside or in a less controlled environment fluctuates significantly, ranging from as low as 3.62°C to as high as 24.98°C. High variability in ambient temperature may affect the overall heating demands inside the house but does not directly affect indoor thermal comfort.

Inside the house of Participant B has a standard deviation of 1.56, with temperatures ranging from 21.37°C to 25.16°C, and an average temperature of 22.87°C.

This level of variability suggests that the temperature is stable indoors with very little fluctuations. This would suggest that exterior and interior insulation could play a crucial role at maintaining a constant temperature indoors. Even though the heat pump in Case study 2 is undersized, having night storage device helps maintaining thermal comfort indoors.

Figure 6. 13 *– Infrared image of the house exterior showing excellent insulation level (case study 2).*

Figure 6.13 showcases an infrared image of Participant B's house exterior.

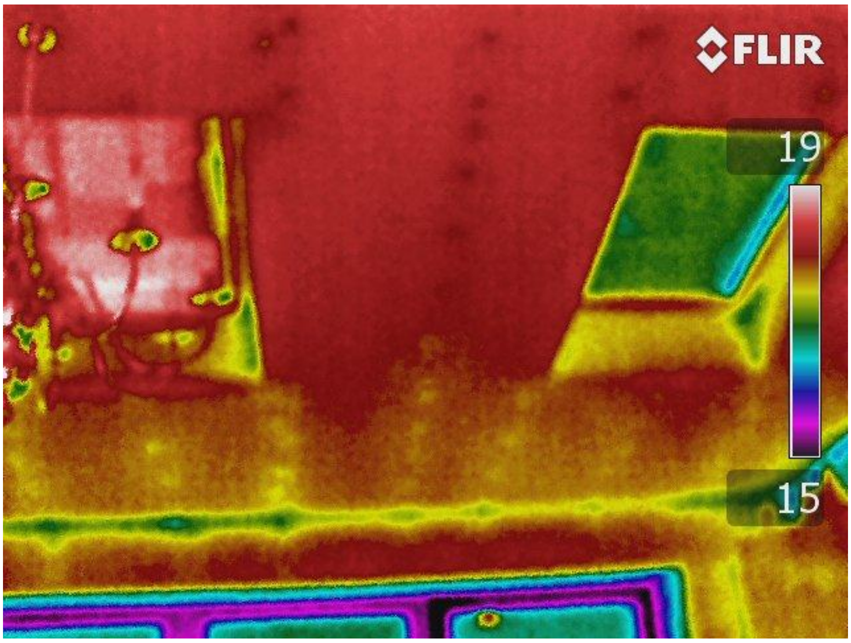


Figure 6. 14 *– Infrared image of the house interior – living room roof (case study 2).*

Figure 6.14 showcases that thermal energy is maintained within the house with very little heat losses. Interior and exterior insulation helps to maintain a thermal comfort inside the house as shown in figures 6.13 and 6.14. Due to thermal bridges at corners, there is very little presence of heat losses inside the house.

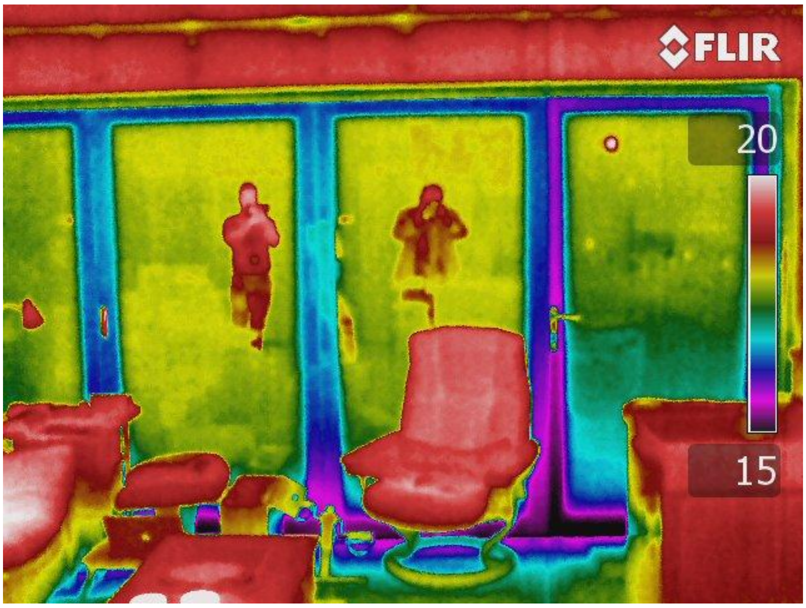


Figure 6. 15 *– Infrared image of the house interior – living room garden door (case study 2).*

Figure 6.15 showcases the level of heat losses through the windows and doors. Participant B has double-glazed windows.

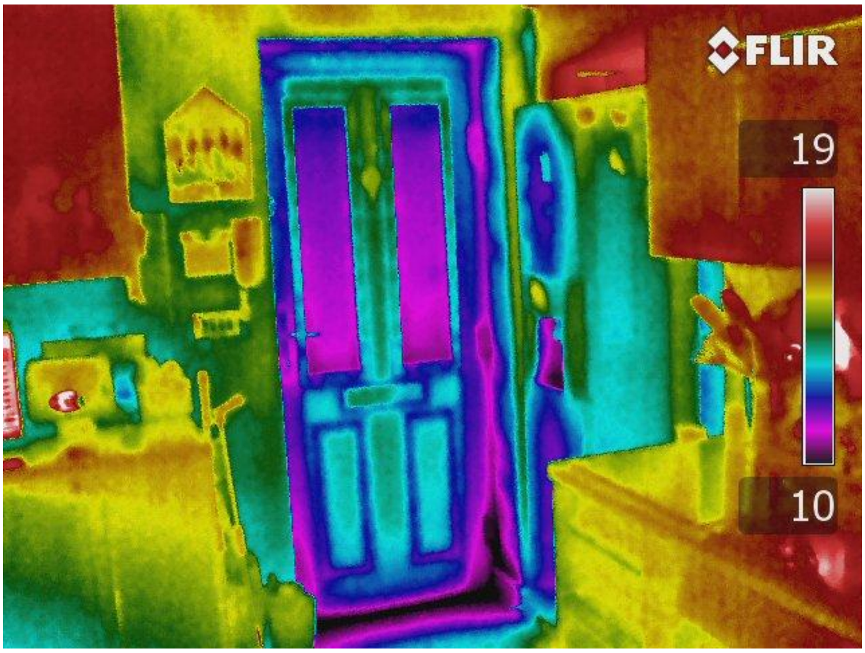


Figure 6. 16 *– Infrared image of the house interior – kitchen side door (case study 2).*

Figure 6.16 showcases the heat losses through a side door. Due to low quality door sealing, a cold draft from the outside causes small heat leaks in that area.

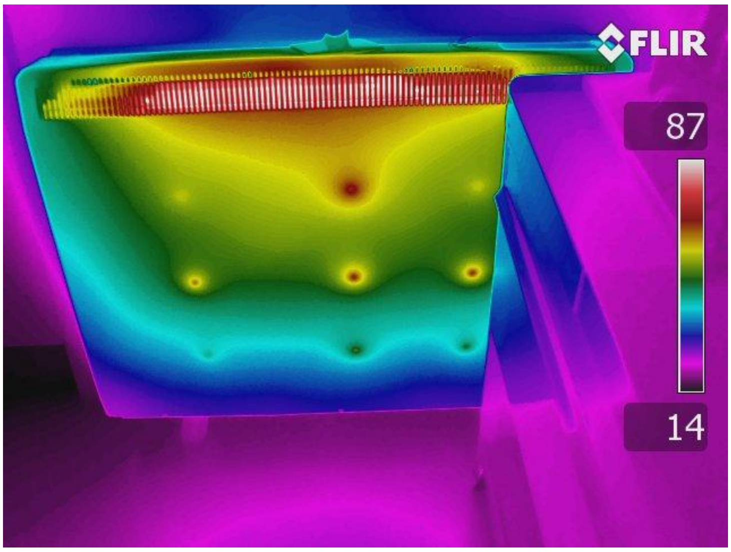


Figure 6. 17 *– Infrared image of the house interior – night storage (case study 2).*

Figure 6.17 represents the night storage in the living room ejecting heat during the day, helping the household maintain a thermal comfort indoors.

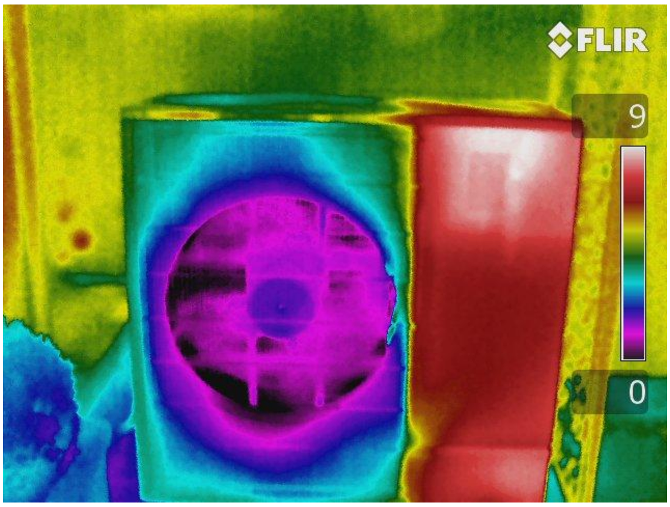


Figure 6. 18 *– Infrared image of the house interior – night storage (case study 2).*

Figure 6.18 showcases an infrared image of the outdoor heat exchanger at participant B's house. It is visible that the fan blows cold air. The right-hand section from the fan is where the compressor is located increasing slightly the temperature around this area.

The period between 15th February 2024 and 20th March 2024 likely reflects a transitional phase between winter and spring, when the heating demand is lower but fluctuating. This period is ideal for monitoring thermal comfort, as it provides data on how well a house maintains internal temperature and humidity in changing conditions. As external temperatures rise, it's important to understand how a house retains heat and how comfortable it remains without heavy reliance on heating systems.

6.4. Thematic Analysis of Interviews

A thematic analysis of the interviews conducted with the ASHP owners from both case studies was performed to identify key themes and insights. Table 6.2 summarise the findings from both interviews and compares the participants' answers from each identified theme.

Table 6. 2 *- Interviews' outcome from both participants.*

Question	Participant A	Participant B
Type of house	Semi-detached	Detached
House insulation	Double-glazed windows; insulated loft; No wall insulation; Cavity walls	Wall insulation, double glazed windows
Type of HP	Air-to-air; 3.5kW AC wall mount split system	Air-to-water; space and water heating; low temperature 40-50; 8.5 kW instead of 12kW wrong calculations from engineers
Installation of HP before or after insulation	After	Before
Installation before or after energy price increase	Just before	At price increase
Change in energy bills	Gas consumption 85% down; electricity 12% up	Not big difference in electricity price; more expensive in winter. (Participant B, 2024)
Insulation effect	HP part of heating system, still uses gas	Significant change in thermal comfort (better or worse)
HP performance in cold weather	Not in used under freezing conditions	COP around 1.50 in cold weather.
HP enough to provide space/how water heating	Space heating only; combined with gas when ambient temperatures drop considerably	Both; 2 Night storage units required; They are charged at night - night energy rate is lower (Economy 7 - 7p/kWh as of February 2024)
Reason to use/switch to HP	More options to heat their home	Health issues - asthma; to be more sustainable; reduce energy bills (which did not work due to price increase).
Right choice?	Cold weather affects the performance; frost makes it inefficient	Nice weather + solar PV no increase in energy bills; in cold weather COP is less than 2
HP part of incentive	No	Yes, but due to delay he got 5000 instead of 8000 GBP

6.5. Comparative Insights from Interviews

6.5.1. Common Themes

Both interviewees shared their experience in using air source heat pumps in cold weather. Both agreed that the units do not provide sufficient heating in winter.

"After the temperature drop too much, I shut of the heat pump and use gas only" – Interviewee A.

"An engineer made calculations on a 12.5 kW heat pump size; however, the installed unit is of 8.5 kW which is not sufficient for our house" – Interviewee B.

Participant A explained that they combine their HP with a gas boiler to satisfy their thermal comfort, and if ambient temperature drops below freezing, they turn of their heat pump. Participant B has a low-temperature air-to-water heat pump at a rated heat capacity of 8.5 kW. The actual required rated capacity was supposed to be 12.5 kW, but due to wrong calculations made from engineers they ended up having the lower capacity unit. Because of that and the fact that their thermal storage is a small one for their house (210 L; not stratified), Participant B has two night storage units to provide additional heating.

"I decided to install two night storage units in the house and charge them at night. One of the benefits of Economy 7" – Interviewee B.

One unit is located in their living room and another one in one of the bedrooms. As Participant B is on Economy 7 energy plan, they pay a rate of 7 p/kWh for the off-peak. This gives them the opportunity to charge the night storage devices at night and use the accumulated heat during the day when the energy price is higher. Their heat pump efficiency averages around 1.5 in cold weather. Both participants have put an effort to improve their houses' insulation. Both have double-glazed windows. Participant A has an insulated loft, whereas participant B has both internal and external wall insulation.

> *"The moment we had our external wall insulation, there was a significant change in the thermal comfort in our house. It finally felt warm" – Interviewee B.*
>
> *"We have cavity walls and if we install exterior wall insulation this may increase the dampness inside the house" – Interviewee A.*

6.5.2. Divergent Views

While both interviewees have common views in using a heat pump, there are some divergent points in their experience. Particularly, Participant B applied for an incentive to have their HP installed, whereas Participant A had no financial support for that. Interviewee A had their heat pump installed to have more options to heat their home, whereas B completely removed any fossil fuel sources from their house due to health issues.

> *"I just wanted to have more options how I can heat my home" – Interviewee A.*

> *"Because of my wife's condition, we decided to remove any fossil fuel from our house. No gas, no conventional cars" – Interviewee B.*

Beside the HP, Participant B is also driving an electric vehicle. Another reason for B to switch to a heat pump was to be more sustainable and to reduce their energy bills. Participant A shared that they had installed their heat pump after they insulated their house and just before the energy price increase, which decreased their gas consumption by 85% but electricity usage increased by 12%. However, the experience of Participant B was different, they had their HP installed before they had external insulation and their thermal comfort was not satisfied, sharing their house was very cold. In addition, their heat pump was installed after the energy price increased which led to higher energy bills at the beginning. After B insulated their house, they shared that there was a significant positive difference, especially with the underfloor heating they have. Additionally, Participant B has solar panels that he said help them to further power his house and HP. B also has an electric vehicle that has a rated range of 190 miles, but they shared the actual range is around 160 miles. At winter this could go down to 110 due to the car heating which depleted the battery further. This further supports the findings from Milev et al. (2021) that at winter because of the vehicles heater the range can drop by approximately 30%. However, Participant B said that even though some changes were required to better plan their trips with the EV, it did not affect their day-to-day life as much.

> *"We want to be more sustainable and also to make our home a better place for my wife" – Interviewee B.*

> *"Switching to an electric car requires some changes in our habits and planning in regards to the trips we make. Yes, range can drop at winter, however, it did not affect my daily life and habits" – Interviewee B.*

According to Figures 6.4 and 6.8, Participant A's heat pump has consumed less energy than Participant B, even though A's HP has been monitored for a longer period of time. One of the reasons for that is the lower capacity of A's heat pump and also because their unit has not been on throughout the time. Additionally, gas was also used in A's house. Whereas with Participant B's case, they have higher capacity heat pump, and it is used primarily to provide heating, with some additional help from the night storage units.

6.6. Summary

This Chapter has shown some limitations in using ASHP in two case studies. These include reduced operational efficiency, thermal comfort variability, and impact on installation timing. Participant A relied on their gas boiler when temperatures dropped below 0°C, indicating that the air-to-air heat pump was ineffective in providing adequate heating in colder conditions. The heat pump operated for only 26 days out of the monitored period, suggesting limited utility during peak winter conditions. Participant B faced issues due to their heat pump being undersized (rated at 8.5 kW instead of the required 12.5 kW), which compromised its heating capacity. This necessitated the use of additional night storage heaters to meet thermal comfort needs. Both participants reported fluctuations in indoor temperatures, affecting comfort levels. For Participant A, the indoor temperature ranged significantly, leading to periods of discomfort. In contrast, Participant B achieved a more stable indoor temperature, but their reliance on additional heating sources underscored the limitations of the heat pump alone. The timing of insulation and heat pump installation played a crucial role in performance. Participant A installed their ASHP after improving their insulation, while Participant B's installation preceded significant insulation upgrades, leading to initial dissatisfaction with thermal comfort. Some of the main challenges still are cold weather performance, integration with existing heating systems, installation and capacity issues, and economic viability. A significant challenge identified in both case studies is the reduced efficiency of ASHPs in cold weather. Both households experienced limitations in heat output during lower ambient temperatures, which impacted their reliance on these systems for consistent heating. Both participants still relied on supplemental heating (gas boiler for A and night storage units for B), suggesting that ASHPs alone may not be sufficient to meet heating demands, particularly in colder climates. Incorrect calculations and undersized units were critical challenges, as seen with Participant B. This not only affected heating efficiency but also led to higher energy bills and discomfort. The rising energy costs and the initial financial burden of installation without sufficient incentives (as noted by Participant A) present barriers to adopting ASHP technology more widely.

While ASHPs offer potential benefits in terms of energy and carbon savings, their performance is limited in cold weather, often necessitating supplemental heating solutions. The need for proper sizing, timely installation alongside insulation upgrades, and considerations of economic viability are crucial for improving user satisfaction and system efficiency.

7. Public engagement and awareness in using heat pumps

7.1. Introduction

This chapter implement a survey with a quantitative and quantitative analysis to explore public engagement and awareness of heat pump technology and the challenges and opportunities that heat pumps form towards Net Zero and low carbon heating technology.

7.2. Awareness, Preferences and Perceptions of HPs vs. Gas Boilers

The homeowner questionnaire aimed to understand public awareness of heat pumps along with preferences and perceptions of HP users compared to traditional gas boilers among UK homeowners. The survey gathered responses from 175 participants, providing insights into the factors influencing heating system choices and the barriers to ASHP adoption. A sample size in the range of 171 can be sufficient to achieve reasonable statistical confidence level for 8% margin error, , particularly if the goal is to identify general trends and perceptions rather than to detect small effect sizes (Morgan 2014). Gathering responses from 175 participants may represent a reasonable balance between the need for data and the practical limitations of survey distribution and response collection. The most common confidence level employed for a questionnaire is 95%. This level is the quantitative representation of uncertainty related to the collected data, which is collected from the data statistics. The margin of error is random sampling error's percentage which can occur. A reasonable margin of error between 6.5 and 7.5% is chosen for this research. With chosen confidence level and margin of error values, the sample size is between 171 and 228, calculated using normal distribution and z-score values.

7.2.1. Demographics

The survey took into consideration household characteristics that could have an impact on preferences to a heating method (e.g. heat pump, gas boiler, wood stove, etc.). These characteristics include but are not limited to demographics such as location, type of house, level of insulation, income, energy bills. These factors could contribute to people's awareness and preferences as to why they would or would not choose heat pump as an alternative to heat their home.

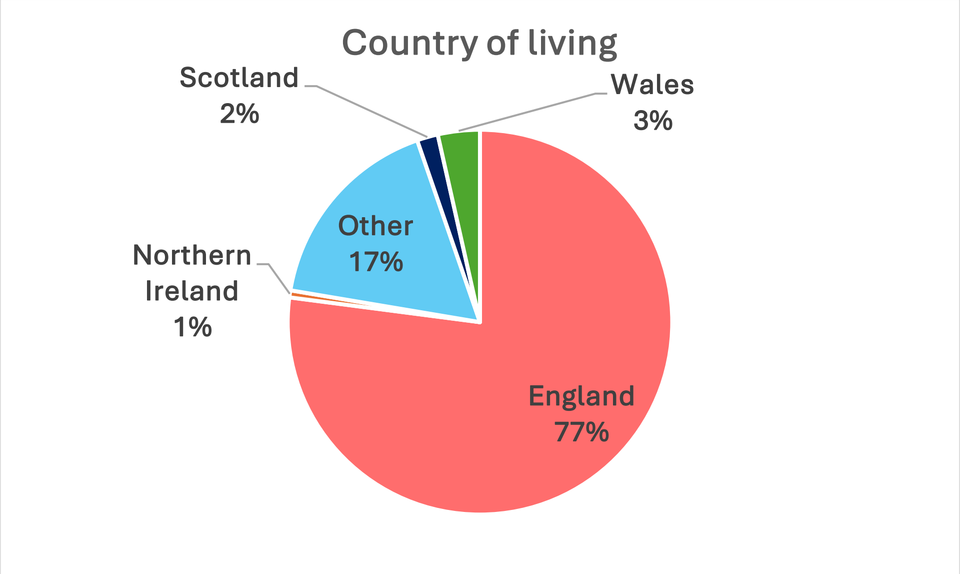


Figure 7. 1 *- Country of living among survey respondents.*

Figure 7.1 showcases that the majority of respondents (77%) live in England.

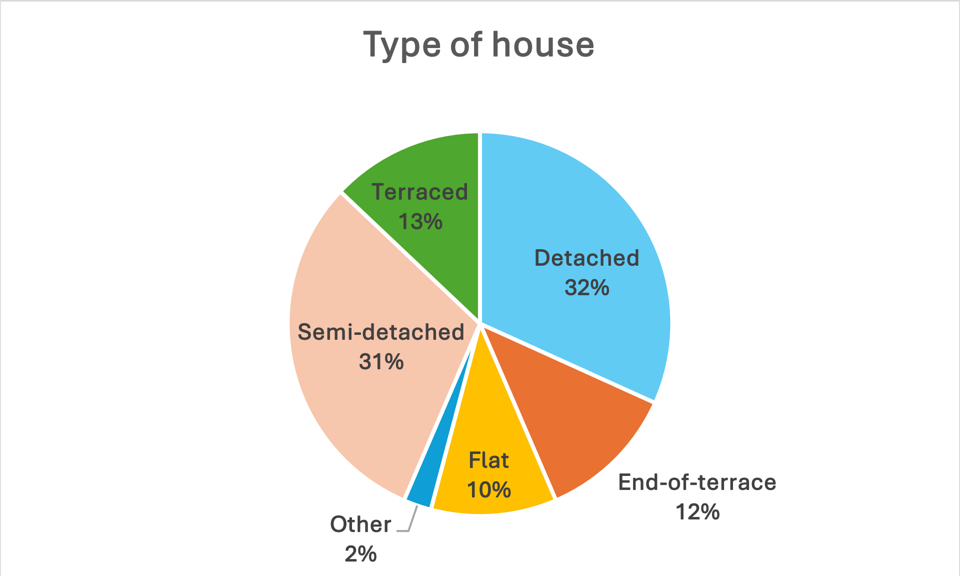


Figure 7. 2 *- Popular house types among survey respondents.*

Figure 7.2 represents the types of house and what percentage of people live in each type. From the figure 7.2 it can be noted that higher percentage of households live in detached and semi-detached houses.

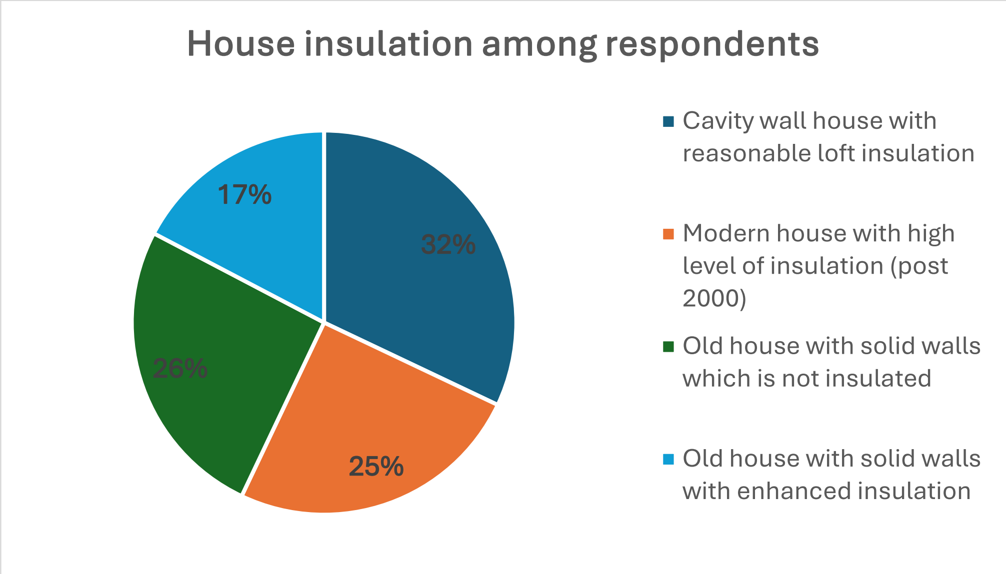


Figure 7. 3 *- House insulation among questionnaire respondents.*

Figure 7.3 represents the insulation level among participants' houses. According to the questionnaire, approximately a quarter of people (26%) live in old uninsulated house with soldi walls. Another quarter has modern housers with high level of insulation. Big portion of residents (32%) has cavity wall house with reasonable loft insulation.

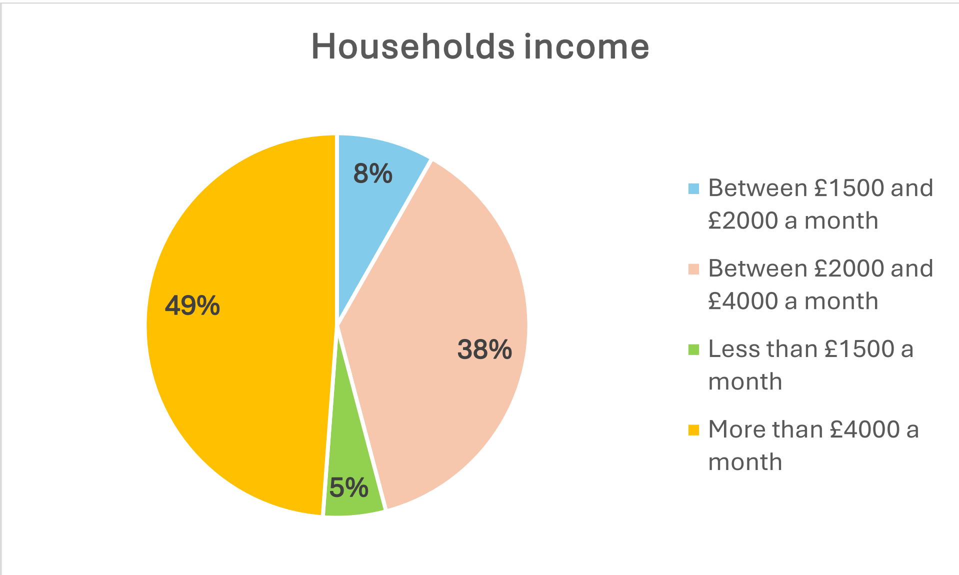


Figure 7. 4 *– Household income among survey respondents.*

Figure 7.4 showcases the monthly household income among participants. Almost half of respondents (49%) report that their income is more than £4000 a month, with 38% sharing their monthly income is between £2000 and £4000.

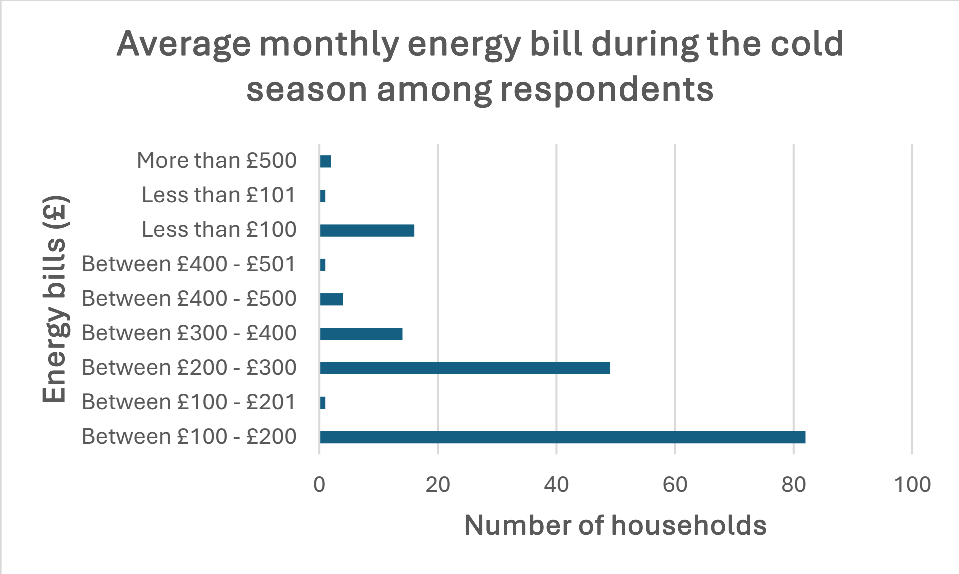


***Figure 7. 5** – Average monthly energy bills during the cold season among survey respondents.*

From figure 7.5 it can be noted that for most respondents the average monthly bills vary between £100 and £200, followed by approximately 50 respondents reporting approximately £200 and £300 per month.

After further analysis it can be determined if income and energy bills (Figures 7.4 and 7.5) play a role into people's awareness and preferences towards a heating method for their home. Additionally, house type and insulation level (Figures 7.2 and 7.3) may be crucial into preferring certain method to heat people's homes.

7.2.2. Awareness

To understand people's opinion and perceptions towards more sustainable heating alternatives and towards Net Zero 2050 plans first it was crucial to determine if respondents are familiar with the difference between heat pumps and gas boilers which is prevalent heating method in the UK (Statista, 2024).

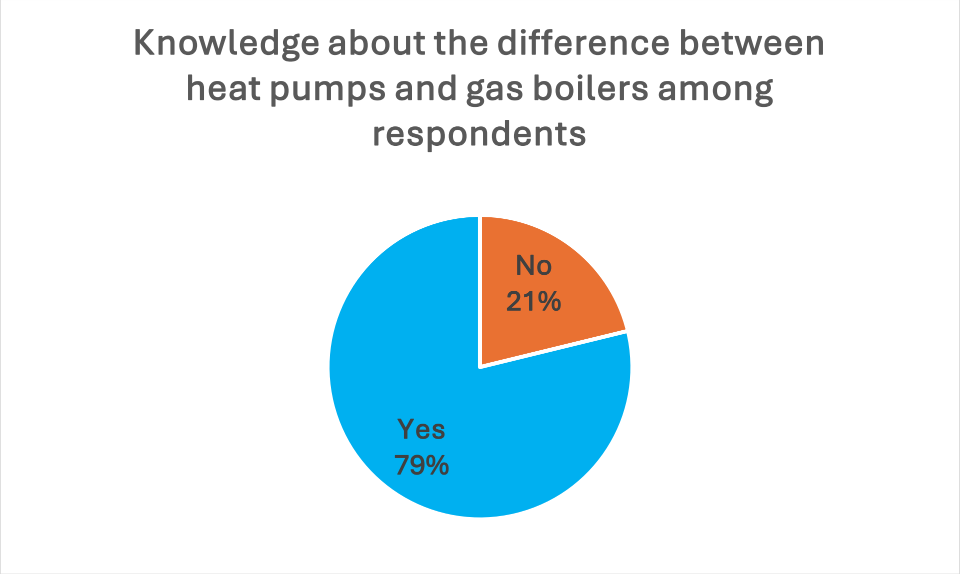


Figure 7. 6 *- Awareness about the differences between gas boilers and heat pumps among respondents.*

The majority of respondents report that they have knowledge about the difference between heat pumps and gas boilers (figure 7.6). This question was important to ensure that if people are not inclined to use heat pumps it is not because of lack of knowledge.

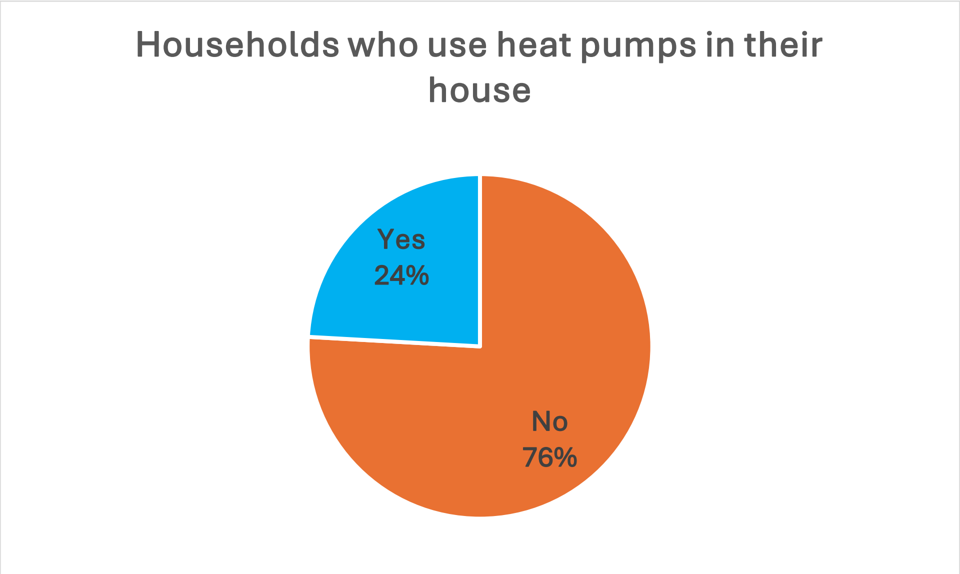


Figure 7. 7 *– Households who use heat pumps in their house*

Almost a quarter of participants (24%) report that they use heat pumps in their house. This figure (7.7) shows a slow adoption rate of HPs in the UK. This also supports the latest reports that the total installation of heat pumps in the UK at the moment is around 250,000 units (Heat Pumps Today, 2024). This is not close to the government's plan to reach installation numbers of 600,000 HPs by 2030 (Lyden et al., 2024).

Respondents were asked to openly describe the reasons why they chose to install heat pumps in their house. Some participants shared that they wanted to replace their old systems. Many people shared that they want to be more sustainable and greener switched to heat pumps:

"To lessen our environmental impact"

"It was a good opportunity to make the shift to sustainable heating"

"Want to 100% electrify to save climate"

"I would insist on a heat pump in my home to reduce energy use and minimize my contribution to climate change"

"To save energy and greener option"

These are among some of the open responses from the survey participants, desiring to be more sustainable and contribute to better climate.

Many people also shared that cost has also influenced their choice to switch to a heat pump in their home:

"Reduce cost and carbon footprint"

"The bedrooms had electric heat and the heat pump runs at a lowered cost"

"Much more comfortable, quitter, cheaper to run"

"Thought it may be cheaper to run!"

"Wanted to remove gas from house since there is a fixed fee for gas service"

"Price and price fluctuations of gas"

"Cheaper, gas free house"

From the open-ended answers, it is evident that cost of gas has influenced many participants to install a heat pump in their house.

Among the reasons to install a HP, people shared that they wanted to replace old heating systems:

"Have wanted to replace aging natural gas forced air furnace for a long time"

Gas furnace was old so we replaced it with a moder ducted heat pump to have both heating and cooling"

"Our home had and aging propane system"

"Gas boiler was 20yrs old. Inefficient."

Old and inefficient heating systems were also the reason to switch to a heat pumps among the survey participants.

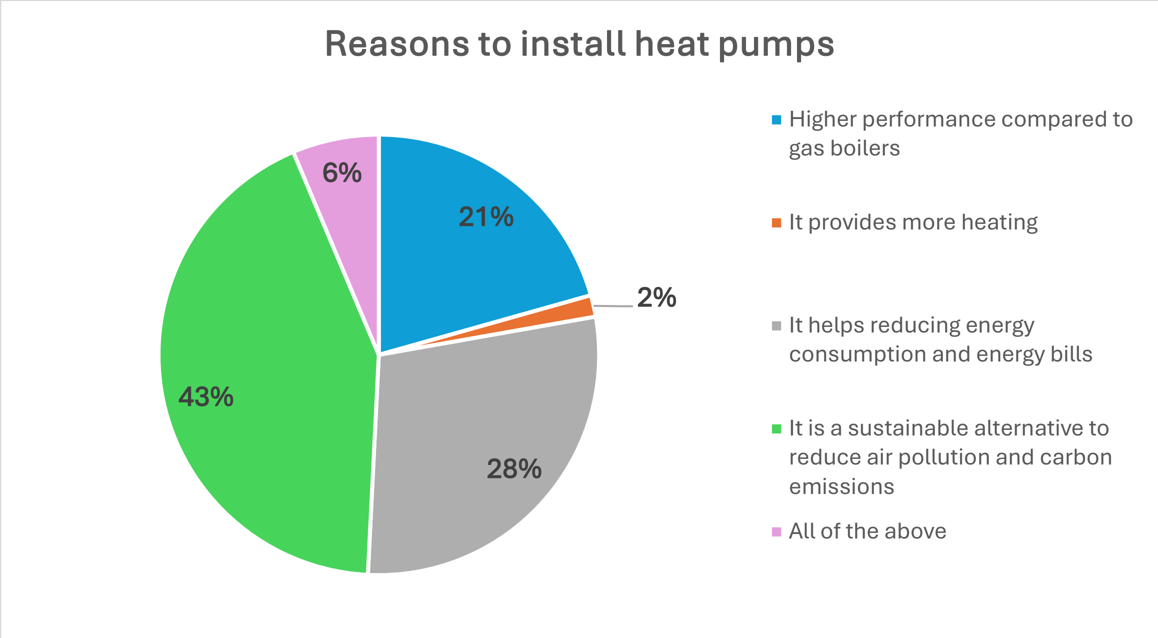


***Figure 7. 8** – Reasons to install heat pumps*

Figure 7.8 reflects the opinion of heat pump users as to why they switched to such alternative to heat their house.

7.2.3. Heat pump usage

From the survey, it was important to understand not only the reason why people decide to switch to a HP, but also what is their experience using such device and if it satisfies their heating demand and thermal comfort in cold weather.

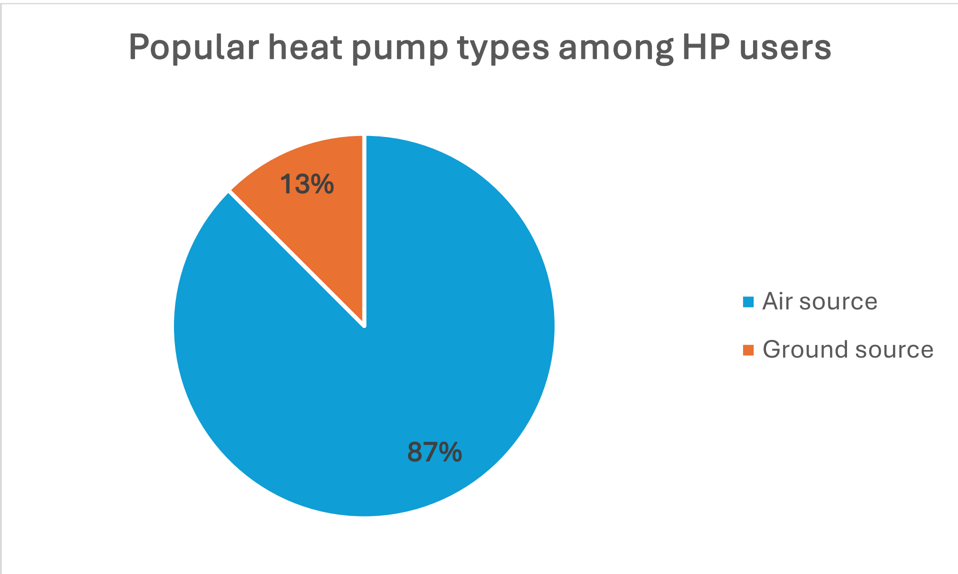


***Figure 7. 9** – Popular heat pump types among users*

First it was important to understand how many people use air source and ground source heat pumps. The majority of respondents (87%) report that they have ASHP in their home (Figure

7.9). This further supports the findings from Statista Research Department (2023), that air source HPs are more popular type among users.

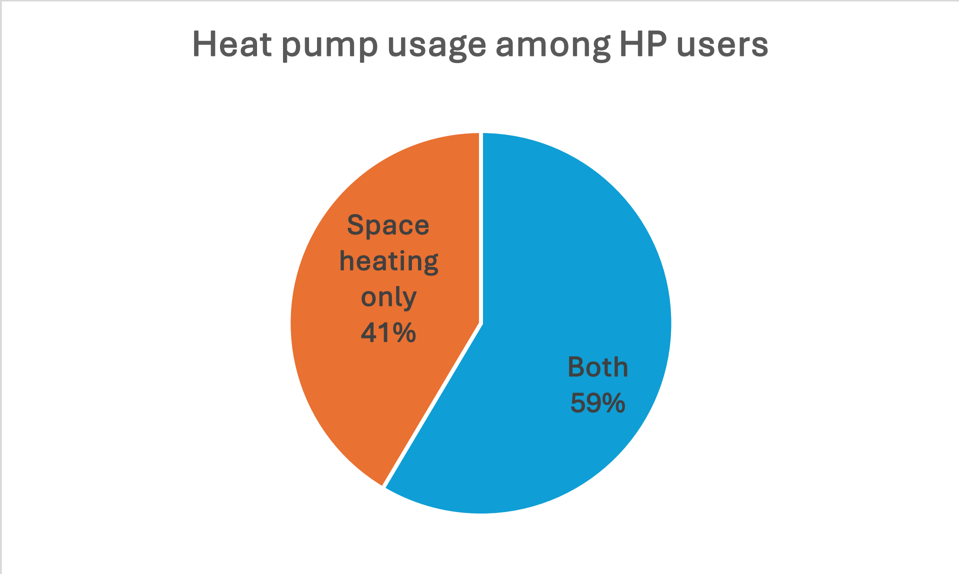


Figure 7. 10 *– Heat pump usage among users*

59% of respondents report that they use the heat pump for both space heating and hot water (figure 7.10).

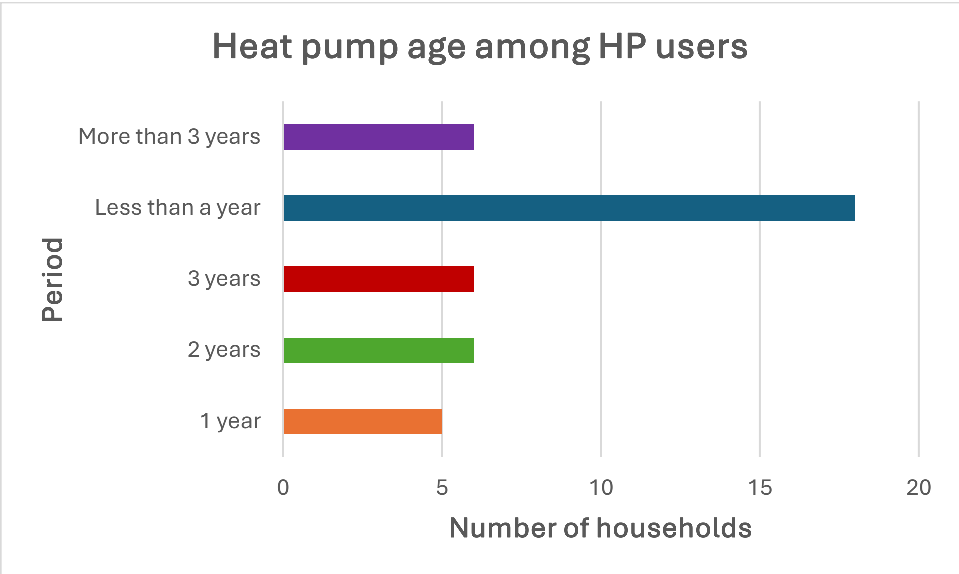


Figure 7. 11 *– Heat pump age among users*

Many of the heat pump users who took part in the questionnaire reported that their system is less than a year old. From the figure 7.11 findings it can be noted that most heat pumps are considerably new, with very few being more than 3 years old. This suggests that the adoption rate of heat pumps has very recently led to the current figures of 250,000 units (Heat Pumps Today, 2024).

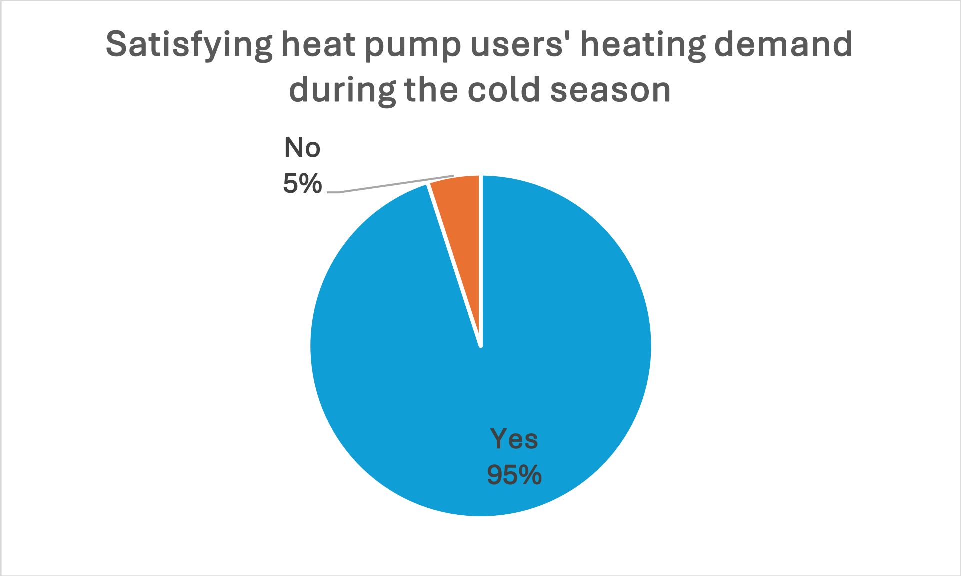


Figure 7. 12 *– Satisfaction of heating demand by users' heat pumps in cold weather.*

Majority (95%) of heat pump user who took part in the questionnaire report that their heating demand is satisfied (Figure 7.12).

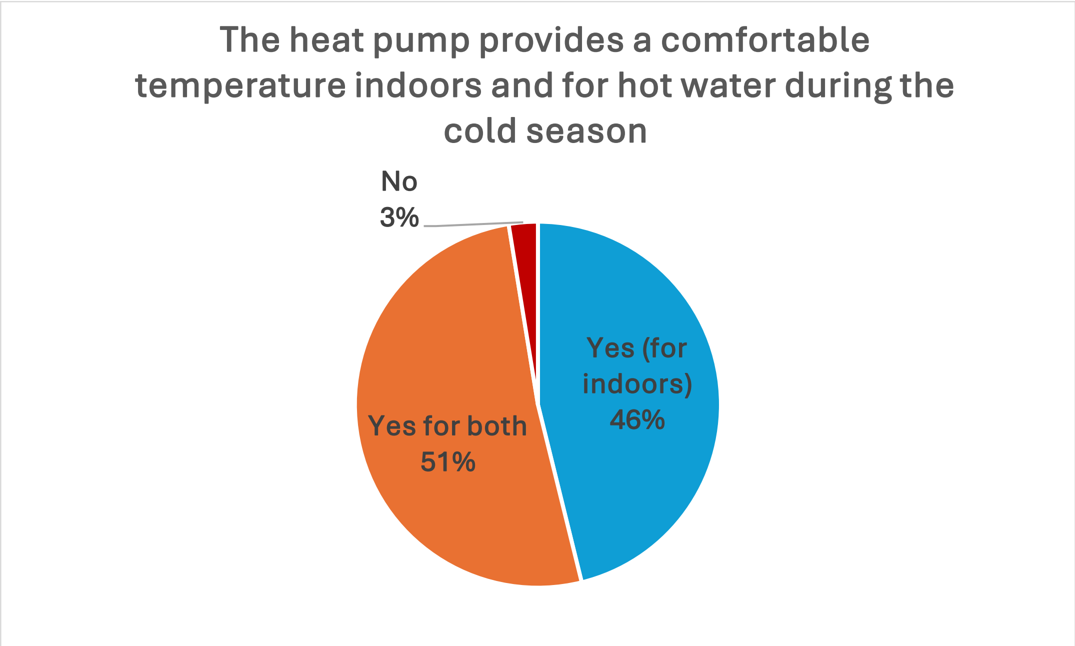


Figure 7. 13 *– Satisfaction of thermal comfort among heat pump users*

Among HP owners, almost half of them (51%) report that their device provides a comfortable temperature for both space heating and hot water. 46% share that their space heating is satisfied, suggesting that either their hot water temperature demand is not met or that their use air-to-air heat pump (figure 7.13).

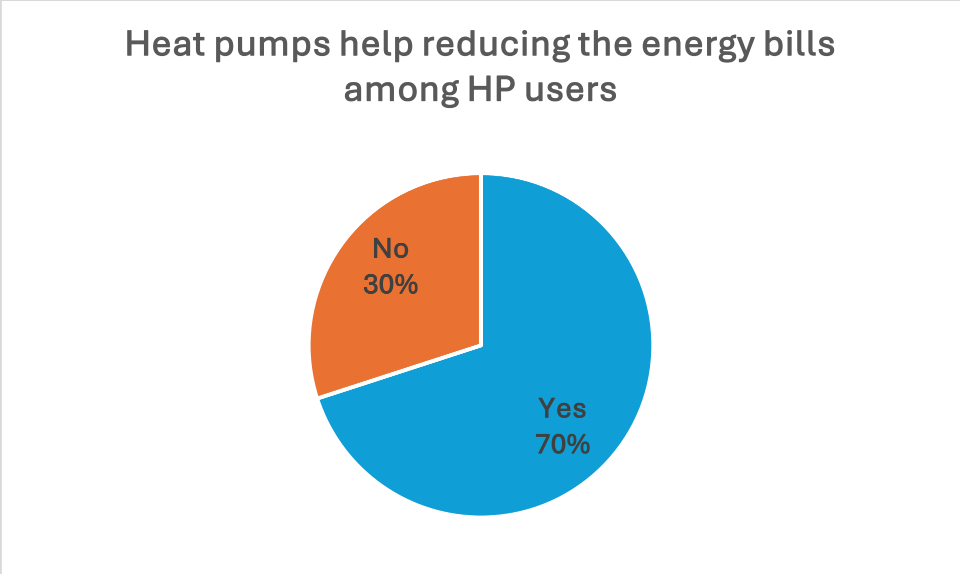


Figure 7. 14 *– Reduction of energy bills among heat pump users.*

More than half (70%) of heat pump users report that their device has helped reducing the energy bills (figure 7.14). This may suggest that not only their heating demand is satisfied but also that their system has high performance.

7.2.4. Financial factors

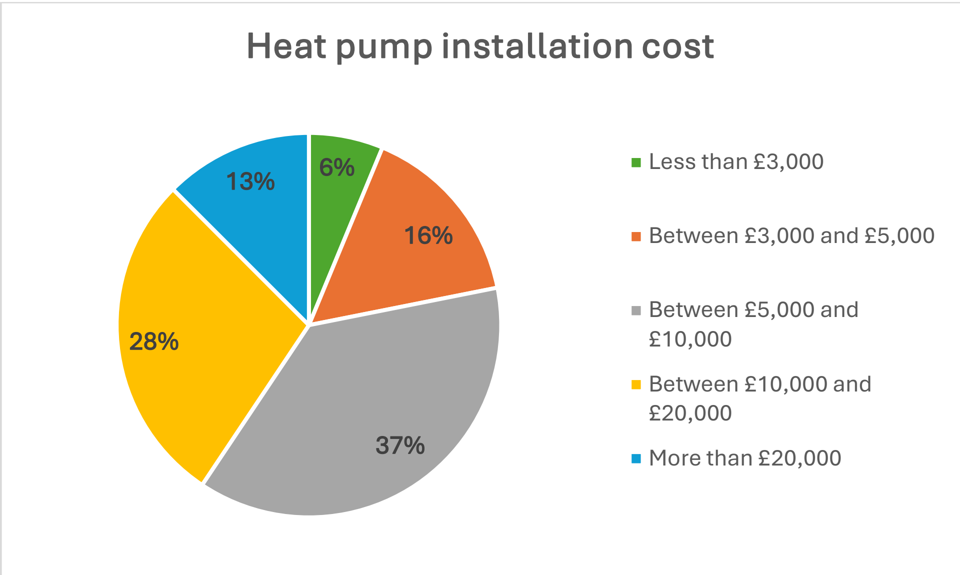


Figure 7. 15 *– Heat pump installation cost among HP users.*

Many heat pump users who took part in the questionnaire reported that their installation cost varied between £5,000 and £10,000 (37% of respondents). 28% of heat pump users shared that the price of the installation of their unit is between £10,000 and £20,000. Only among 22% of participants, the installation was less than £5,000 (figure 7.15). These findings suggest that the initial cost of heat pumps is higher than gas boilers as indicated by Myers et al. (2018). This may point out to the reasons for the slow adoption of heat pumps in the UK.

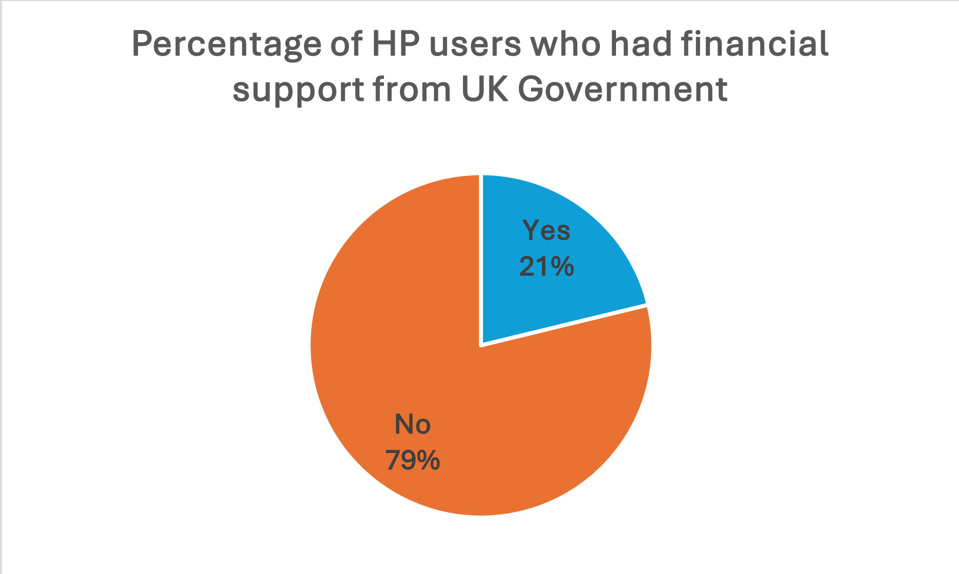


Figure 7. 16 *– Heat pump users who had financial support from the UK Government.*

Only 21% of heat pump users received a financial support from the government (figure 7.16). This may suggest why the financial burden of a new heat pump installation can be high for people who would like to swich from other heating methods.

7.2.5. Reasons not to install a heat pump

To further explore the perception of heat pumps among UK households, it was important to understand the reasons why HPs may not be a well-received alternative to gas pointing to the potential factors for the slow adoption rate.

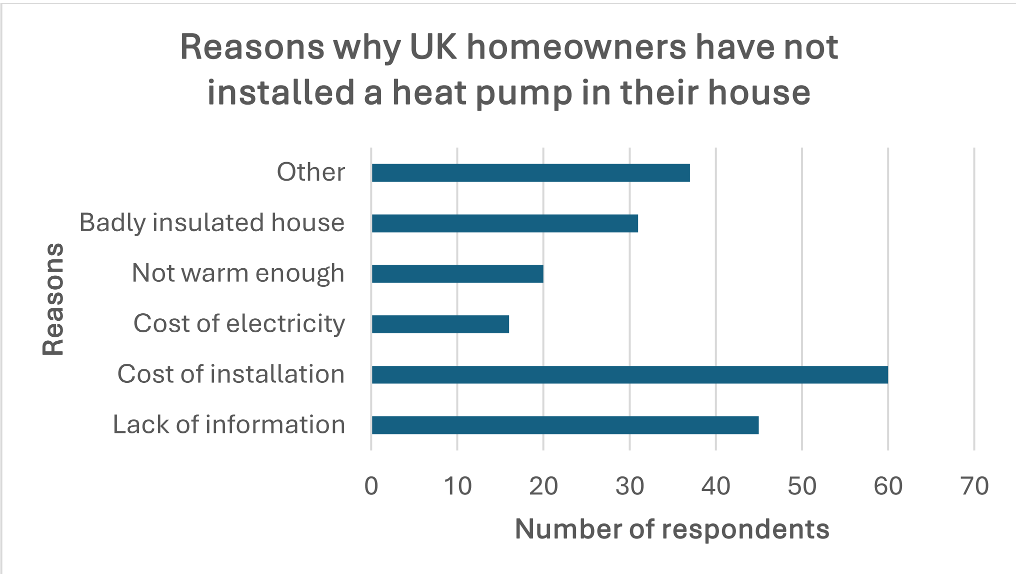


Figure 7. 17 *– Reasons why some UK homeowners have not installed heat pumps.*

When UK homeowners were asked why they have not installed a heat pump yet, many report that the cost of installation and lack of information are the main reasons to avoid this technology. Figure 7.17 further supports the findings from figure 7.15, suggesting that the initial cost of HPs is high, which may pose a big financial burden on UK homeowners, especially in the ongoing cost-of-living crisis. Another important reason why people have not considered installing a HP was because of bad insulation in their house. Insulation affects the heating demand and the energy consumption by the heat pump as explored in Chapter 5.

7.2.6. Key findings

- **Preference Trends**: The survey results indicate that 76% of respondents currently use gas boilers, while 24% have switched to HPs. Among those using heat pumps, shared the environmental benefits as a main reason to swich from fossil fuels (43%) and the potential energy bill savings (28%) as primary motivations. 41% of heat pump owners use their device for space heating only, and 59% for both space heating and hot water. The majority of respondents (87%) reported that they use air source heat pump in their house, confirming the findings from Statista Research Department (2023).
- **Barriers to Adoption**: Key barriers to HP adoption identified in the survey include high initial installation costs (29%), lack of information or awareness about heat pump technology (21%), and concerns about performance during colder weather because of bad insulation (15%).
- **Motivations for Switching**: For current heat pump users, the most cited reasons for adopting the technology are environmental benefits (43%). Among HP users, around 21% have been provided government incentives. Notably, 70% of heat pump respondents reported a decrease in their energy bills compared to their previous systems. The majority of HP users (44%) reported that they had their unit installed less than a year ago.

7.2.6.1. Satisfaction levels among heat pump users

The satisfaction levels among HP users were assessed to gauge their experiences with the technology in real-world conditions. The majority of heat pump users reported positive experiences, with 95% indicating their heating demand during cold weather is satisfied. Key factors contributing to satisfaction included comfortable temperature indoors (46%) and satisfactory thermal comfort for both indoors and hot water (51%). 3% of heat pump users report that their thermal comfort is not satisfied.

7.2.6.2. Insights from Demographic Analysis

An analysis of the demographic data collected in the survey revealed:

- **Geographic Distribution**: The geographic analysis showed that HP adoption was more prevalent in England, possibly due to financial incentives, population density, housing stock, and climate conditions. England has a higher population density and more urban areas compared to Wales, Scotland, and Northern Ireland (Office for National Statistics, 2022). Urban areas tend to have more resources and infrastructure for installing heat pumps, such as trained installers and access to equipment.

- **House Type and System Suitability**: Majority of respondents reported living in detached houses (32%) and semi-detached houses (31%). The house insulation type was more evenly distributed among respondents with 32% living in cavity wall house with reasonable loft insulation, 26% in uninsulated old house with solid walls, 25% in modern house with high level of insulation, and 17% owning an old house with solid walls with enhanced insulation.

7.3. Comparison to Case study 1

In Case Study 1, Participant A, who resides in a semi-detached house with an air-to-air heat pump, primarily relies on their gas boiler during colder weather when the ambient temperature drops below 0°C. This finding contrasts with the broader trends observed in the homeowner questionnaire, where 95% of heat pump users indicated that their heating demand was satisfied even during cold weather. Participant A’s experience of having to switch off the heat pump in freezing conditions aligns with the 15% of survey respondents who expressed concerns about heat pump performance in poorly insulated homes or extreme cold, suggesting a significant barrier to exclusive HP reliance.

Moreover, Participant A's decision to keep the gas boiler as part of their heating solution reflects the survey's identification of a lack of confidence in heat pumps' ability to fully replace traditional systems, particularly in less insulated houses. While 70% of heat pump owners reported a decrease in energy bills, Participant A’s increased reliance on gas during cold periods partially mitigates these savings, highlighting a discrepancy between expected and actual performance for some HP users.

7.4. Comparison to Case study 2

In Case Study 2, Participant B, who lives in a detached house with an air-to-water heat pump, reported significant changes in their heating system’s performance and thermal comfort after improving their home’s insulation. This supports the survey findings where respondents in well-insulated homes (25% of survey participants) were more likely to report satisfactory performance and economic benefits from HPs. Participant B’s installation of additional heating devices such as night storage units, due to the underperformance of their undersized heat pump, further underscores the importance of proper sizing and insulation.

While the homeowner questionnaire revealed that 76% of respondents still use gas boilers, Participant B's complete shift away from fossil fuels aligns with the 24% of survey participants who have fully transitioned to heat pumps, motivated by sustainability and health concerns. The reliance on supplementary heating sources by Participant B mirrors the broader concern in the questionnaire about the initial installation costs and performance of HPs in colder weather, reflecting a key area for improvement in heat pump technology and installation practices.

7.5. Comparison with the case studies' interviews

Both interviewees from the case studies appreciated the environmental benefits of HPs, consistent with the 43% of survey respondents who cited environmental benefits as a primary motivation for switching to heat pumps. However, differences in satisfaction with performance during colder months highlight variability in user experiences. Interviewee A reported having to switch off their heat pump in low ambient temperatures, reflecting the 15% of survey participants concerned about cold-weather performance. In contrast, Interviewee B, despite having some issues with an undersized unit, continued using the heat pump supplemented by night storage heaters, suggesting a higher level of commitment and adaptability in overcoming these challenges.

These contrasting experiences underline the need for a tailored approach to heat pump adoption, with considerations for insulation levels, proper sizing, and supplementary heating options. The alignment of Participant B's experience with survey findings on enhanced thermal comfort after insulation improvements suggests that addressing these factors could significantly enhance user satisfaction and HP performance, potentially increasing the uptake among homeowners currently reliant on gas boilers.

7.6. Summary

Overall, the questionnaire results suggest that while heat pumps are viewed positively by many HP owners' respondents, particularly for their environmental benefits and potential cost savings, significant barriers to wider adoption remain. High installation costs, lack of awareness, and concerns about performance in cold weather were key issues identified. Addressing these barriers through targeted incentives, educational campaigns, and technological improvements could enhance the adoption of heat pumps and support the UK's transition towards a low-carbon heating sector.

8. Heat pumps vs District heating

8.1. Introduction

This chapter explores a case study produced by the author from Nottingham Ice Centre (NIC) (Figure 8.1) where district heating (DH) is used normally for heating and this chapter explores the potential use of heat pumps to extract the excess heat from the chillers used to maintain the ice.

One of the issues of DH is that it is provide by the Nottingham's incinerator which burns waste, which is considered to be sustainable compared to the energy sector, bust scientifically not a zero-carbon method.

In recent years, the global energy landscape has undergone significant turmoil, characterized by an unprecedented increase in energy prices. Both electricity and gas prices have experienced dramatic spikes, driven by a combination of geopolitical tensions, supply chain disruptions, and the transition toward greener energy sources. According to the International Energy Agency (IEA), global natural gas prices reached record highs in 2022, nearly tripling in some regions compared to historical averages (IEA, 2022). Electricity prices have similarly escalated, exacerbating financial pressures on households and businesses alike. This rapid rise in energy costs is particularly concerning, given its far-reaching impacts across various sectors and the broader economy.

Among the industries significantly impacted by rising energy costs is the leisure sector, which includes sports and recreational facilities that require continuous energy inputs to maintain their services. Nottingham Ice Centre, a popular ice skating and sports venue in the UK, exemplifies the economic challenges posed by current energy prices. Maintaining an ice rink is an energy-intensive process due to the significant cooling required to keep the ice surface in optimal condition. The ice-making and refrigeration systems, which operate continuously, consume large amounts of electricity, and the rising cost of this electricity directly affects the centre's bottom line. This economic pressure is compounded by the need to maintain a comfortable environment for spectators and athletes, which involves additional heating costs—often sourced from district heating networks, where prices have also escalated.

In such a scenario, it becomes imperative for facilities like Nottingham Ice Centre to explore innovative methods to mitigate rising energy costs. One promising approach is to recover the heat ejected through the cooling towers during the refrigeration process. When chillers work to create and maintain the ice, they produce waste heat that is typically expelled into the environment. However, this expelled heat represents a valuable, untapped resource that can be harnessed through heat recovery methods. By capturing and repurposing this heat, Nottingham Ice Centre could achieve a dual benefit: reducing its reliance on external heating sources and enhancing its overall energy efficiency.

Heat recovery not only aligns with sustainability goals by reducing carbon emissions and improving energy efficiency, but it also presents a substantial economic opportunity. By lowering the amount of energy needed from district heating systems, facilities can reduce their exposure to volatile energy prices and achieve more predictable operational costs. Different methods for heat recovery can be explored and analysed, particularly the use of heat pumps or thermal storage systems. Heat pumps can transfer the waste heat from cooling processes to other parts of the building or system that require heating, thereby lowering the need for additional energy input. Thermal storage, on the other hand, involves storing the recovered heat for later use, thus providing flexibility in energy management and further cost savings.

This project explores the potential of heat recovery as a strategy for mitigating rising energy costs for energy-intensive facilities like Nottingham Ice Centre. This chapter will examine various methods, including heat pumps and thermal storage, to assess their feasibility, efficiency, and economic viability. By doing so, the aim is to provide a comprehensive understanding of how these systems can be implemented to not only safeguard against high energy prices but also contribute to a more sustainable energy future for leisure and recreational facilities.

Figure 8. 1 *- National Ice Centre building.*

8.2. Energy background

The National Ice Centre (NIC) at Nottingham is looking at opportunities around heat capture and recovering.

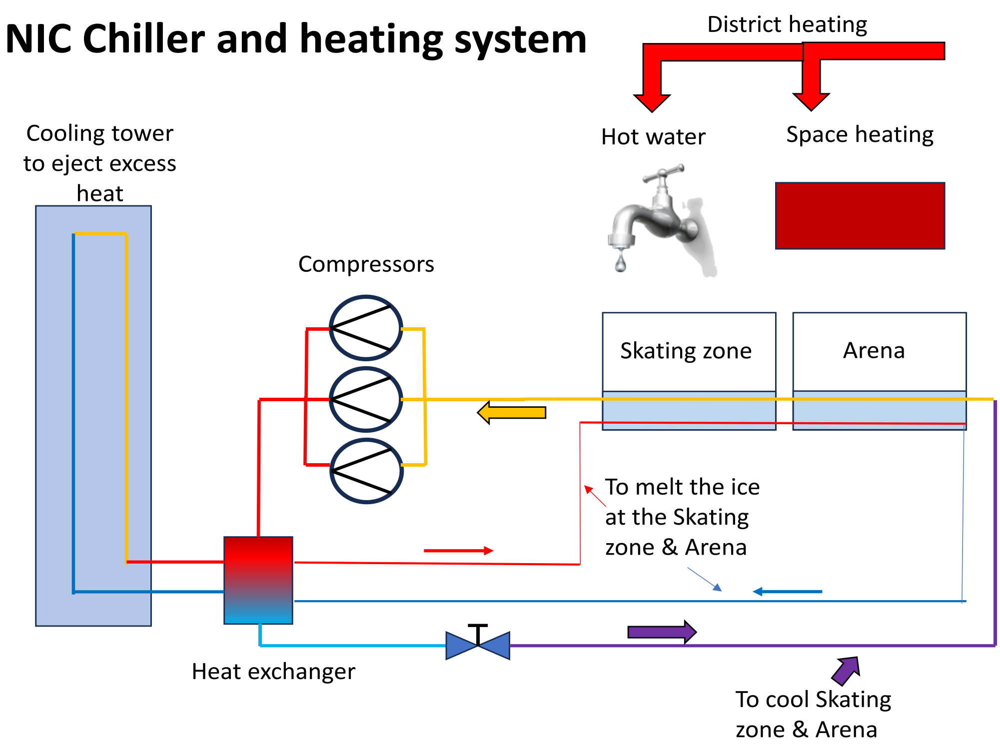


Figure 8. 2 *- Current NIC system configuration of cooling Chillers and heating system*

Figure 8.2 represents the current energy schematics of NIC. The chillers are maintaining the ice on both skating and arena zones with the help of 3 compressors, heat exchanger and an expansion valve. The cooling tower helps ejecting some of the heat from the chillers systems. Through district heating, NIC provides hot water and space heating to the building when required.

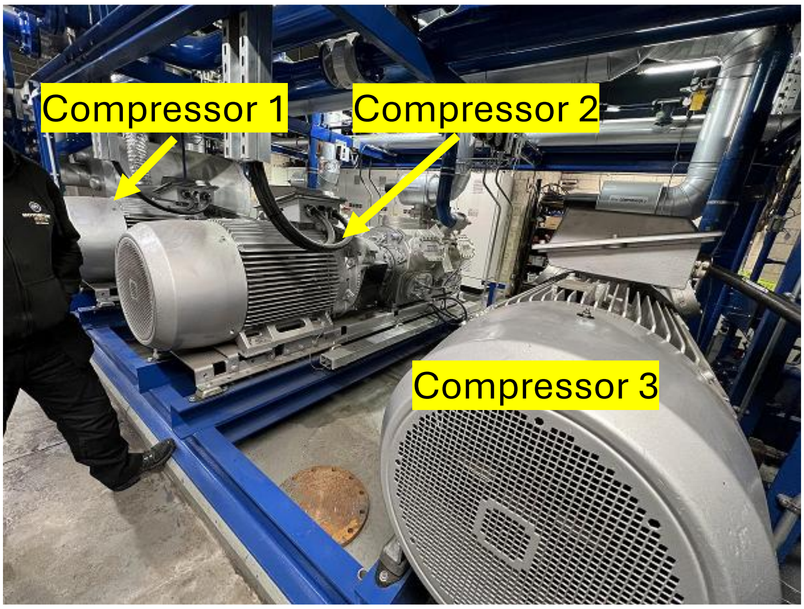


Figure 8. 3 *– NIC chiller compressors.*

Figure 8.3 represents the three compressors part of the chiller systems in NIC to make and maintain the ice in the skating zone and in the arena.

Infrared images of the chiller compressors

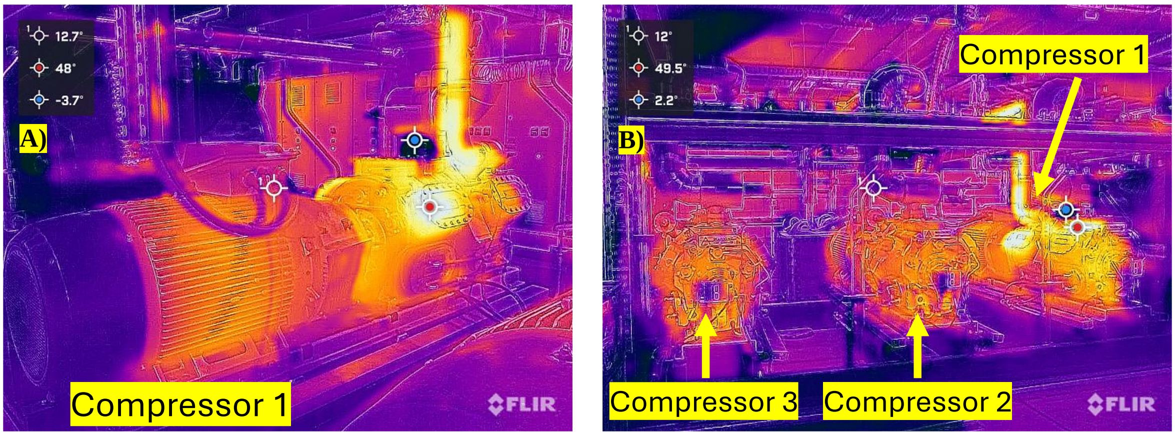


Figure 8. 4 *– Infrared images of the chiller compressors*

Figure 8.4 A showcases a thermal image of compressor 1. The high temperature indicates the output location, where the refrigerant is leaving at a high temperature. Figure 8.4 B showcases the three chiller compressors at a different view.

Infrared images of the chiller condenser

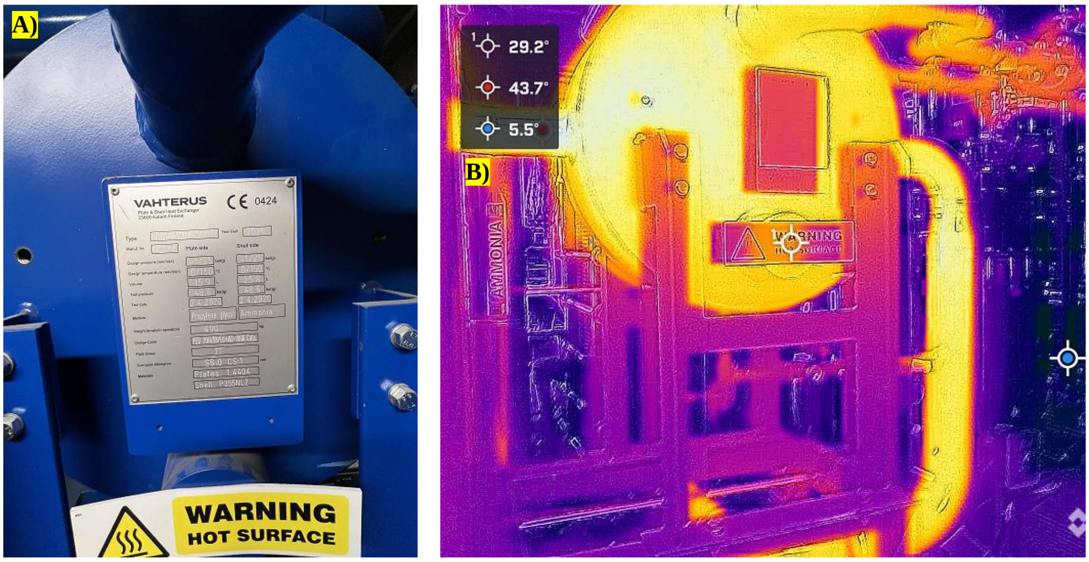


Figure 8. 5 *– Chiller condenser*

Figure 8.5 A shows the shell heat exchanger which acts as the condenser while ice is maintained in the skating zone and the arena at NIC. Figure 8.5 B represents the thermal image of the heat exchanger showcasing where temperature fluctuations occur.

According to monitored data (figure 8.6), it is estimated that the building is ejecting Approximately 3 GWh per annum of heat (or approximately 250 MWh/month on average) (figure 8.7) through the cooling tower connected to the chillers that are utilised to maintain the ice within the skating and arena zones. Equations 6 to 10 (Chapter 3.5.2) were used to calculate the performance and cost effectiveness (Chapter 8.3) of the proposed heat pump models.

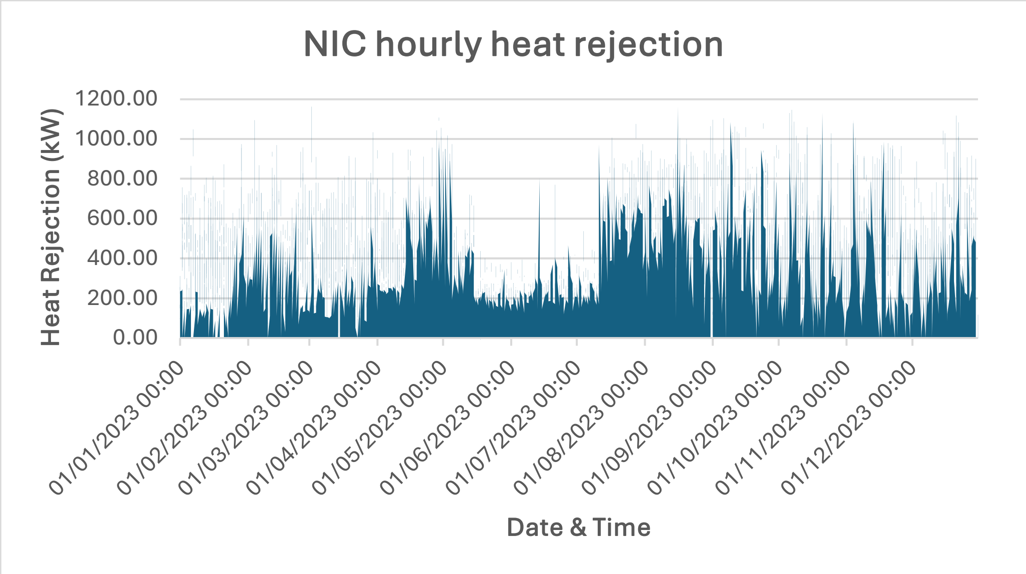


Figure 8. 6 *- NIC hourly heat rejection through the cooling tower.*

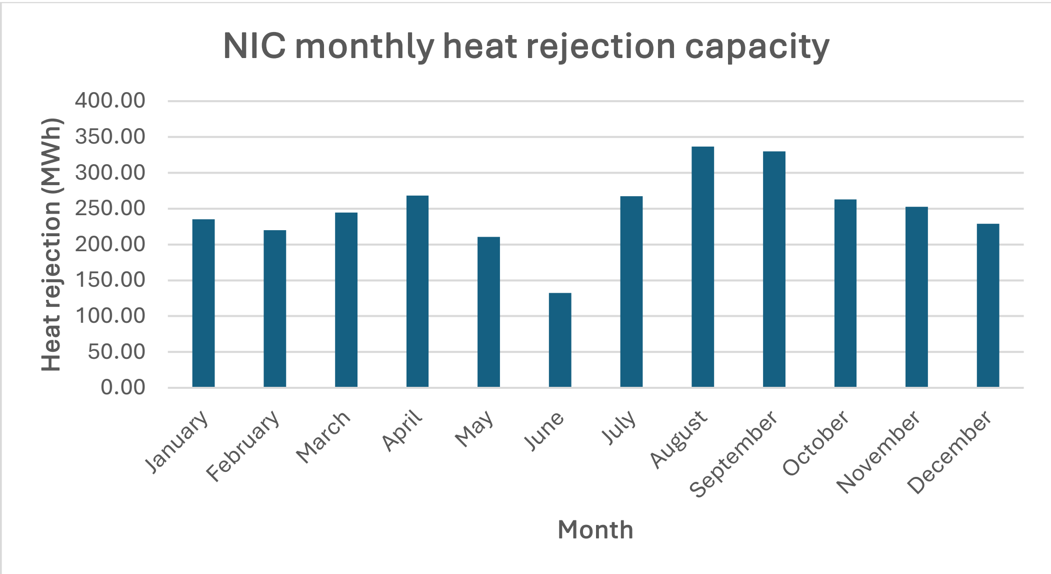


Figure 8. 7 *- NIC monthly heat rejection duty.*

Installation of a three-way valve has been specified that will reject the heat through the cooling tower but with the potential future connection points to utilise the rejected thermal energy to be used elsewhere.

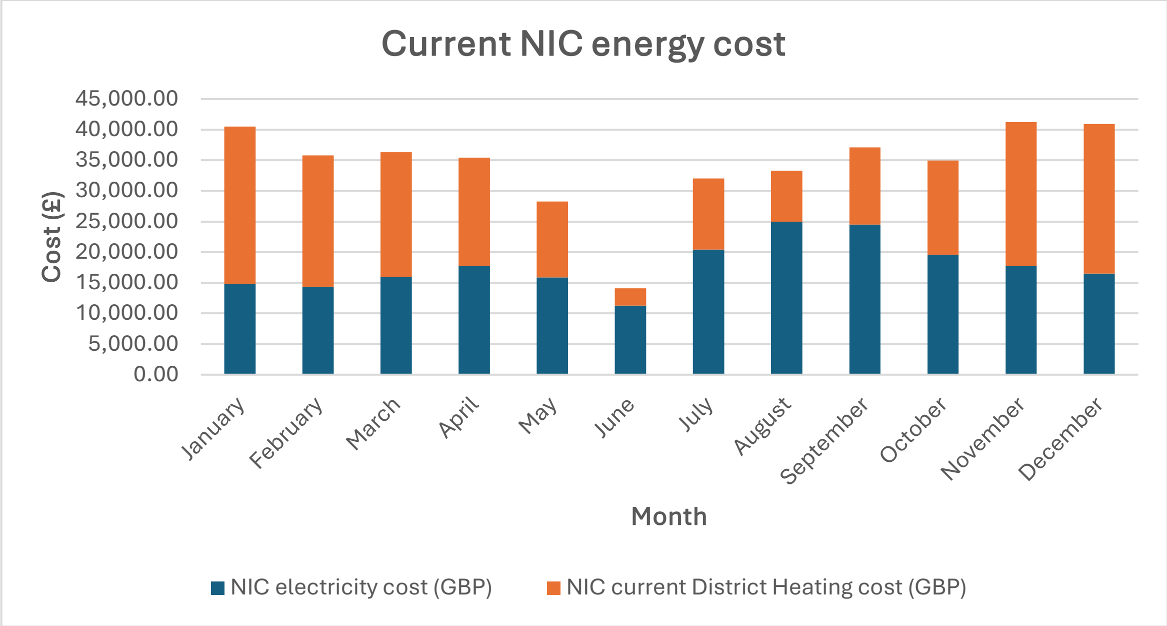


Figure 8. 8 *- Current NIC energy cost.*

Currently, NIC's energy (both electricity and heating) consumption costs approximately £410,000 per year (Figure 8.8). NIC is looking into cost-effective alternatives to mitigate the increasing energy prices. One of the suggested alternatives is to utilise heat pump system to recover some of the rejected heat. NIC has been initially offered potential heat pump units that may be suitable for this purpose (Carrier, 2024) (Table 8.1).

Table 8. 1 - Proposed heat pump models and their specifications.

Proposed heat pump models and their specification						
Heat pump model		**Cooling capacity to source (kW)**	**Unit power input (kW)**	**Heating capacity (kW)**	**COP**	**Condenser leaving temperature**
1	61XWHHZE03	297	100	389	3.89	70
2	61XWHHZE03	289	123	404	3.28	82
3	61XWHHZE03	350	103	444	4.3	70
4	61XWHHZE03	241	119	353	2.96	82
5	61XWHHZE03	140	59	194	3.32	70
6	61XWHHZE05	396	189	573	3.04	82
7	61XWHHZE05	225	91	310	3.4	70
8	61XWHHZE07	575	299	856	2.86	82
9	61XWHHZE07	337	144	471	3.27	70
10	61XWHHZE10	794	378	1147	3.03	82
11	61XWHHZE10	226	91	311	3.41	70

8.3. Heat pump recovery system analysis

Heat pumps were first analysed to estimate its suitability as heat recovery system implemented as part of the chillers to further utilised the wasted heat from the chillers' heat exchanger (condenser). Through three-way valves the heat pump unit could be integrated in the current chiller system. These three-way vales can provide the means to bypass the cooling tower when more heat is required. Figure 8.9 represents a schematic of the proposed idea. Through the heat pump the building can be provided with hot water and space heating when necessary. Equations 5 to 8 (Chapter 3.5.2) were applied to determine the ability to recover heat from the chiller system, for each of the proposed heat pump models (Table 8.1).

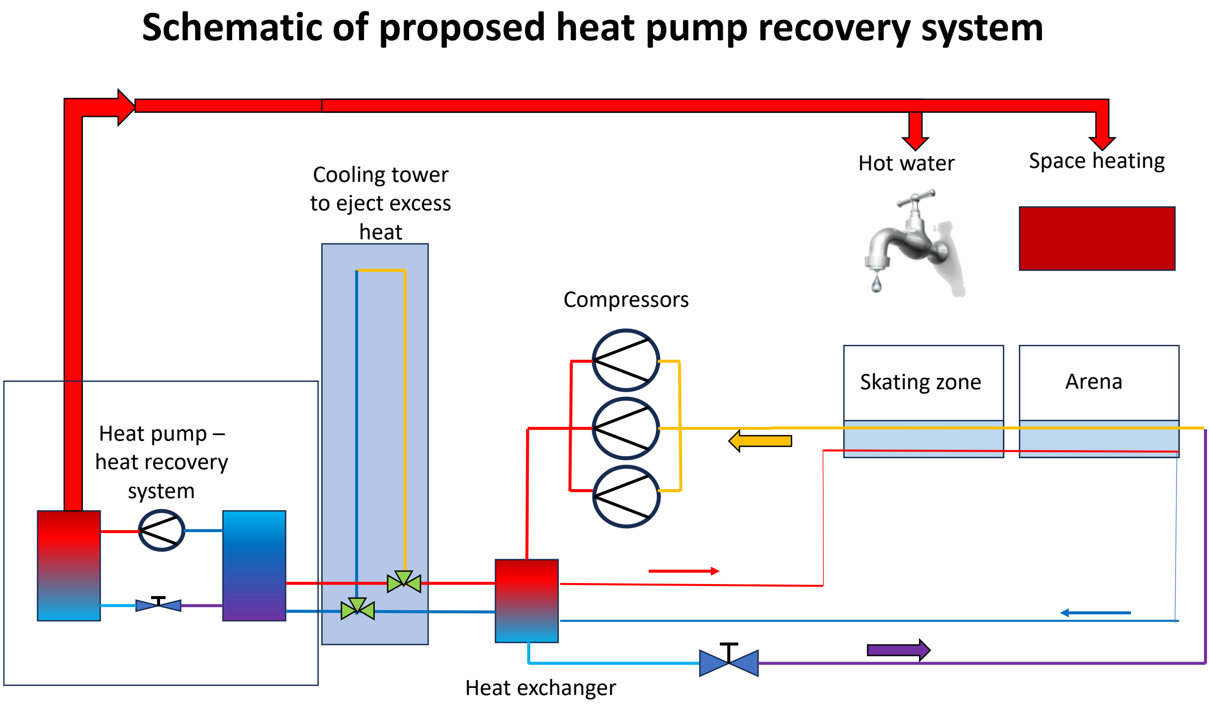


Figure 8. 9 – Schematic diagram of the proposed heat pump recovery system.

First, the value of the rejected heat through the cooling towers was compared to the current district heating cost (figure 8.10). After further investigation and analysis of the proposed heat pumps, the required electricity and running cost for the units has been calculated. Models 5, 7, and 11 (Table 8.1) have low heating capacity. After a detailed analysis it was evident that these models would not be sufficient to provide the required heating for NIC. This suggests that additional thermal energy would be required from the district heating system. This has been detailed in the attached Excel sheet.

The running cost of the proposed heat pump models has been calculated (with and without district heating for the low power heat pumps) along with the current electricity usage by the building (figures 8.11 and 8.12). After that, the running cost has been compared with the current electricity usage by NIC to estimate if a heat pump recovery system would be a cost-effective solution.

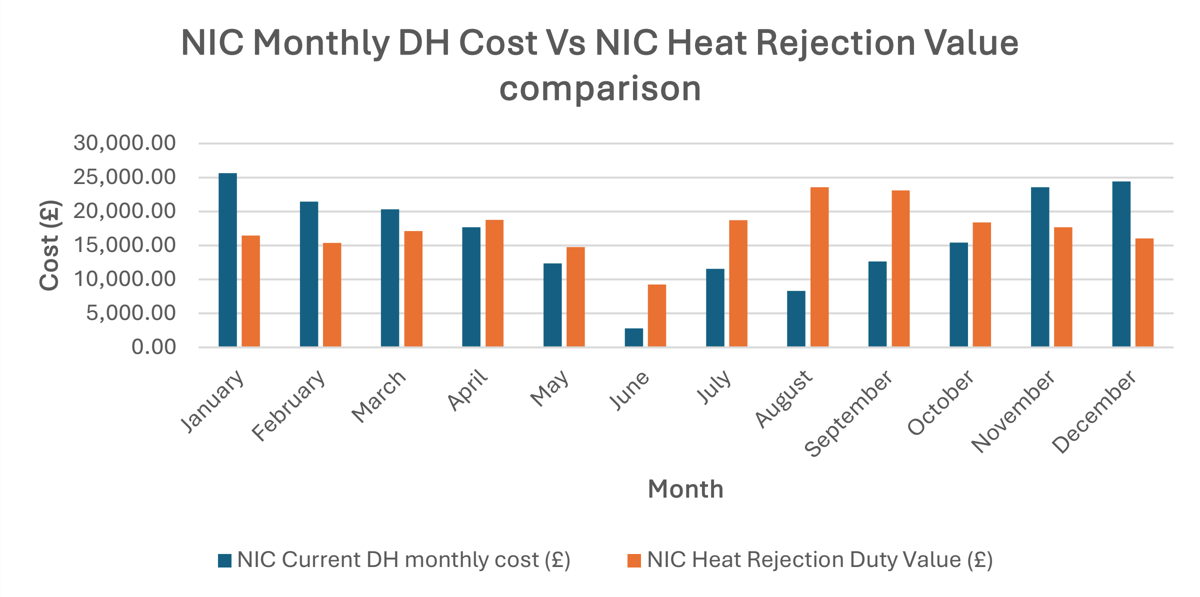


Figure 8. 10 *- NIC monthly district heating cost and NIC heat rejection value comparison.*

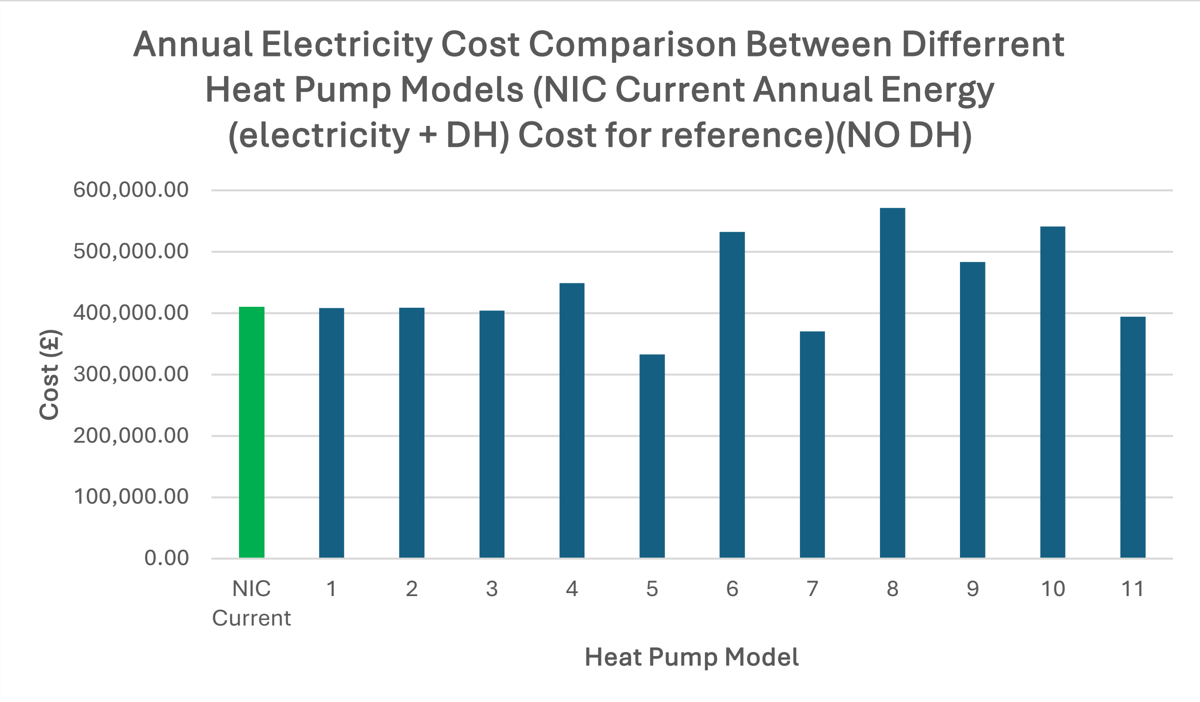


Figure 8. 11 *- Annual electricity cost comparison between the proposed heat pump models and the current NIC annual energy cost (without district heating support for the low power heat pumps).*

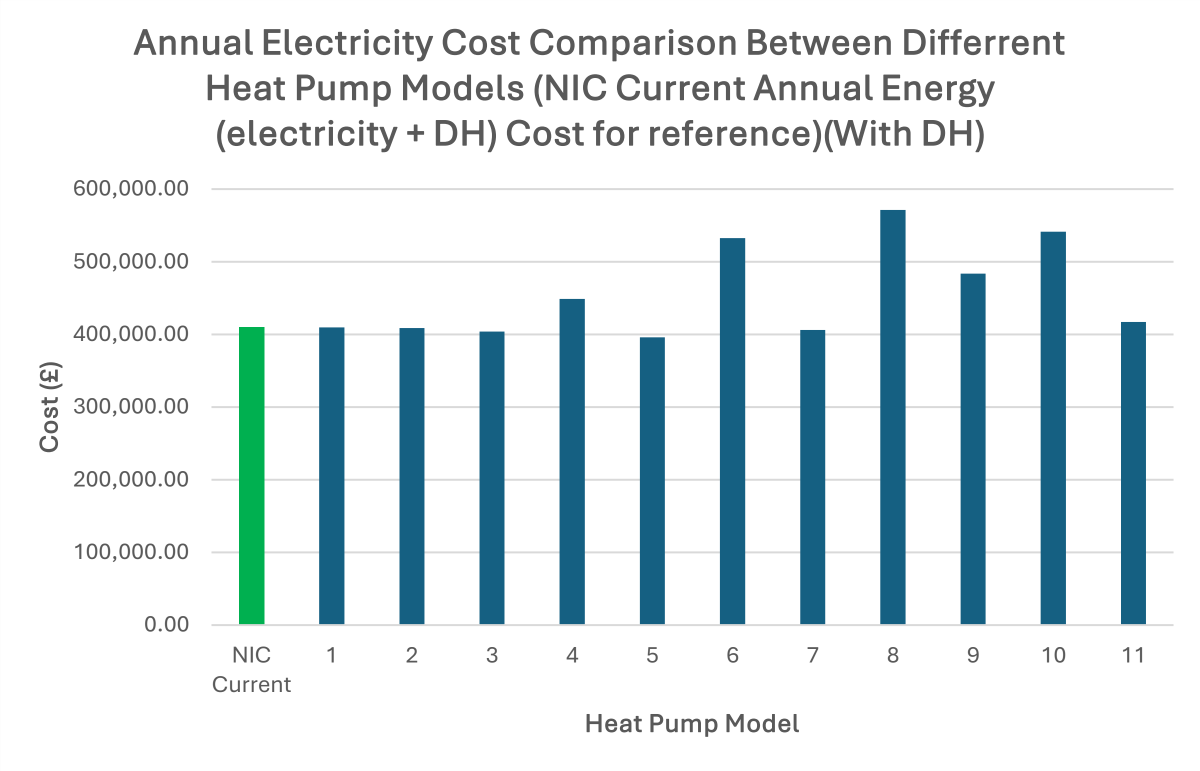


Figure 8. 12 *- Annual electricity cost comparison between the proposed heat pump models and the current NIC annual energy cost (with district heating support for the low power heat pumps).*

The low heating capacity of models 5, 7, and 11 could only provide approximately 50% of the building's heating demand, additional thermal energy would be required from the district heating system. The additional thermal energy cost has been added to low power models.

After analysing the results, it is evident that the running cost of a heat pump system would not be more cost effective for NIC. In addition, with high heating capacity models, such as 6, 8, 9, and 10, the running cost would be even higher than what the building is currently paying for.

8.4. Thermal storage recovery system analysis

After the initial heat pump recovery system analysis, it was evident that such a device would not be cost effective for the NIC. The water off the chiller condenser, heading to the cooling tower, is of temperature ranging between 10 and 20 °C, depending on the ambient temperature (figures 8.13 and 8.14).

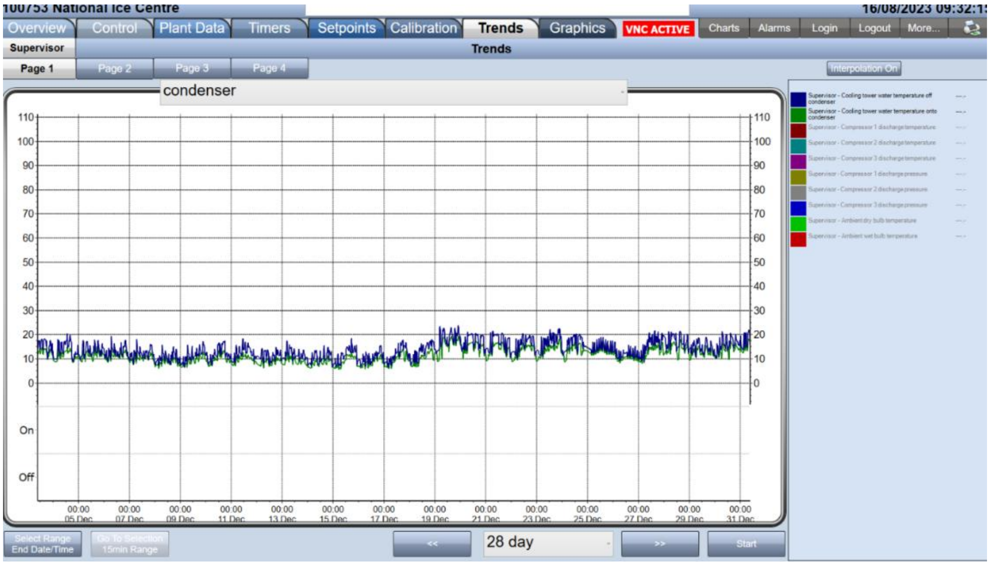


Figure 8. 13 *- Cooling tower water off condenser – Wintertime (Data provided by NIC).*

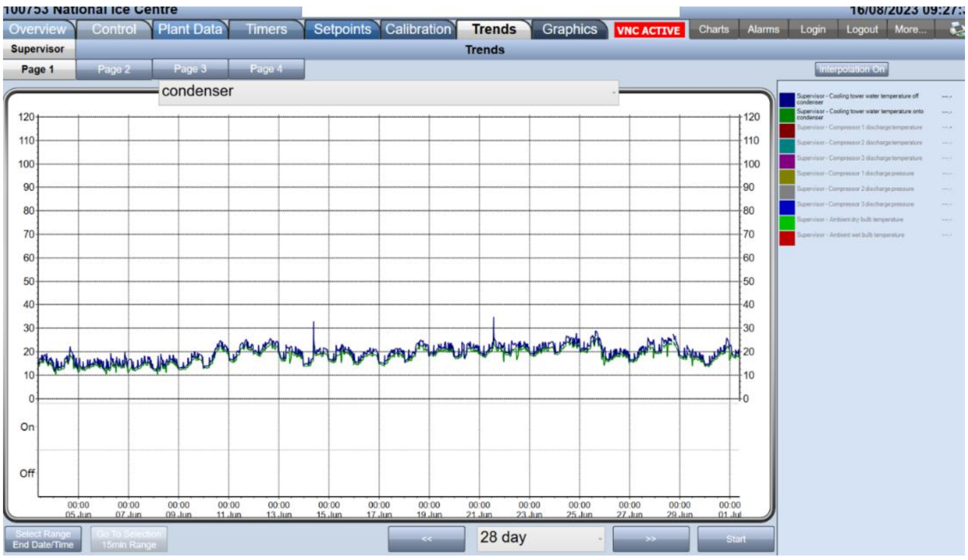


Figure 8. 14 *- Cooling tower water off condenser – Summertime (Data provided by NIC).*

The mains water in the UK is usually at temperatures ranging from as low as 6 to 20°C depending on the ambient temperature (Hart-Davis, 2024).

A thermal storage connected to the chiller condenser where mains water is flowing has the potential to slightly warm up the tap water. District heating will be required to increase the water temperature to the desired levels. However, a medium thermal storage would reduce the district heating usage, potentially reducing NIC's energy costs.

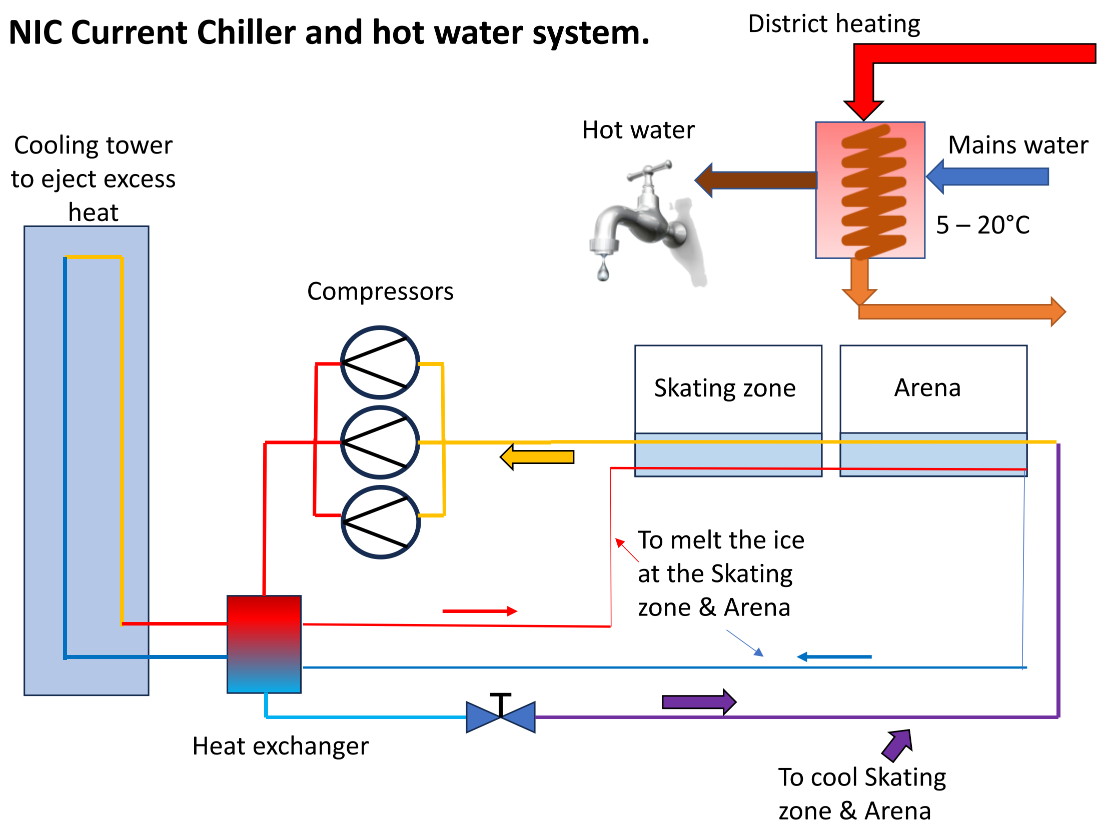


Figure 8. 15 *- NIC current chiller and hot water system.*

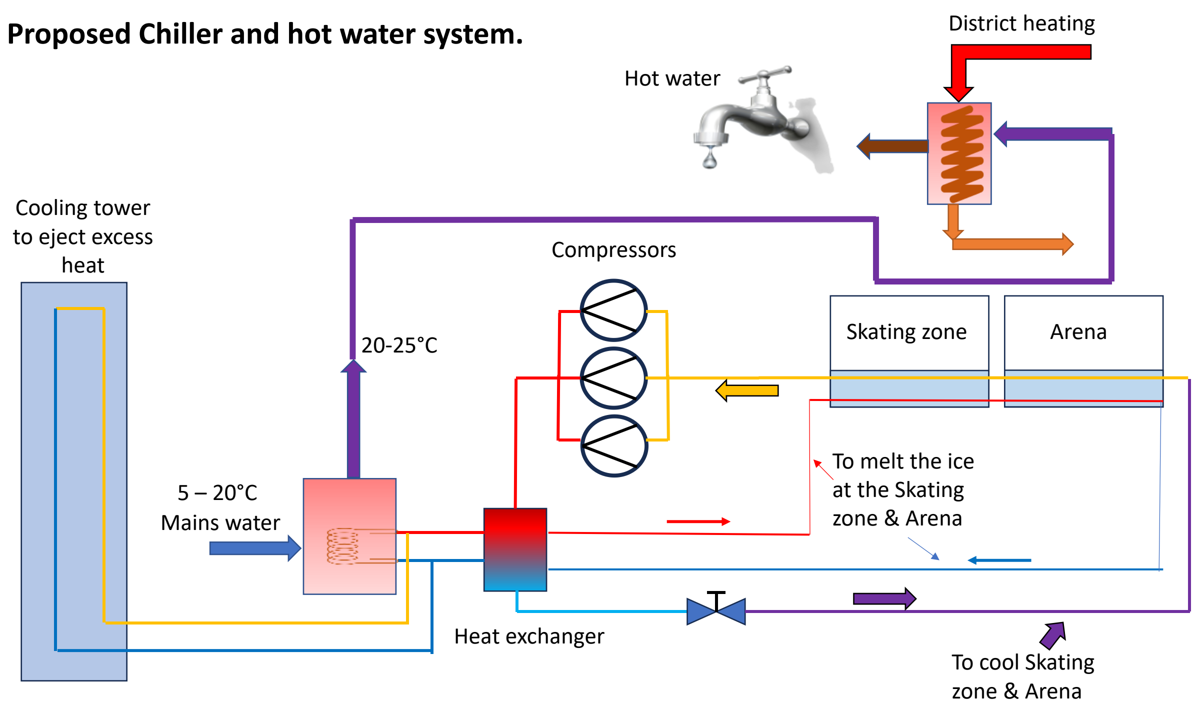
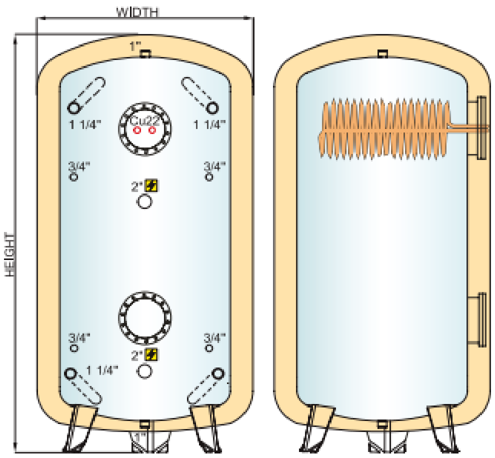


Figure 8. 16 *- Proposed chiller and hot water system using enhanced thermal storage.*

Figure 8.15 and 8.16 showcase a schematic vew of NIC's current chiller and hot water system; and the proposed system involving a thermal storage to recover some of the ejected heat from the chillers.



A typical solution for an AKVA EK accumulator tank:

Couplings	Pieces	Size	Further details
Network / Boiler coupling	4	1 1/4"	Typically 2" in models over 2000 litres
Thermometer/Thermostat	4	3/4"	
Electric immersion heater coupling	2	2"	
Domestic water coil couplings	2	Ø 22 mm	In upper accumulator section. Lower hatch often fitted with second coil either for preheating domestic water or input of solar energy.
Drain connection	1	1"	
Air bleeder connection	1	1"	

An LK35 coil is typically fitted in the upper hatch of the AKVA EK.
Options include a wide selection of coils in various sizes that may be used for heating domestic water or feeding thermal energy into the accumulator.

Adaptable components: electric immersion heaters, coils, double coils, baffle plates, special connections, etc. Further details available from our sales staff.

Designation	Width [mm]	Height [mm]	Weight [kg]	Capasity [L]	P [bar]	Insulation [mm]	Standing loss [W]	Energy class	LVI-no
AKVA EK 300	710	2050	140	284,0	3	100	66,0	B	5235100
AKVA EK 500	800	2050	170	450,0	3	100	74,0	B	5235054
AKVA EK 750	950	2050	210	749,2	3	100	94,0	B	5235056
AKVA EK 1000	1050	2100	240	958,4	3	100	106,0	B	5235058
AKVA EK 1500	1250	2150	300	1486,4	3	100	128,0	C	5235060
AKVA EK 2000	1400	2200	350	1972,4	3	100	145,0	C	5235062
AKVA EK 2500	1500	2250	380	2500	3	100	-	-	5235101
AKVA EK 3000	1600	2300	420	3000	3	100	-	-	5235064
AKVA EK 4000	1800	2450	500	4000	3	100	-	-	5235102
AKVA EK 5000	2000	2500	630	5000	3	100	-	-	5235103
AKVA EK 6000	2150	2500	780	6000	3	100	-	-	-
AKVA EK 7500	2150	3000	940	7500	3	100	-	-	-

***Figure 8. 17** - Thermal storage options (Northman Group, 2024)*

Different volumes of thermal storage devices are available (figure 8.17). An analysis involving a 5000L storage was conducted where the chiller condenser is heating up the mains water. 5000 L was chosen as it would provide the right balance. If the device is too small the water will heat up quickly, but it will be discharged faster. If the storage is larger, it will not be discharged fast but it more energy will be needed to heat up the water in it. Equations 10 to 15 (Chapter 3.5.2) were used to calculate the thermal storage cost effectiveness (Chapter 8.4).

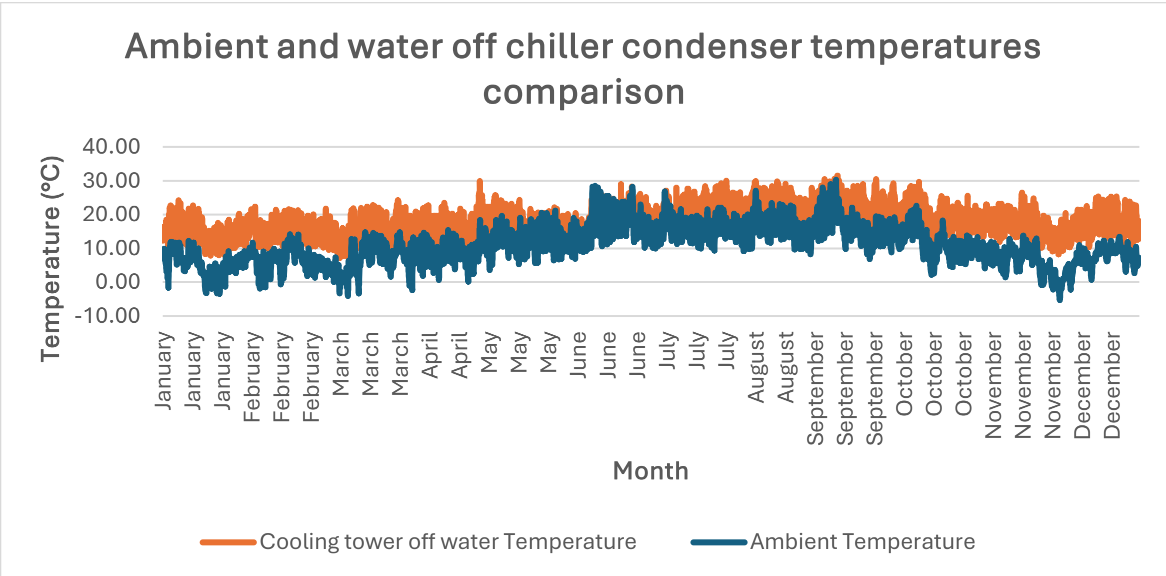


***Figure 8. 18** - Ambient and Water off chiller condenser temperature comparison.*

After analysing the data for the water off condenser temperature provided by NIC, it was compared with the ambient temperature for the given period (Figure 8.18).

After finding out the mains water temperature, the two situations presented in Figures 8.13 and 8.14 were analysed to determine how much energy will be needed by District Heating (DH) to warm the tap water to the desired level, which is around 60°C. Both situations were compared, and the energy cost was also included to determine if it will be cost effective long term.

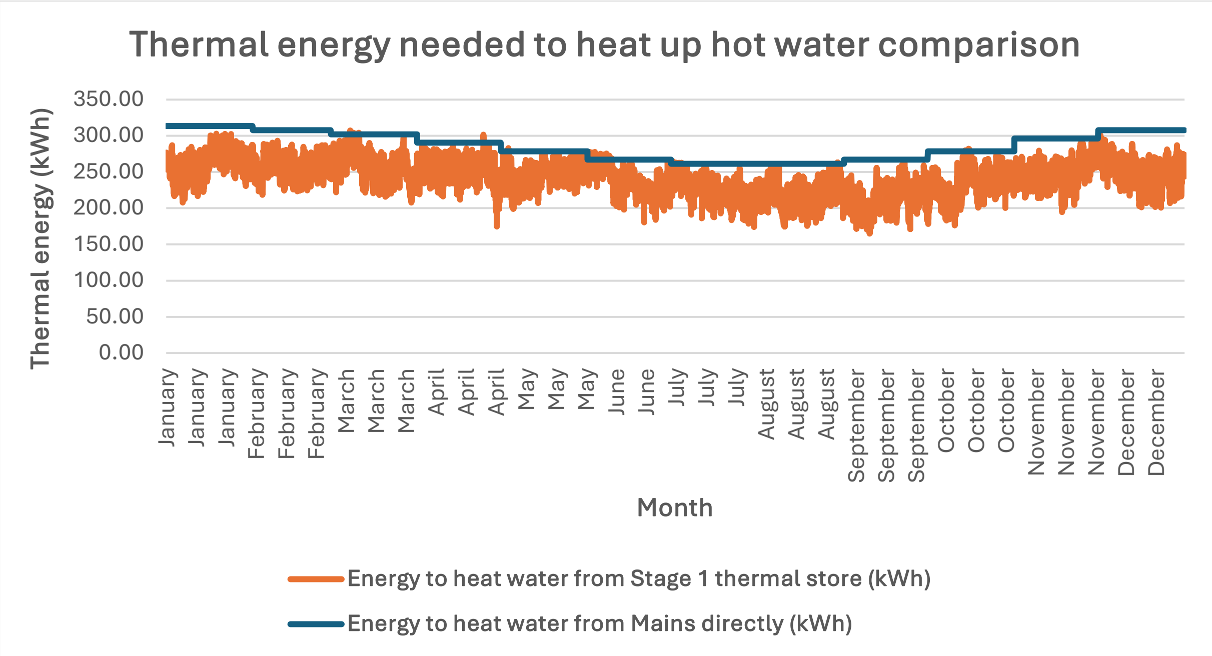


Figure 8. 19 *- Thermal energy required to heat up mains water comparison.*

Figure 8.19 presents the thermal energy needed to warm up the mains water to the desired level in both situations (with and without a thermal storage medium. This is also based on the tap water temperature which changes throughout the year, depending on the season (Hart-Davis, 2024).

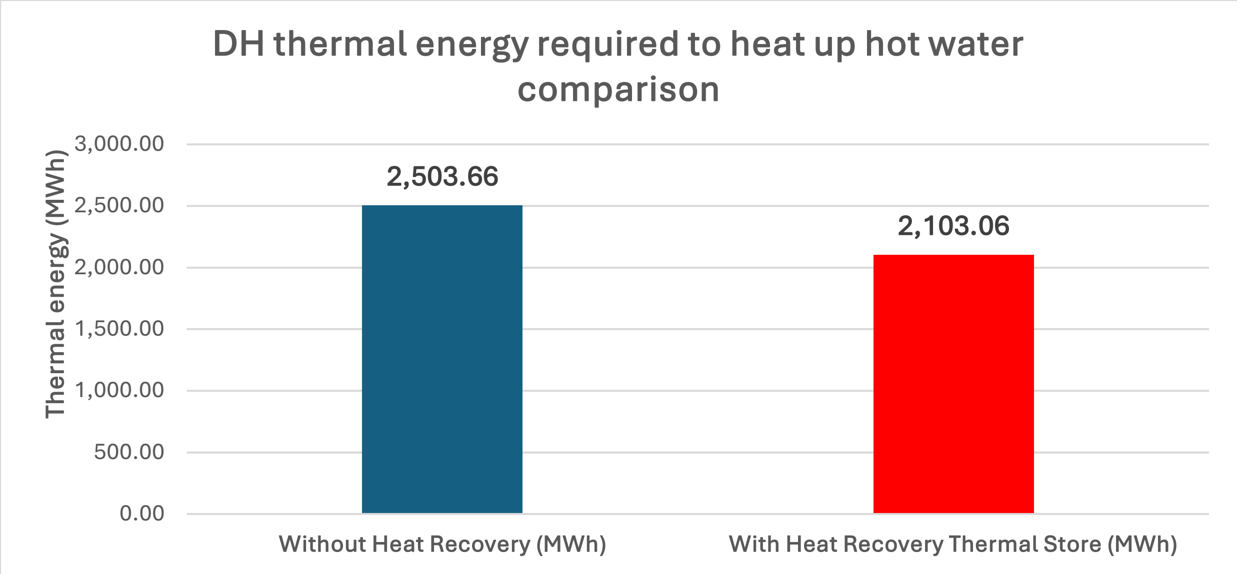


Figure 8. 20 *- Annual thermal energy required by District Heating to heat up mains water to the desired levels comparison.*

Figure 8.20 represents the thermal energy required to heat up the tap water in both situations (with and without a thermal storage medium) per annum. It is evident that with a thermal storage medium used to recover some of the heat from the chiller condenser, the amount of energy needed by DH is reduced. This also affects the cost.

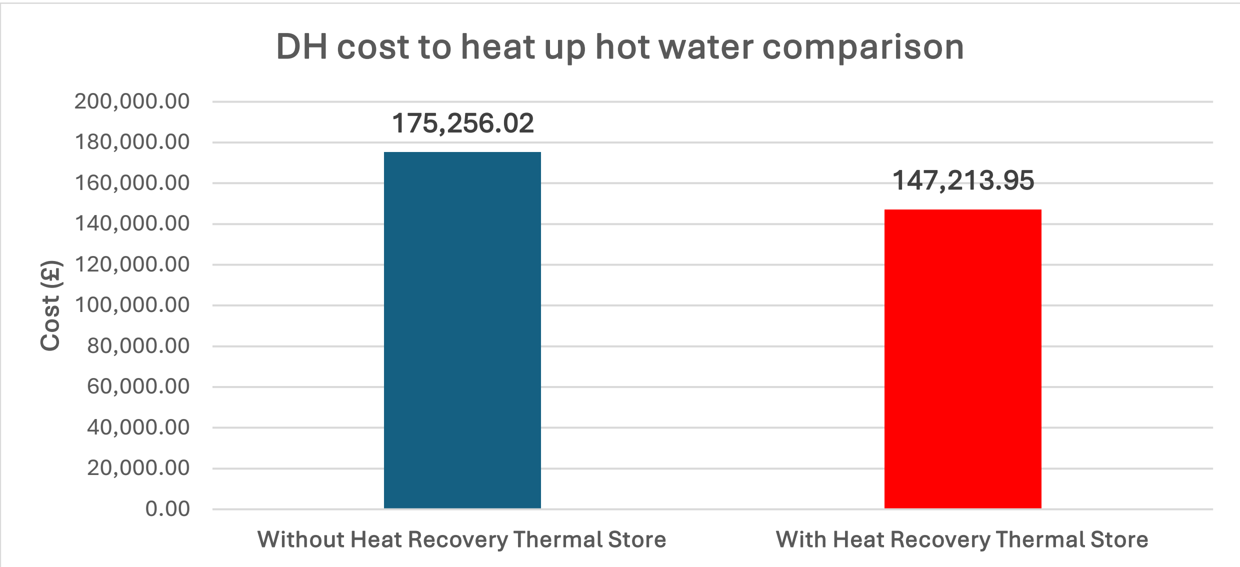


Figure 8. 21 *- Annual DH cost to heat up mains water comparison.*

From Figure 8.21 it is evident that the annual DH energy costs are reduced. This heat recovery method appears to be more cost effective than additional heat pump system to recover the ejected thermal energy. The thermal storage method could potentially save around £28,000 per year based on the conducted analysis above. After careful analysis and calculations of how much energy is required by DH to heat up the water in NIC, it was estimated that above 5000L the investment may not be optimal as the energy requirement and cost will increase.

The temperature of the cooling tower and the volume of the thermal storage can influence how much the collected water can be warmed up and how much energy will be required by DH to further increase the temperature of the thermal storage to 60°C. That is why the look-up table (figure 8.22) showcases the amount of energy required by DH to heat up the water to 60°C for different thermal storage volumes at various cooling tower temperatures.

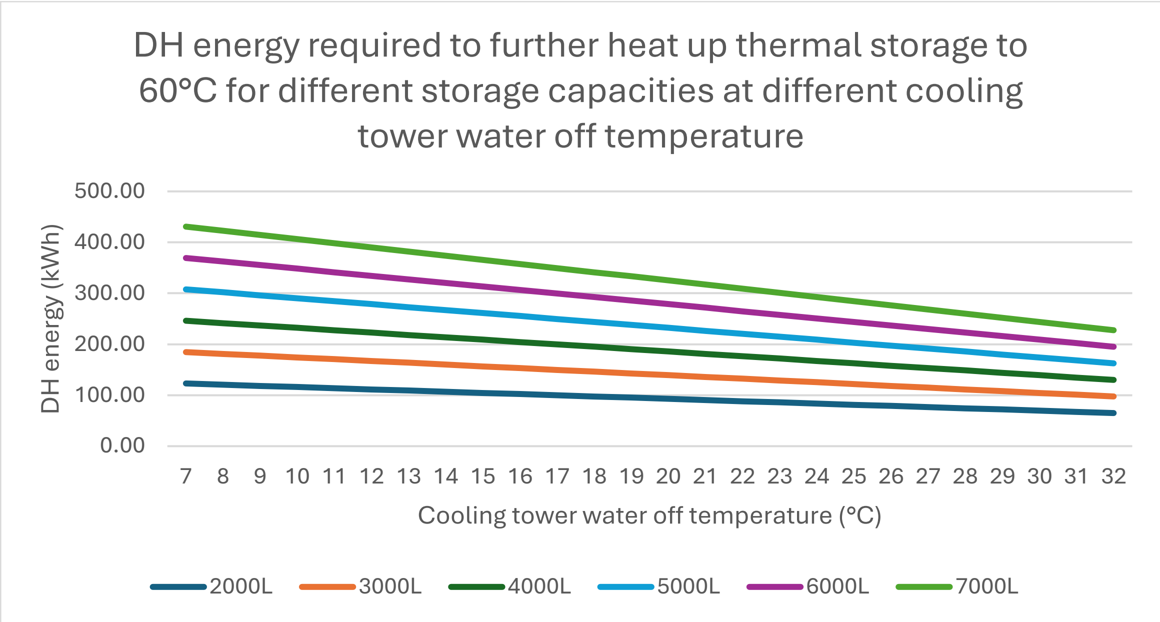


Figure 8. 22 *- Look-up graph of DH energy to heat up thermal storage to 60°C for different storage capacities at different cooling tower temperatures.*

As the heat rejection from the cooling tower fluctuates according to the ambient temperature, the time to heat the thermal storage water will also be affected as showcased in Figures 8.23 and 24.

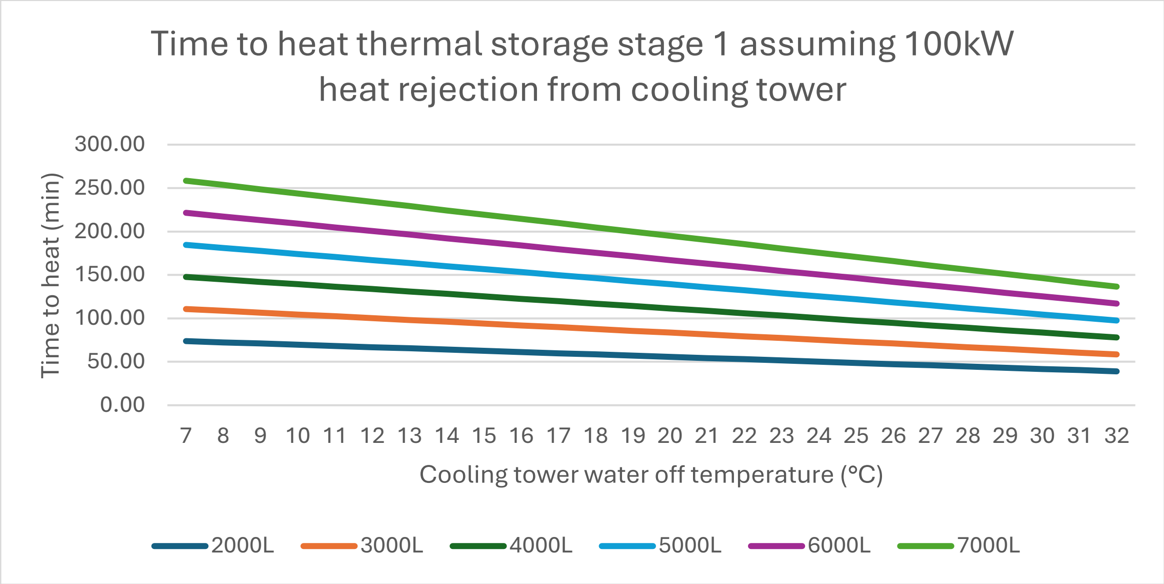


Figure 8. 23 *- Time to heat thermal storage stage 1 assuming 100kW of heat rejection from cooling tower.*

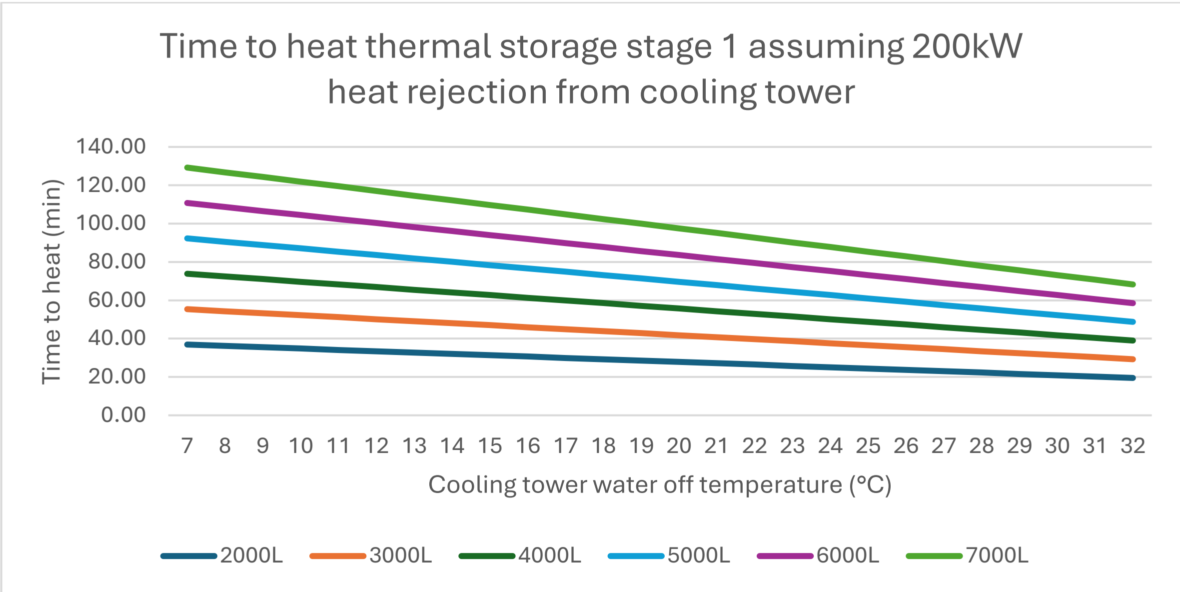


Figure 8. 24 *- Time to heat thermal storage stage 1 assuming 200kW of heat rejection from cooling tower.*

From Figures 8.23 and 8.24 is evident that the time to heat the thermal storage water decreases as the heat rejection power increases.

Due to the challenging nature of monitoring the exact amount of space and water heating it will not be possible to exactly estimate how much how quickly the thermal storage will be discharged.

According to (Lyon, 2022) the average tap water flow is approximately 10 l/min or 0.16 l/s. This is important because it will allow to estimate roughly how quickly the how water in the thermal storage can be discharged before it requires to be heated up again. Figures 8.25 and 8.26 represent the time the hot water will be exhausted for various thermal storage capacities and how many times it will take to be charged again per day, respectively.

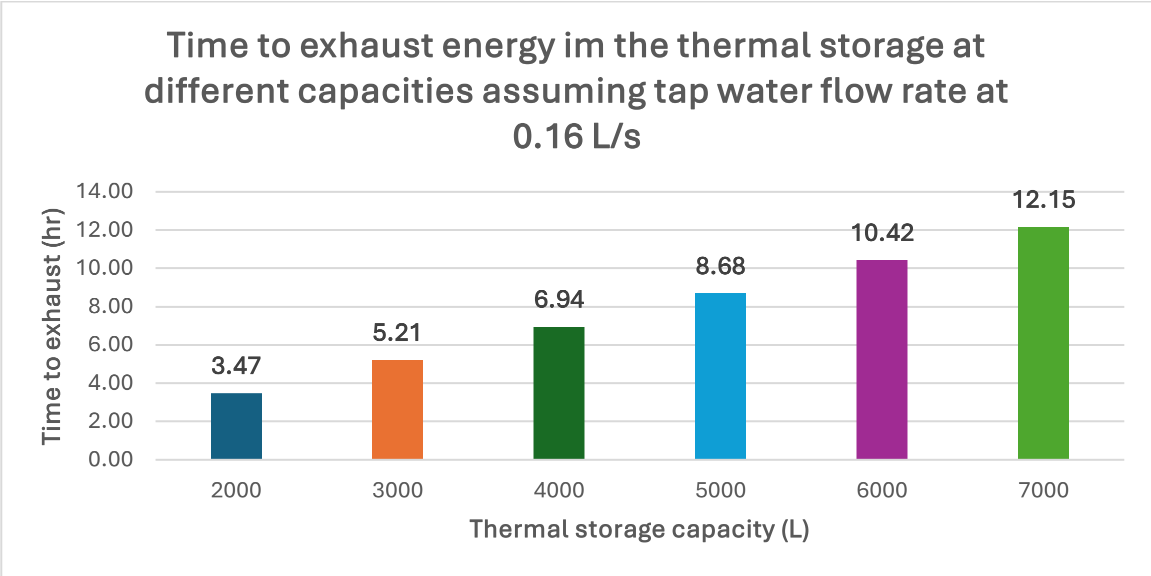


Figure 8. 25 - *Time to discharge thermal storage at different capacities.*

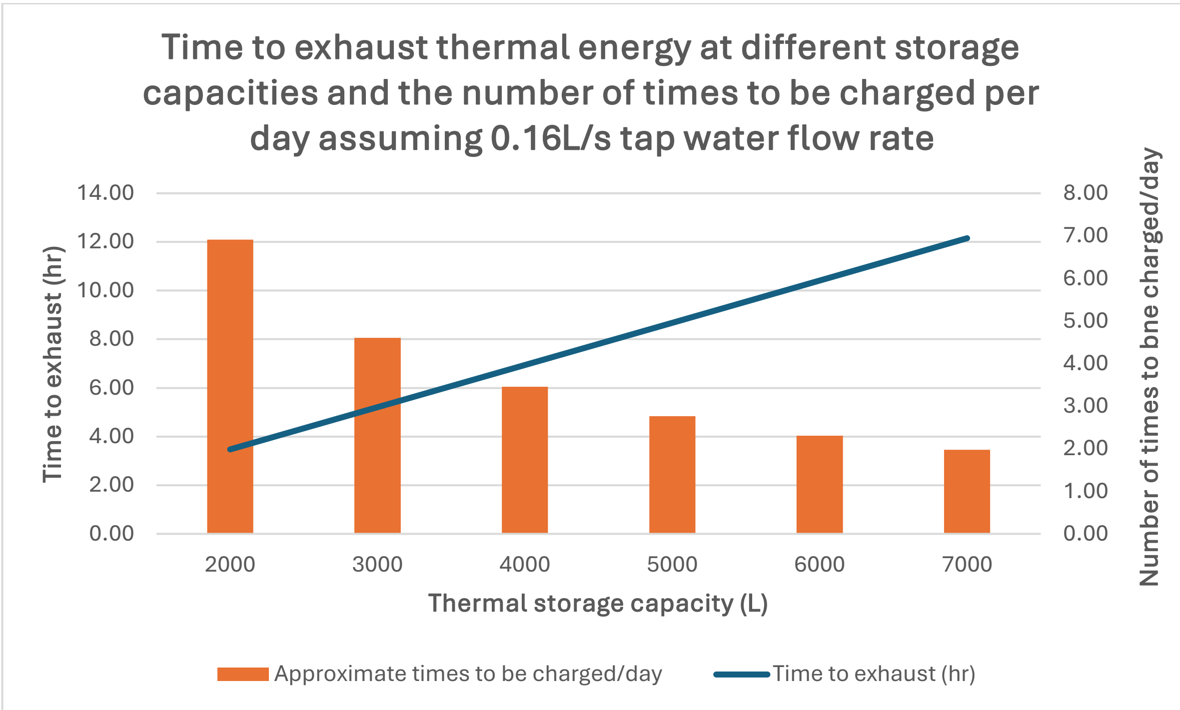


Figure 8. 26 - *Time to discharge thermal storage at different capacities*

From Figures 8.25 and 8.26 it is evident that with the increase of thermal storage capacity the time to discharge it decreases, however, the number of times to be charged decreases. This suggests that the capacity of the storage may not affect the amount and cost of energy by DH significantly. The main factor in regard to cost is the price of the thermal storage vessel. Table 8.2 presents various thermal storage capacities available at the market and the price range.

Table 8. 2 *- Thermal storage capacities and their price range.*

Thermal storage capacity (L)	Price range (£)
2000	1000 – 2000
3000	2000 – 4000
4000	4000 – 5800
5000	4300 - 8700

8.5. Summary

Based on the current prices of electricity and the analysis above, it may not be recommend investing in a heat pump as a heat recovery method. Based on the analysis it was estimated that a device with a heating capacity lower than 350 kW would not be able to satisfy the heating demand in the building, meaning that district heating would still be required to fill in the gaps in thermal energy. There will not be any considerable change in energy cost with such method and it will not be economically feasible. To completely satisfy the heating demand in the building using a heat pump recovery higher heating capacity is necessary. However, the analysis provided estimates that this will lead to higher energy cost due to the high electricity price.

A thermal storage as a heat recovery method would be a beneficial approach to utilise the ejected thermal energy from the chiller cooling tower. District heating is still required to fill in the gaps in the heating demand. However, due to the lower cost of DH compared to electricity, the energy cost for NIC will decrease. The reason for that is the lower demand for thermal energy from district heating.

9. The expansion of EV use and the effect on the power grid

9.1. Introduction

This chapter investigates the UK electricity grid recent winters demand profile and explores the effect of EV cars on the grid assuming all cars become EV and also the effect of cold weather on the range of EVs due to change in temperature in winter. This study investigates the additional energy needed in winter for the car to cover the same range. This chapter looks also at the profile of the power grid in winter and explores the measures needed to ensure reliable grid during winter with the introduction of HPs and EVs.

9.2. Electricity grid profile in the UK

It is important for power stations to maintain capacity security, so the provided electricity is sufficient to satisfy the demand. In addition, a balance between the supply and the demand of electrical energy must be in place, as it affects the frequency of the grid. According to the GB Security and Supply Standard, the frequency fluctuations must be limited to ±0.2 Hz for normal power station operation (Teng et al., 2016). In wintertime, the load pattern of the grid fluctuates as seen in Figure 9.1 which almost takes the profile of a mouse.

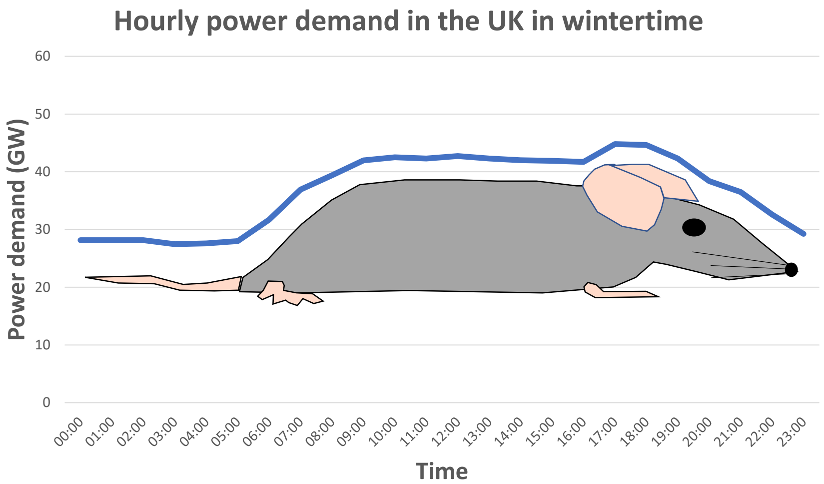


Figure 9. 1 *- Hourly power demand in the UK in wintertime which resembles a mouse profile (based on data from (Stolworthy, 2022)).*

Figure 9.1 showcases the hourly power demand in the UK in cold seasons. The shape of the curve resembles a mouse profile. In particular, the back torso and the ears areas show when peaks on the grid appear. At around 5 am the power demand gradually reaches approximately 42 GW over a period of 4 hours. It remains relatively flat until around 4 pm where the load on the grid increases sharply by roughly 3 GW. With the demand curve's shape of a mouse, it would be challenging to use more renewable energy and provide stable electrical energy.

Currently, the UK is on the path to reduce fossil fuels from the energy generation mix. It is expected the country to reach net zero carbon emissions by 2050 (HM Government, 2021). Some of the strategies the government is planning to adopt in order to become carbon neutral is to increase the capacity of wind and solar sources of electricity, electrify the transportation by banning fossil fuel vehicles by 2050, and decrease dependence on fossil fuels for the heating sector by implementing heat pumps as part of the Heat and Building Strategy for meeting the net-zero 2050 targets (HM Government, 2021). In addition, lockdown restrictions led to 13% drop in carbon emissions in 2020 compared to 2019 (Climate Change Committee, 2022). On top of that the electricity price has increased sharply, approximately 43% as of 2022 compared to 2020 (Yurday, 2022).

Figure 2 below presents the current electricity generation mix in the UK. From the graph it is evident that the majority of the current electricity is generated by gas at around 47% (Stolworthy, 2022). The capacity of wind and solar have increased slightly in 2021 compared to 2020 (Harris et al., 2022). Although, the wind and solar capacities have increased, the environmental conditions are still not favourable for these sources to provide and maintain steady electricity throughout the day (Stolworthy, 2022). This suggests that UK still have to rely on fossil fuels to provide electricity during peak hours or when wind and solar are not enough and therefore contribute to more carbon emissions (Figure 9.2) (Stolworthy, 2022).

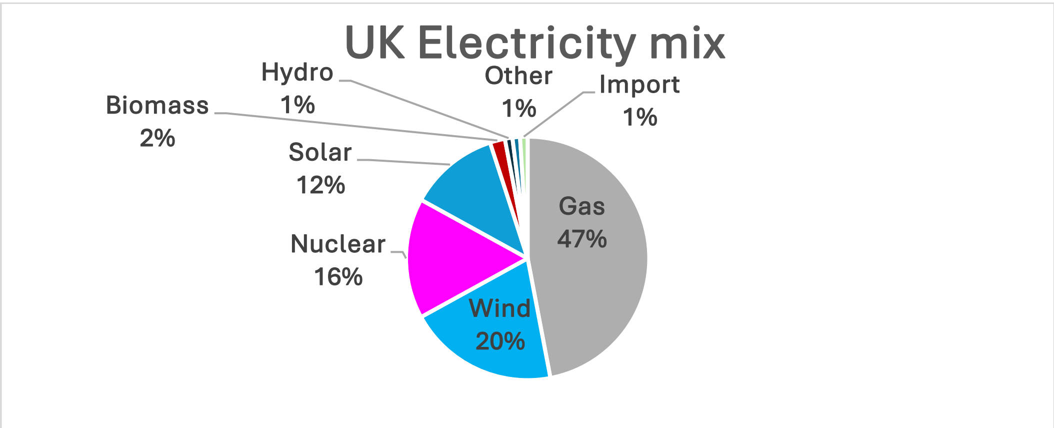


Figure 9. 2 *- UK electricity generation mix 2022 (based on data from Stolworthy (2022))*

The Covid-19 pandemic is considered as one of the most impactful global health emergencies in the century. It has not only affected the health of people, but also indirectly through lockdowns the economy of almost every country around the world as well as the energy demand and consumption.

With the confinement measures many people throughout the world were forced to work from home, which is expected to have some effect on the electricity consumption. For most countries the start of lockdown measures were implemented between February and March 2020. After that each country individually assessed the right time to open the businesses and the borders depending on the infection rates (Li et al., 2022). For Germany and most of the US, there was a considerable reduction in electricity demand (Li et al., 2022). In addition, Poland is a country that similar to the UK implemented more than one lockdown for 2020 (Malec et al., 2021). Research investigating the impact on the energy demand in Poland due to Covid-19 concluded that the restrictions caused a drop of approximately 23% in energy consumption during the first lockdown in March-May period 2020 and around 11% during the second lockdown in October-November period of the same year (Malec et al., 2021). A similar situation can be noticed in Turkey (Türkiye) where the first incident of Covid-19 was detected in March 2020 and restrictions followed soon after (Bulut, 2020). In April and May of the same year, the electricity production dropped by around 15% and 16.5% respectively compared to the same months in 2019 (Bulut, 2022). According to the same research, the electricity consumption of the industry and residential sectors increased slightly in 2020 compared to 2019, but there was a considerable reduction for the business sector in 2020, suggesting that the businesses have great influence on the energy consumption in Turkey (Bulut, 2022).

In the UK the first lockdown measures were introduced on 26th March 2020. During this time people were advised to stay at home and work from home (The Institute for Government, 2022). In June of the same year the restrictions were slowly removed until 5th November 2020, when a second lockdown came into force, which continued until 2nd December (The Institute for Government, 2022). Particularly, in the UK the only increase that was noticed during 2020 was of gas consumption as the majority of people were forced to work from home (Sen and Al-Habaibeh, 2021). Industry and business buildings tend to be more energy efficient when it comes to heating (Sen and Al-Habaibeh, 2021). Overall, it was estimated that there was a drop in electricity consumption in the commercial and industrial sectors between March and June of 2020, which resulted in a significant reduction of carbon emissions. However, households with houses that were not properly insulated were affected by increased energy bills during the winter lockdown period (Sen and Al-Habaibeh, 2021).

9.2.1. Change in demand

As shown in Figure 9.1, the electricity demand in the UK resembles a mouse profile. What is the cause in the change in demand? To address this, the authors have investigated the grid patterns in the UK in winter before and during Covid-19 pandemic lockdown. Firstly, a graph using data from Gridwatch (Stolworthy, 2022) has been developed to showcase the daily demand in wintertime along with each source of electricity in the UK. The reason for that was to see how the demand fluctuates throughout the day and when load peaks occur. After that, the annual electricity consumption in the UK from 2012 to 2021 was compared. This allowed us to monitor whether the overall consumption is increasing or decreasing. The Covid-19 restrictions took place in 2020 and 2021 in the UK. In particular, the strictest and longest measures happened between March 2020 and June 2020, as well as November 2020. That is why the daily electrical energy consumption on a November weekday and on a weekend for 2019, 2020, and 2021 was explored as the ambient temperatures can drop as low as 1°C during that month as shown in Figure 9.3 (Time and Date, 2022). This analysis allowed to determine not only how lockdown measures affected the energy consumption, but also if the demand curve followed the same fluctuations curve as pre and post pandemic period.

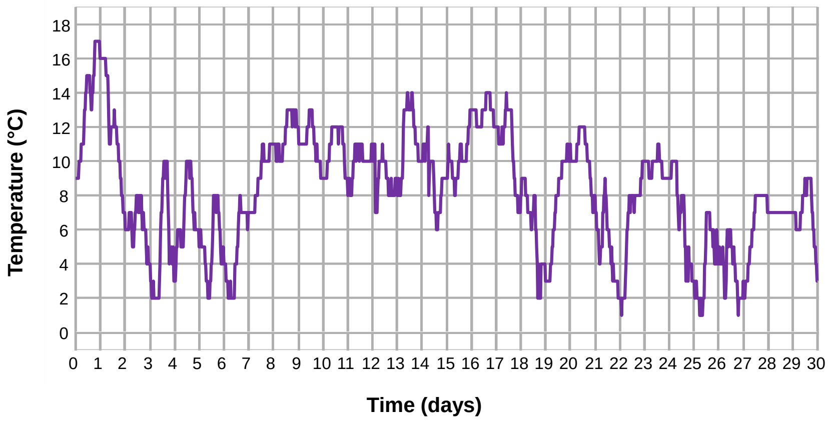


Figure 9. 3 *- Ambient temperature in Nottingham, UK in November 2020 (based on data from (Time and Date, 2022)).*

Figure 9.4-a and 9.4-b represent the daily power demand in winter and the annual electricity consumption in the UK respectively.

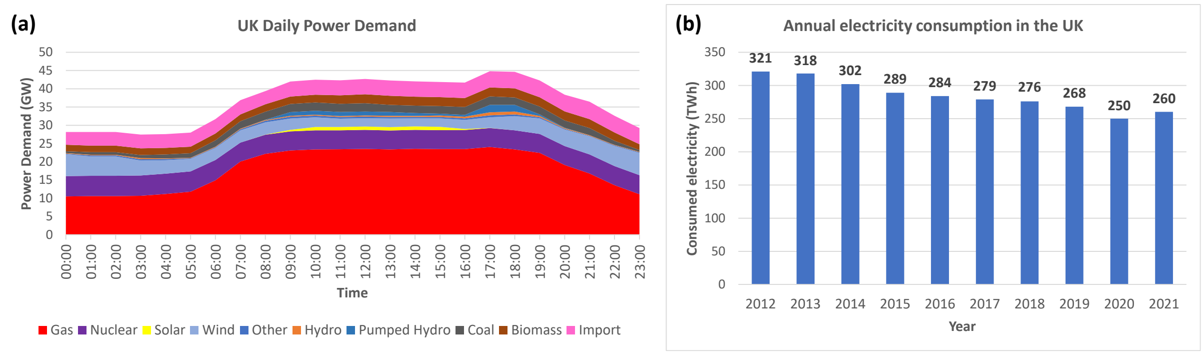


Figure 9. 4 *- The Daily power demand in the UK (a) and Annual electricity consumption in the UK (b) (based on data from Stolworthy, 2022)*

From Figure 9.4a it is evident that the majority of the demand is satisfied by gas. There are very sharp peaks on the grid at around 5 am and again at 4 pm. From Figure 9.4b, it can be noticed that in 2020 the annual consumption was lower than the rest of the years. In 2020 there were 2 lockdowns that took place, one in spring and one in winter (The Institute for Government, 2022).

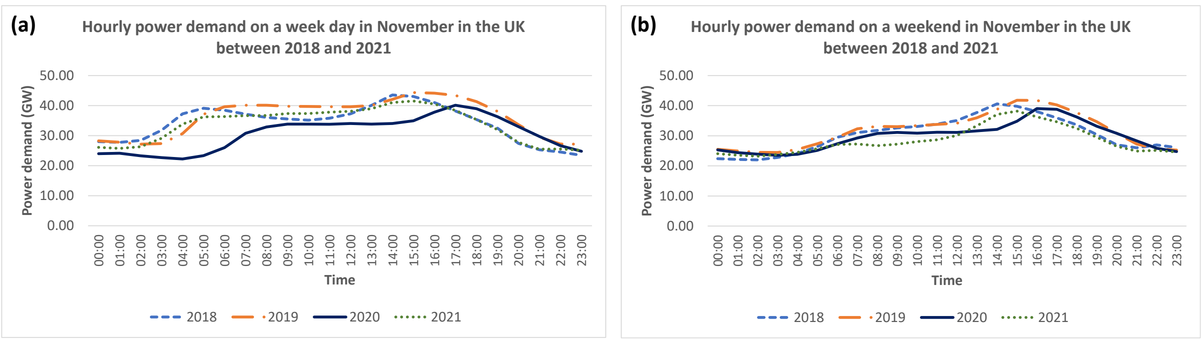


Figure 9. 5 *- Hourly demand comparison on a weekday (a) and Hourly demand comparison on a weekend (b).*

Figures 9.5a and 9.5b represent the hourly demand on weekdays and on weekends respectively in November. November was chosen specifically as the 2nd lockdown in the UK took place for the whole duration of that month in 2020. In both figures, the power demand followed a similar pattern, in the shape of a ‘mouse’. The main noticeable change is during the weekdays in 2020, the increased demand in the morning starts at around 7 am, and the evening one at around 5 pm, compared to approximately 4 am and 4 pm for 2018, 2019, and 2021. One of the reasons for the shift of the demand peaks is the daily habits and activities of people across the UK. Many were forced to work from home due to the Covid-19 restrictions (The Institute for Government, 2022). In regard to Figure 9.5b, there is no considerable change in the demand pattern during the weekends for all the analysed years.

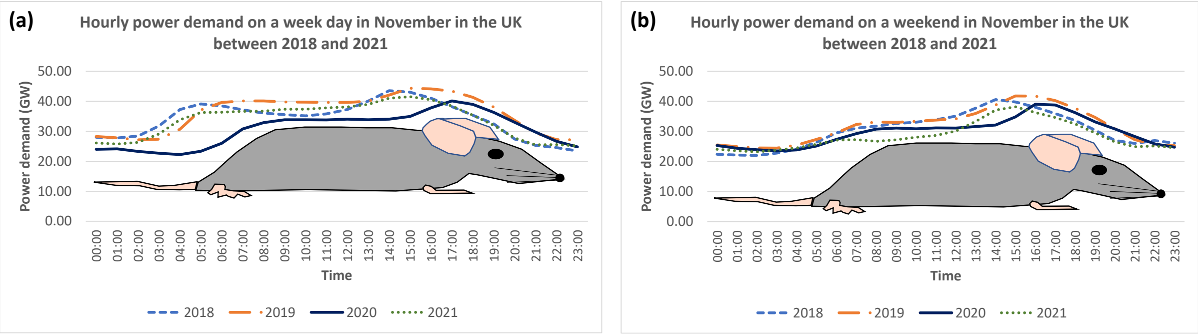


Figure 9. 6 *- The Shape of the hourly weekday demand (a) and the shape of the hourly weekend demand comparison (b).*

Figures 9.6a and 9.6b present the shape of the power demand curves compared to previous years and with 2020 lockdown period. The shape of the 2020 curve resembles a mouse following the same trend as previous years. This shows that Covid-19 affected only the amount of consumed electricity, but it did not impact the shape of the demand curve.

One of the challenges when using heat pumps and electric vehicles is how to balance the grid so that the demand is flat and not cause a problem in cold winter evening with the lack of wind and solar energy.

9.3. The expansion of electric cars in the UK

9.3.1. Transportation in the UK

According to the Department for transport in the UK there were a total of 38.9 million vehicles in the country (Figure 9.7).

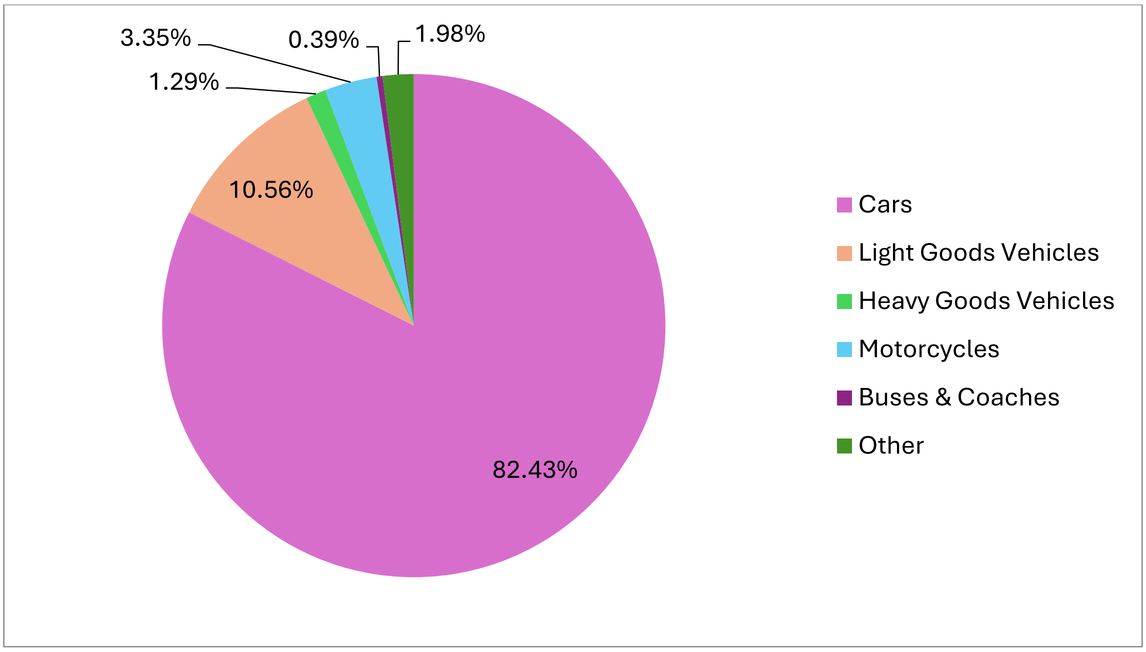


Figure 9. 7 *- Percentage proportion of vehicles type in the UK fleet (UK Government; Department for Transport, 2019).*

The number of cars in the UK is about 32 million or roughly 82 per cent of the total number of vehicles. Popularity of cars plays a vital role when it comes to emissions, fuel and energy consumption. In a socio-demographic study related to the choice of a vehicle type, it was revealed that education, income and knowledge about vehicles is crucial when it comes to vehicle preference (Simsekoglu, 2018).

Table 9. 1 *- Most popular conventional cars in the UK (UK Government; Department for Transport, 2019).*

Brand and model	Licensed units for 2019	Percentage popularity
Ford Fiesta	1.5	26.32
Ford Focus	1.2	21.05
Vauxhall Corsa	1.1	19.30
Volkswagen Golf	1	17.54
Vauxhall Astra	0.9	15.79
TOTAL	5.7	100.00

From table 9.1 can be determined that Ford is the most popular car brand in the UK.

The Department for Transport provides statistics for electric cars in the UK as well.

Table 9. 2 *- Most popular electric cars in the UK (UK Government; Department for Transport, 2019).*

Brand and model	Registered units in 2019	Percentage from the total amount of EVs registered in 2019
Tesla Model 3	5,500	20.37
Nissan Leaf	4,500	16.67
Jaguar I-Pace	3,500	12.96
BMW i3	3,400	12.59
Volkswagen e-Golf	2,900	10.74
Renault Zoe	2,900	10.74
Nissan E-NV200	1,500	5.56
Tesla Model S	1,400	5.19
Tesla Model X	1,400	5.19
TOTAL	27,000	100.00

According to the data of the registered EVs for 2019 in the UK, Tesla Model 3 is the most popular electric car in the country (Table 9.2).

Based on that was acquired, the specifications of these electric vehicles and represented them in the table below:

Table 9. 3 *- Popular electric vehicles in the UK and their specifications.*

Brand and model	Popularity (%)	Battery capacity (kWh)	Energy consumption (kWh/100km)	Range (km)
Tesla Model 3	20.37	62	25	248
Nissan Leaf	16.67	30	16	187
Jaguar I-Pace	12.96	90	22.7	396
BMW i3	12.59	46	18.64	246
Volkswagen e-Golf	10.74	32	16	200
Renault Zoe	10.74	23.3	16	144
Nissan E-NV200	5.56	38	20.5	185
Tesla Model S	5.19	100	16.3	613

Table 9.3 provides specifications for the most popular EVs in the UK.

The number of electric vehicles is slowly increasing, not only because they are an eco-friendlier solution to the environmental issues, but also, they are more efficient than conventional cars (Holmberg and Erdemir, 2019). In addition, electric vehicle owners are eligible to a subsidy from the government, which is another reason people may choose EV over petrol/diesel cars.

In regard to the carbon intensity of petrol and diesel cars, the Department for Transport in the UK have determined that a conventional vehicle in the country is contributing to about 122 grams of carbon dioxide per kilometre (gCO_2/km) (UK Government; Department for Transport, 2018).

The distance that a car travel affects how much carbon emissions will be released into the atmosphere. In the UK the total distance that cars and taxis are traveling per year is 415 billion kilometres, or approximately 12,968.75 km on average for a single car (UK Government; Department for Transport, 2019).

9.3.2. Electricity demand in the UK

Electricity is vital to maintain not only the industry but also the everyday life of people. From lights in our home, to charging our phones and electric cars to even power computers.

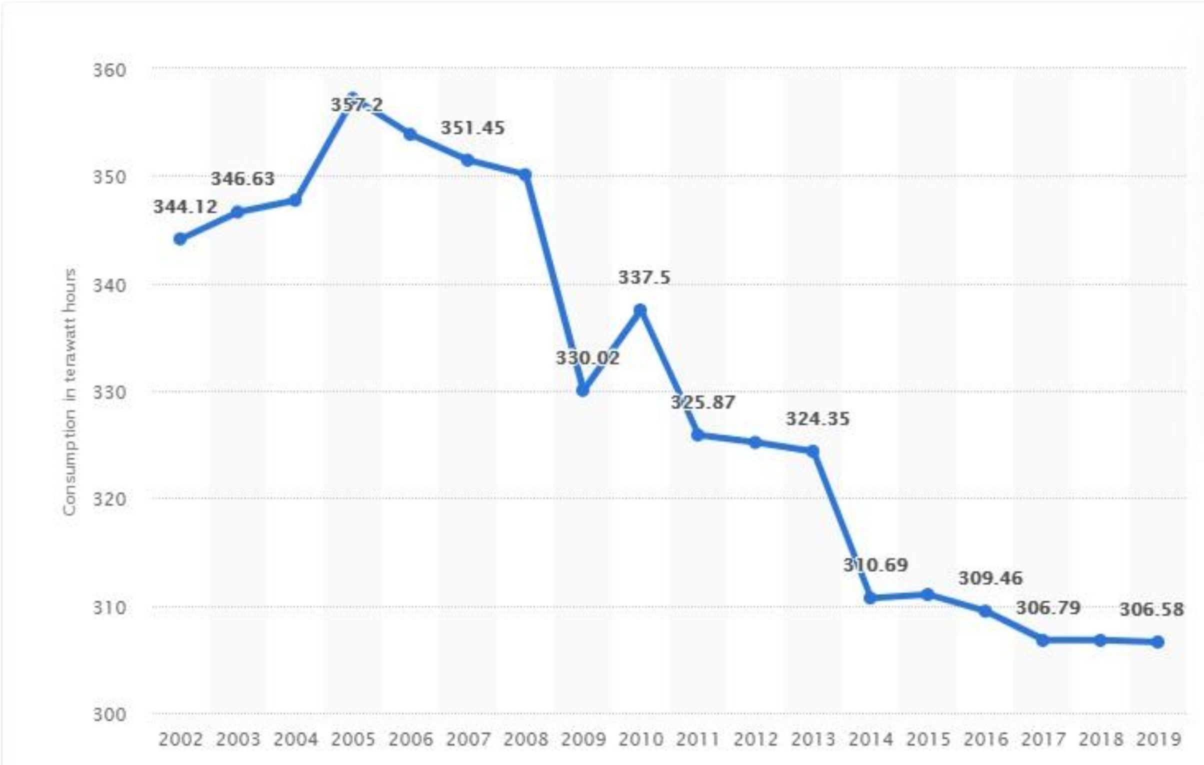


Figure 9. 8 *- Electricity consumption in the UK between 2002 - 2019 (Statista, 2020).*

As it can be seen in the figure 9.8, the United Kingdom's electricity demand has decreased considerably over the past 6 years. One of the reasons for that is the improvement of technology; more efficient appliances, computers and electric cars.

Over the past few years, the electricity generation mix has slightly shifted to using more environmentally friendly resources.

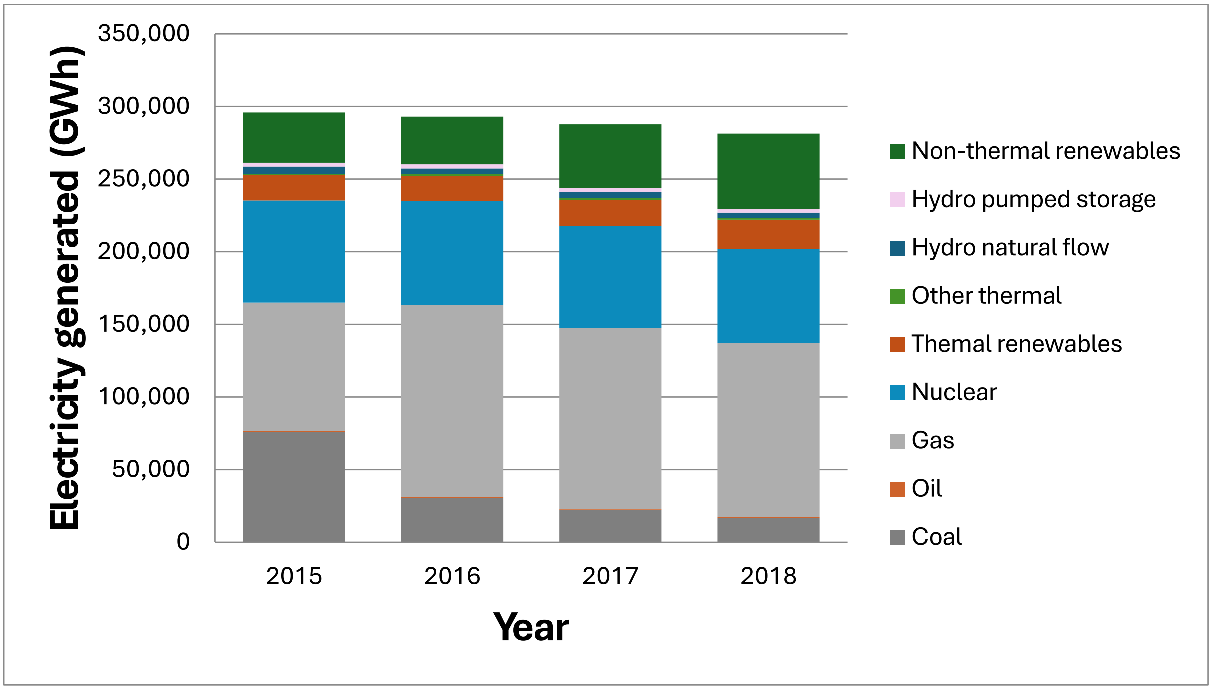


Figure 9. 9 *- Electricity generation by fuel in the UK between 2015 - 2018 (UK Government. 2019).*

From figure 9.9 it can be seen that for the last 4 years the usage of coal as source of electricity generation has been reduced and the sector has focused on more eco-friendlier solutions such as nuclear and renewable resources. The use of gas as a resource has increased as well.

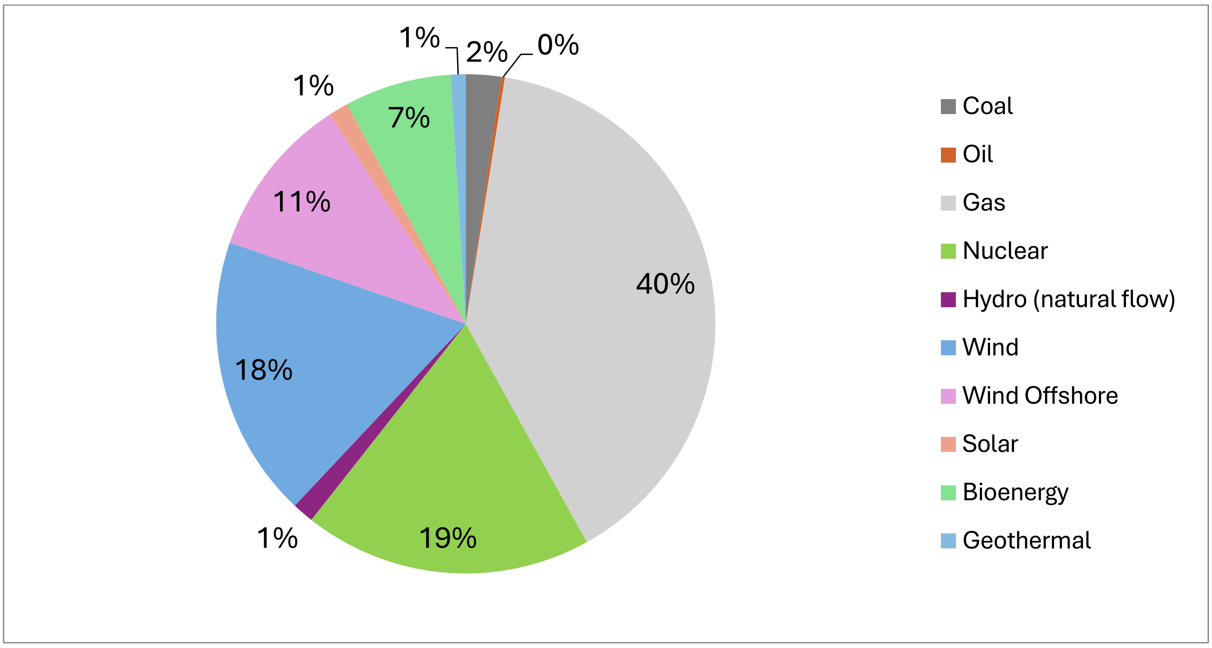


Figure 9. 10 *- Electricity generation mix in the UK for 2019 (GOV.UK. 2020).*

It is evident from the Figure 9.10 above that the UK has reduced the usage of coal as a fuel considerably and is still focusing on increasing the use of nuclear and renewables.

9.3.3. Carbon emissions in the UK

Carbon dioxide represents approximately 81 per cent of the total greenhouse gas emissions in the UK. For 2019 according to the Department for Business, Energy and Industrial Strategy the total amount of carbon emissions were estimated to be 351.5 million tonnes of CO_2 and the total amount of greenhouse gases in the country was 435.2 million tonnes of CO_2.

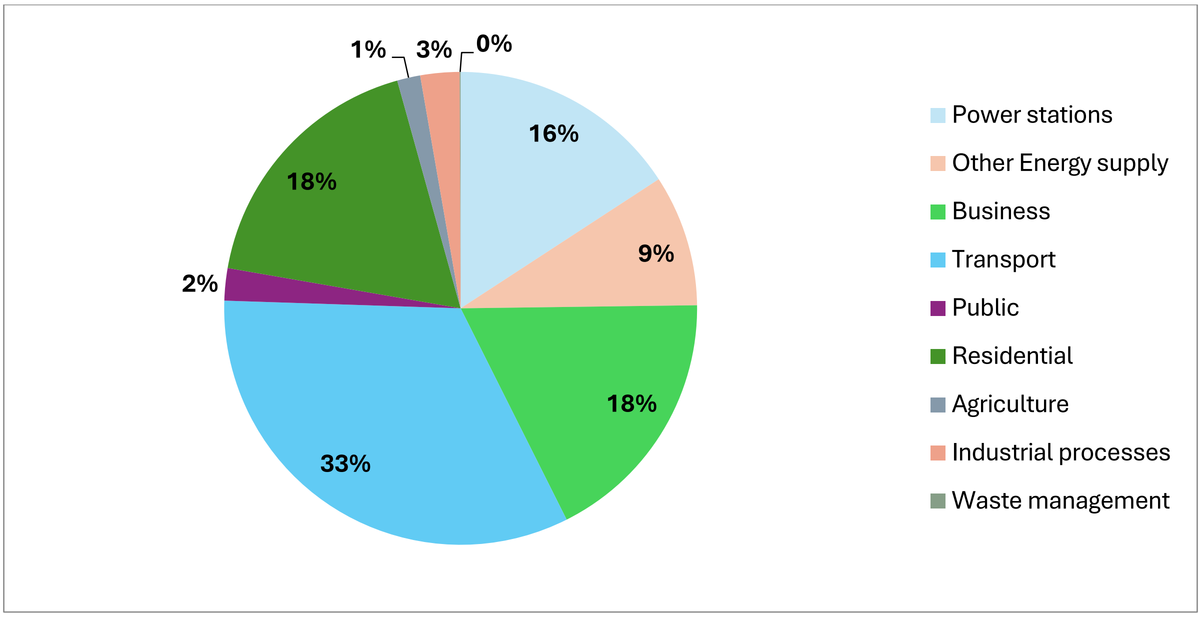


Figure 9. 11 *- Greenhouse gas emissions by source in the UK for 2019 (reproduced) (Data.gov.uk. 2020).*

Figure 9.11 above represents the proportion of carbon emissions from each sector in the United Kingdom. Transport contributes to 33 per cent of the total carbon emissions in the country or 119.6 million tonnes of CO_2 for 2019. Power stations generate approximately 16 per cent of the total carbon dioxide emissions or about 57.4 million tonnes of CO_2 for 2019.

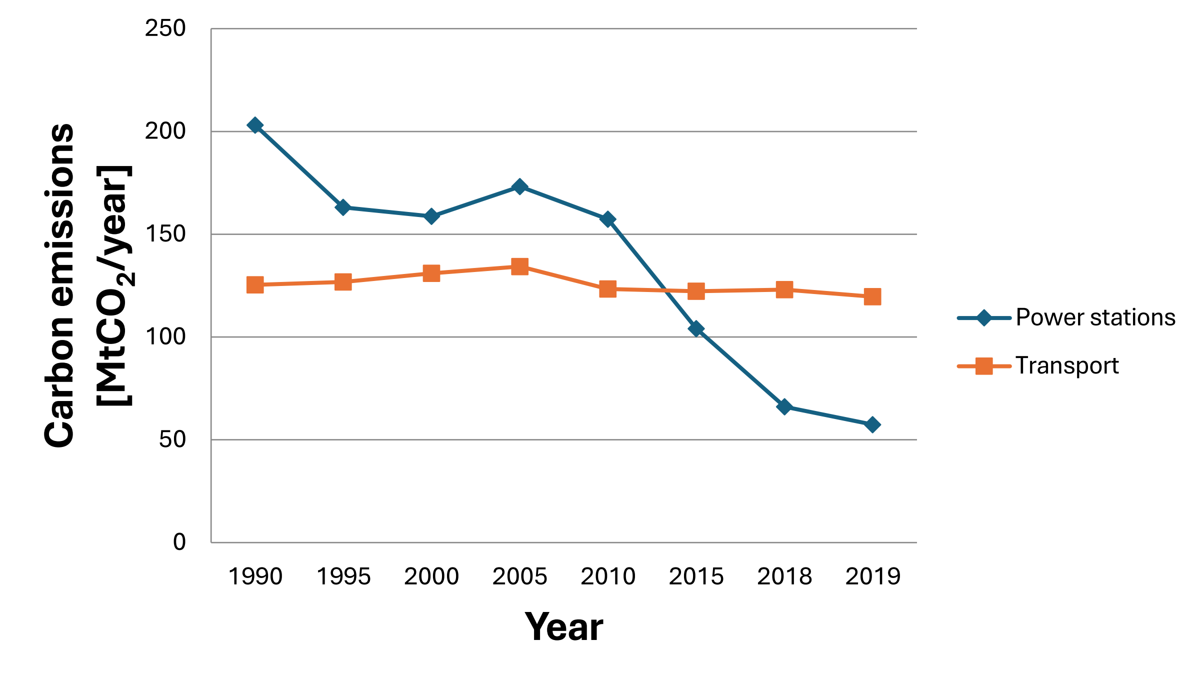


Figure 9. 12 *- Carbon emissions from the Transport and Electricity grid sectors (Data.gov.uk. 2020).*

From Figure 9.12 it is evident that transport emissions have remained roughly the same for the last 30 years, while the carbon levels from the electricity generation sector have dropped significantly over the last 5 years. Ever since the reduction of coal as a fuel for electricity production and the implementation of renewables and nuclear power to the grid has aided to reduce the carbon dioxide levels in the UK.

Each source of electricity has different carbon intensity. Carbon intensity represents the amount of carbon dioxide that is emitted per kilowatt hour of electricity produced [gCO_2/kWh].

The table below represents the carbon intensity of each source that is used to generate electricity in the UK:

Table 9. 4 *- Carbon intensity of each source of electricity in the UK (Parliamentary Office of Science & Technology, 2011).*

Source of electricity	**Carbon Intensity (gCO_2/kWh)**
Nuclear	26
Coal CCS	220
Gas CCS	200
Hydro	7
Solar PV	88
Geothermal	15
On-shore Wind	20
Offshore wind	10
Bioenergy	165

Coal and Gas contribute to most of the carbon dioxide emissions in the country (Table 9.4). With the reduction of coal usage and the increase of nuclear power and renewable sources of electricity the CO_2 levels have improved for the last 5 years.

In a study comparing the life cycle of both conventional and electric cars was estimated that the manufacturing carbon emissions for internal combustion vehicles are roughly 31g for a single vehicle and 48 g for a single electric vehicle. Although, electric cars contribute for higher CO_2 levels during manufacturing, they do not produce any emissions while driven, while for a conventional car additional 30 g CO_2 are emitted from fuel production processes and about 163 g while driven. There are additional carbon emissions for conventional cars due to the transportation of fuel to gas stations. From that study it was concluded that conventional cars have higher impacts regarding carbon dioxide emissions related to the life cycle of the vehicles (Holmberg and Erdemir, 2019).

In this chapter the effect EVs' effect on the electricity demand is investigated. And also, the effect on carbon emission is explored.

9.3.3.1. Determining the additional electricity

In a situation where all cars are replaced by electric vehicles would cause a rise in the electricity demand.

In order to properly calculate how much the power demand would increase, average values of energy consumption by electric cars had to be determined. Each brand and model have different power consumption, that is why most popular electric vehicles in the UK and their specifications have been studied. The following formula was used to estimate an average value of the energy consumption by the EVs according to their percentage popularity:

$$\sum_{i=1}^{n} = (EC_i \times PP_i) \quad \text{(Eq. 30)}$$

Where: $\boldsymbol{EC}$ is the electricity consumption by the electric cars (kWh/100km); $\boldsymbol{PP}$ is the percentage proportion of the electric vehicles according to brand and model's popularity, and it is represented as (value)%/100; n is the number of cars that are included in our study.

Applying Eq. (30) it was estimated the average energy consumption by a single electric car.

Through Chapter 9.3.2, it was determined what is the number of cars in the UK (32 million) and their annual distance travelled (415 billion km) (UK Government; Department for Transport, 2019).

After estimating the average energy consumption by EVs (Eq. 30), the total energy required by all (32 million) electric cars on the UK road was calculated, when they replace all conventional cars:

$$ER = (ADT \div 100) \times AEC \quad \text{(Eq. 31)}$$

Where: $\boldsymbol{ER}$ is the energy required to power all the electric cars in the UK (kWh); $\boldsymbol{ADT}$ is the average distance travelled in a year by all cars in the country (km); and $\boldsymbol{AEC}$ is the average energy consumption by the electric cars (kWh/100km). After ER was found it was then converted it Terawatt hours (TWh).

According to a UK Government report the distribution losses through the electricity grid in Great Britain account for 7 per cent (UK Government, 2003). That was taken into account when the total electricity required to power all EVs in the country was calculated.

The electricity consumption in both current and EVs scenarios were compared.

9.3.3.2. Heating of car's passenger compartment

Electric Vehicles will need to consume some of the power from the battery for heating the passengers' compartment. Hence, heating will affect electricity consumption and the available range. When considering the average interior space volume of light-duty vehicles, it has been estimated to be 2.93 m^3 (Fueleconomy.gov., 2019). Assuming the internal temperature is kept at 21^{o}C as the desired temperature, the minimum average ambient temperature in the UK during the winter season is estimated to be 1°C (Met Office, n.d.). The following equation hence can be used to determine the heat required to warm up the car's interior:

$$E = m \times c \times (T_d - T_c) \quad \text{(Eq. 32)}$$

Where: $\boldsymbol{E}$ is the energy required to reach the desired temperature (J) $\boldsymbol{T_d}$; $\boldsymbol{m}$ is the mass of air inside the car (kg); $\boldsymbol{c}$ is the specific heat capacity of the air inside the car (J/kg. °C); and $\boldsymbol{T_d}$ is the desired temperature (°C); $\boldsymbol{T_c}$ is the initial temperature (°C)

Before applying Equation 32, the mass of air ($\boldsymbol{m}$) is determined using the following calculation:

$$m = \rho \times V \quad \text{(Eq. 33)}$$

Where $\boldsymbol{\rho}$ is the density of the air (kg/m^3); and V is the volume of the car's interior space volume (m^3).

The heat losses through the windows and external envelop are calculated using equation 34 (Al-Habaibeh et al., 2010):

$$P = 5.67 \times \varepsilon_{hot} \times \left[\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_{out}}{100}\right)^4\right] + 3.8054 \times \vartheta \times (T_i - T_{out}) \quad \text{(Eq. 34)}$$

Where: $\boldsymbol{P}$ is the thermal power loss through convection and radiation in (W/m^2); $\boldsymbol{\varepsilon_{hot}}$ is the emissivity which for glass is 0.93 (unitless) (Engineeringtoolbox, n.d.) and for iron/aluminium is 0.29 (Engineeringtoolbox, n.d.); $\boldsymbol{Ti}$ is the surface temperature (K); $\boldsymbol{T_{out}}$ is the ambient temperature (K); *3.8054* is the convection heat transfer coefficient ($W/m^2.K$); $\boldsymbol{\vartheta}$ is the wind speed (m/s). For $\boldsymbol{\vartheta}$ the speed of a car is chosen to be on 60 miles/h or 97 km/h, which is in SI units will be 27m/s.

In order to determine $\boldsymbol{T_i}$ for the windows' surface and the car's body surface properly, a thermal image of a vehicle is taken, and a temperature data logger was attached to the external body of the car to evaluate the temperature performance. The car was driven at 60 miles per hour and the external surface temperature of the car was measured. Figure 9.13 presents the infrared image of the car, with calibrated temperature readings. The results have indicated that $\boldsymbol{T_i}$ for the windows was 9.9°C and the vehicle's body surface was 5.5°C. The authors have used a diesel engine car to estimate the windows and body temperature when the internal compartment is at 21°C. The assumption is that an electric car will need to maintain the same internal temperature from the batteries for a similar journey and weather conditions.

Figure 9. 13 *- The infrared image of the tested car during winter with calibrated temperatures based on the measured values from the temperature data logger.*

Equation 34 is used to estimate the heat losses through the windows and windscreens area which and their temperature is of 9.9 ºC (Figure 9.13) and an area of 2.96 m^2; and also, for the car body (doors and panels) which is estimated to have an area of 5.57 m^2 (Jackson, 2008) and at a temperature of 5.5ºC. Equation 33 is used to calculate the energy needed to keep the passengers' compartment at a temperature of 21ºC with the assumption that the driver is the only person on-board without other passengers. This analysis will provide the amount of energy that will be needed from the battery to keep the diver at a comfortable temperature and prevent condensation on the windscreen (ignoring any electric heaters used directly to heat the windscreen). This is expected to influence the actual range of the car in cold weather and the analysis will provide an insight into this. The average range of an electric car is calculated using Equation 30 to determine the average battery capacity and Equation 31 to find out the average range of an EV. Equation 31 is used to calculate the range when the heating is needed and to compare the range in warm weather when heating is not needed but ignoring air conditioning systems for cooling. The analysis assumed the driver's body will produce 100 watts of heat while in the car.

9.3.3.3. Carbon emissions

The analysis of the CO_2 levels is divided into two parts; Emissions from the transport and the electricity generation sectors. Both of these sectors are subject to a considerable change if electric cars are introduced into the British fleet. The idea is to analyse both sectors separately in order to acquire more accurate results. After establishing appropriate results for each sector, a comparison of the total carbon emissions per annum are compared with the ones when EVs are implemented into the UK traffic.

9.3.3.4. Emissions from the transport sector

Through Chapter 9.3.3, the amount of carbon emission in the UK in each sector was investigated, energy and transport in particular.

The investigation started with the estimation of CO_2 levels from cars in the UK per year. This was achieved by using the following equation:

$$Em = ADT \times CI \qquad \text{(Eq. 35)}$$

Where: ***Em*** is the carbon emissions (kg); ***ADT*** is the annual distance travelled by all cars in the UK (km); and ***CI*** is the carbon intensity of cars in the country ($kgCO_2/km$). After that ***Em*** was converted to Million tonnes.

Electric cars produce zero emissions while driven. That is why the value from Equation 35 was subtracted from the EV scenario, because it can be assumed they would not generate carbon dioxide while on the road. Both current and possible future carbon dioxide emissions from the traffic sector were compared.

9.3.3.5. Emissions from the electricity production sector

Power stations generate carbon emissions. Depending on the source, CO_2 levels differ. Fossil fuels such as coal and gas produce higher amounts of carbon dioxide during electricity generation, while nuclear power stations and renewable sources (i.e. wind turbines and PV panels) emit much less CO_2. In the introduction of this Chapter 9.3 it was determined how much carbon emissions are generated annually for each sector (Data.gov.uk, 2020) and the carbon intensity of each energy source in the UK (Parliamentary Office of Science & Technology, 2011) along with the electricity generation mix (GOV.UK, 2020).

The additional power that would be required by the electric cars in the United Kingdom would contribute to an increase in CO_2 levels. That is why the additional energy required by EVs was distributed, calculated from Equation 36, across the current generation mix. Then it was calculated how much carbon dioxide would each source emit additionally.

$$CO_2 = ES \times CI \qquad \text{(Eq. 36)}$$

Where; ***CO_2*** is the carbon emissions ($kgCO_2$); ***ES*** is the amount of energy produced by each electricity source (kWh); and ***CI*** is the carbon intensity of each corresponding source ($kgCO_2/kWh$). After that ***CO_2*** levels was converted to $MtCO_2$.

Equation 36 was used for each source of electricity and then the values were summed in order to determine how much more emissions from the power station sector would increase.

Both current and possible future emissions from that sector were compared.
Total carbon emissions in the UK generated per year from each sector in both scenarios were compared, allowing us to determine what would be the effect of electric vehicles on the UK carbon emission if they replace all conventional cars.

9.3.4. Results

9.3.4.1. Determining the additional electricity

The first step in our study was to determine the average energy consumption among electric vehicles, based on their popularity in the UK. After Equation 30 was applied, it was calculated that the average energy consumption of EVs is 19.45 kWh/100 km.
After this value was acquired, the author was able to calculate how much the energy demand in the UK would increase, using Equation 31. It was calculated that the additional electricity needed would increase by 80.7 TWh. Then the 7 per cent losses of the grid through distribution was added and it was calculated that the electricity generation would increase by around 86.3 TWh.

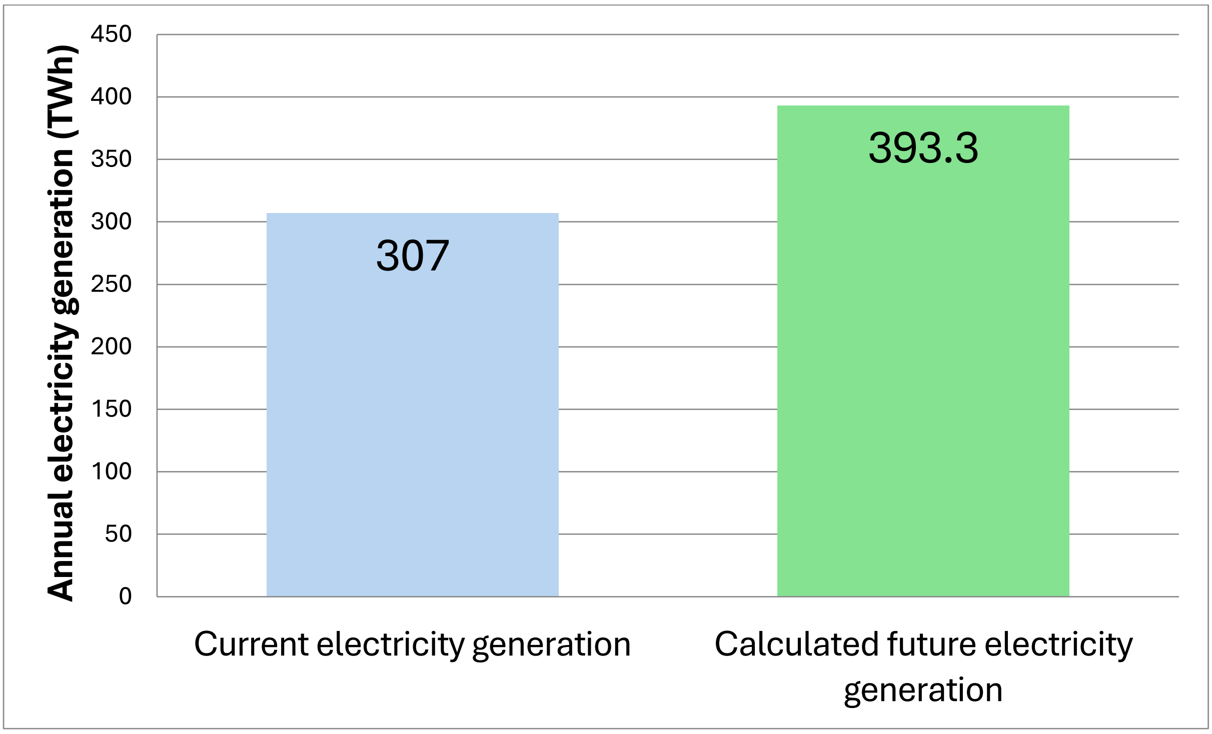


***Figure 9. 14** - Current and possible future electricity production comparison in the UK.*

Figure 9.14 shows that when EVs are introduced to the traffic fleet, the electricity generation per year would increase by about 22%. It was assumed that in the current power generation, the 7 per cent losses are added, making the total annual electricity production 307 TWh.

9.3.4.2. Car heating

The power needed to heat the car's interior during the winter, including heat losses through windows and car's body surface; assuming a car speed of 60 miles per hour and the ambient temperature of 1^{o}C, is calculated to be 5.36 kW. Which when expressed in terms of range, this will be equivalent to a reduction in the range of about 28%, given the above-assumed conditions and that only the driver is on-board (Figure 9.15). When the drop of range in winter is included this suggests that the calculated future electricity could reach 503.4 TWh.

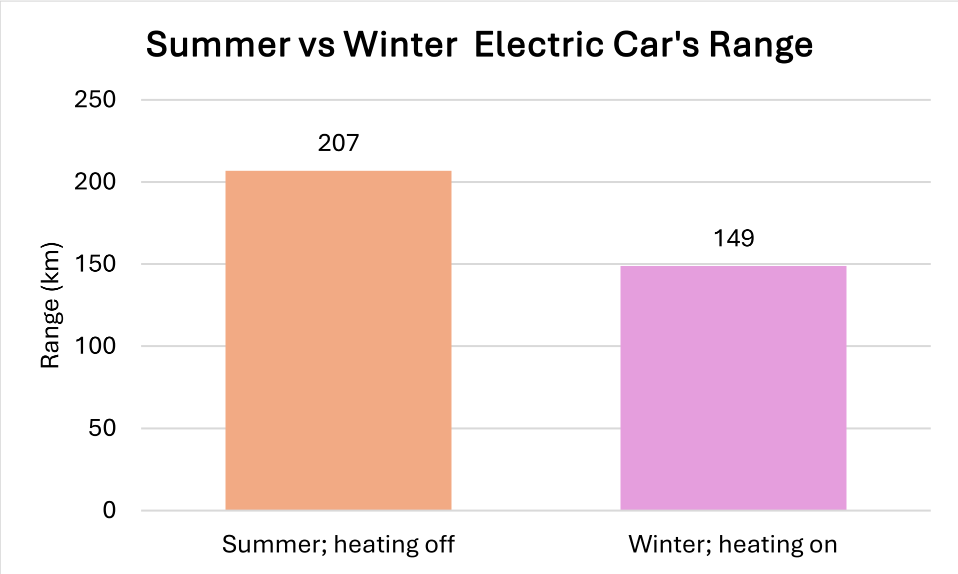


Figure 9. 15 *- A comparison between an EV during the summer and an EV during the winter with heating on.*

9.3.4.3. Carbon emissions

➢ **Emissions from the transport sector**

In Chapter 9.3.1 it was acquired the values for carbon intensity of cars in the UK and how much distance they travel per year. After equation 35 was applied, it was calculated that annually, all cars in the UK emit about 50.63 $MtCO_2$. It was assumed these emissions would be removed from the traffic sectors if electric vehicles replace conventional cars. According to the Department for Business, Energy and Industrial strategy's latest report, traffic generated approximately 119.6 $MtCO_2$ for 2019 (Data.gov.uk. 2020).

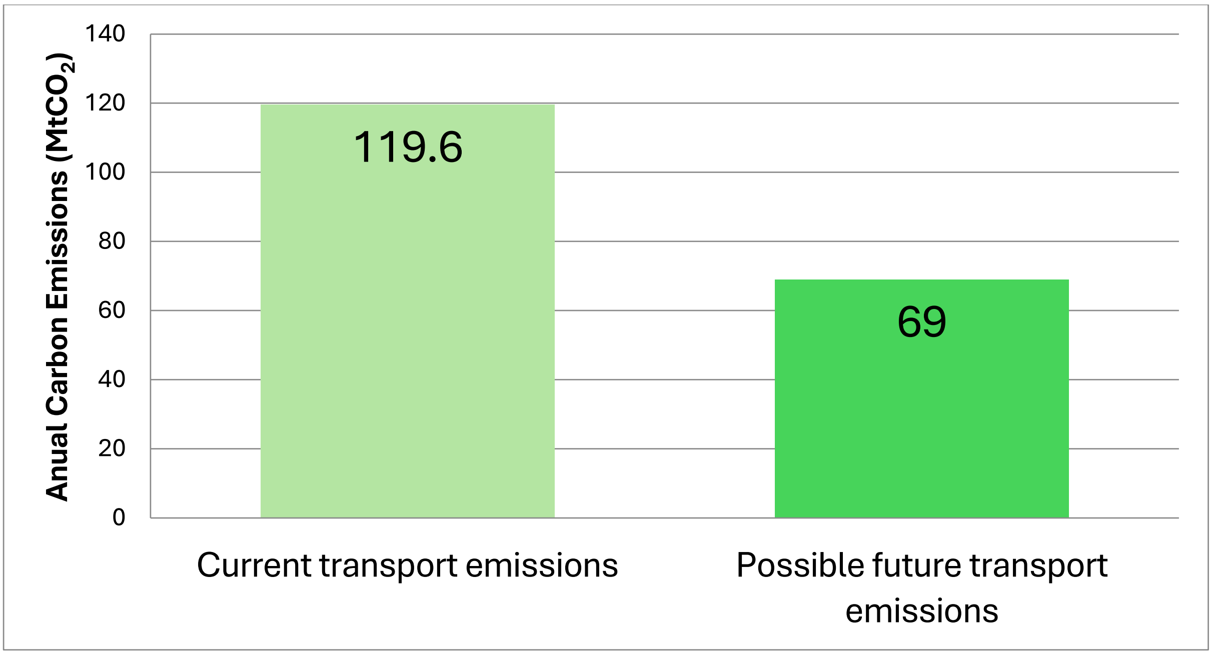


Figure 9. 16 *- Comparison between the current and possible future CO_2 emissions from the transport sector.*

Figure 9.16 represents what CO_2 figures would look like with electric vehicles replacing conventional cars in the UK. This suggests that emissions from petrol/diesel cars generate about 42 per cent from the total transport carbon levels, and that is how much carbon dioxide will be reduced by with electric cars.

- **Emissions from the electricity production sector**

After it was calculated how much more electricity has to be generated to power all electric vehicles in the UK that will replace conventional cars, it was assumed this additional power will be distributed across the sources according to the current generation mix represented in Figure 9.10.

After the additional electricity generation was distributed the across the appropriate sources this is how much additional power each source has to produce annually:

Table 9. 5 *- Additional electricity distributed across the appropriate sources in the UK.*

Major power producers	**Electricity produced (TWh)**
Coal	1.84
Oil	0.19
Gas	31.82
Nuclear	15
Hydro (natural flow)	1.12
Wind	14.7
Wind Offshore	8.5
Solar	1.03
Bioenergy	5.6
Geothermal	0.79
Total	80.7

After it was established how much power each source has to produce, and how much carbon emissions they produce per kilowatt hour of electricity generated (Table 9.5) the amount of carbon dioxide that will be generated from each power source was estimated using equation 38 and how much CO_2 levels will increase from the Energy sector. Through secondary data from Chapter 9.3.3 it was estimated that the amount of carbon emissions from power station per year are 57.4 $MtCO_2$ (Data.gov.uk. 2020).

Table 9. 6 *- Additional carbon emissions from each source of electricity in the UK.*

Major power producers	**Carbon emissions ($MtCO_2$/year)**
Coal	0.40
Oil	0.03
Gas	6.36
Nuclear	0.39
Hydro (natural flow)	0.008
Wind	0.29
Wind Offshore	0.085
Solar	0.09
Bioenergy	0.92
Geothermal	0.012
Total	8.6

This suggests that CO_2 level from the energy sector will increase by about 8.6 $MtCO_2$/year (Table 9.6).

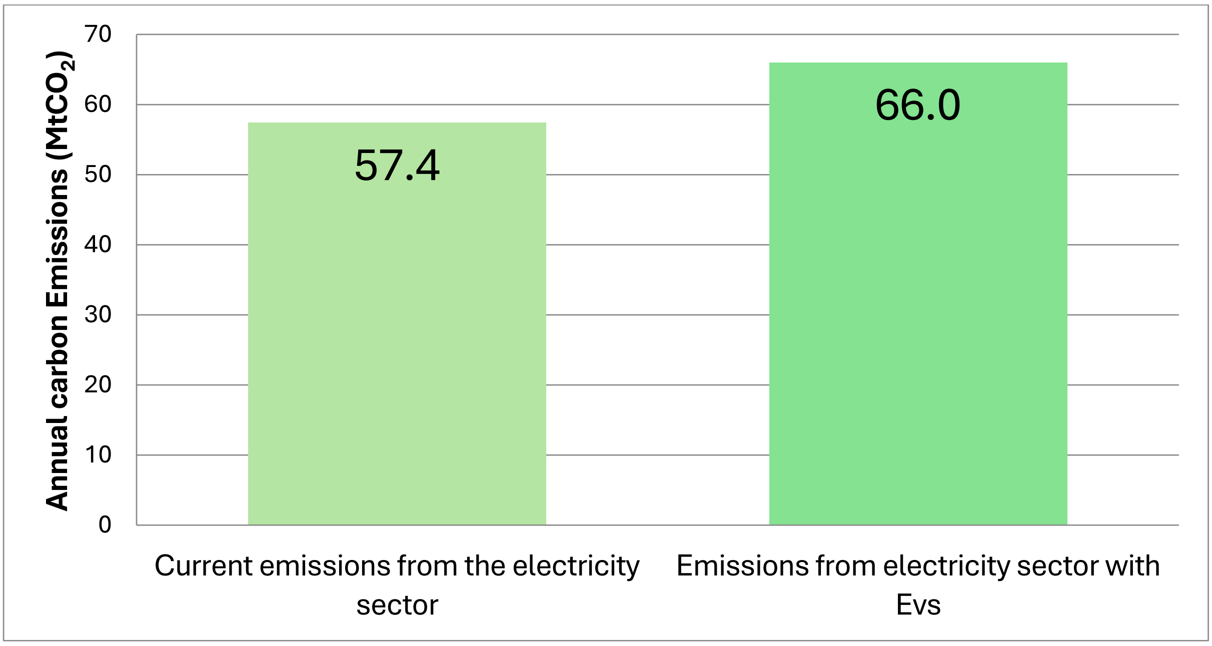


Figure 9. 17 *- Emissions comparison of the electricity generation sector.*

From the figure 9.17 it can be concluded that carbon emission levels will increase by about 13 per cent. When the drop of range of EVs in winter due to heating is also included, the emissions from the electricity sector would increase to 84.48 $MtCO_2$/year.

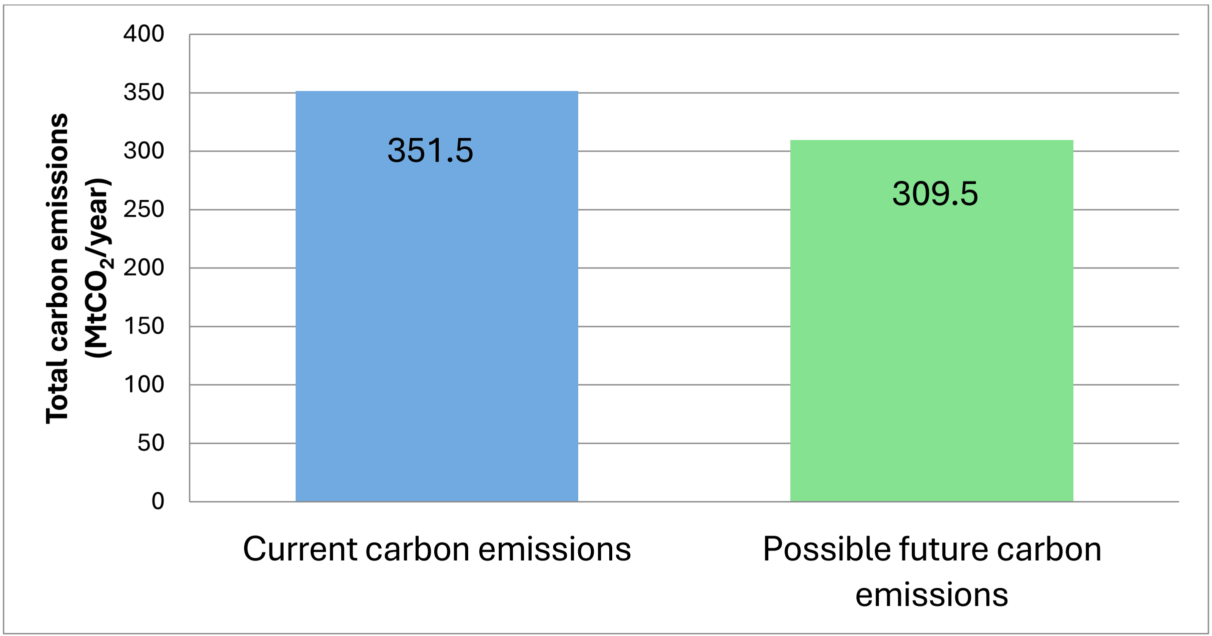


Figure 9. 18 *- Current and possible future emission comparison from all sectors combined.*

After comparing total CO_2 levels per annum in the UK with and without EVs replacing conventional cars it is evident from the Figure 9.18 that total carbon emissions will decrease by 42 $MtCO_2$/year or by about 12 per cent. However, if the drop of range in in winter is included due to heating required inside the car, the total possible emissions could increase to 396.16 $MtCO_2$/year, which may lead to higher emissions in total unless more eco-friendly sources of electricity are introduced in the UK. With the decrease of coal-fired power stations and the potential reduction of gas usage, the total carbon emissions may drop when EV are massively adopted in the UK.

9.4 Summary

Chapter 9 investigates the effect of electric vehicles on the carbon emissions in the UK. It was determined how much additional electricity has to be produced in a year to power all EVs and how the CO_2 levels will change. In this analysis data from the UK Government was used. The most recent one was from 2019. This suggests that if EVs are introduced into the British transportation as a replacement of conventional cars, the figures for power generation and carbon emissions are a subject to change. These changes would be more affected by the electricity generation mix. The UK has set targets to become one of the first countries to pass a law for net zero emissions by 2050 (UK Government, 2019b). These targets are planned to be achieved by implementing carbon capture and storage technologies and shifting to more environmentally friendly sources of electricity.

Although the figures for carbon emissions from the power generation sector across the years may vary, it was assumed that these changes will not be significant.

It also has to be mentioned that the UK Government is planning to bring forward the end of the sale of new petrol and diesel cars and vans in the country from 2040 to 2035 (UK Government. 2020).

The life cycle assessment of conventional and electric cars was not covered in this chapter, as the focus of this research was the energy consumption of driving the cars and the effect on the carbon emission in the UK. Future investigation on that matter would be required in order to acquire more comprehensive results, once detailed data is available.

The manufacturing of both vehicles produces carbon emissions, but the production of EVs contribute for slightly higher levels of CO_2. On the other hand, conventional cars emit carbon emissions when driven, while EVs do not produce any emissions while operated. In addition, conventional cars require fuel in order to be driven. The extraction of oil, its distillation to gasoline and diesel, and the transportation to the fuel to the gas stations produce additional carbon emissions (Holmberg and Erdemir, 2019). For that reason, in this chapter it was assumed that there will not be a significant change in carbon levels from manufacturing, fuel production and transportation, and they will remain the same. This is subject to change, as there are constant innovations in the electric cars design and their manufacturing processes.

In addition, fossil fuels are a limited resource. At current rate of production and usage, it is expected that oil and natural gas will be depleted within the next 50 years, and coil will run out in about 100 years. Not only more renewable resources would be needed to provide electricity, but also other methods to power our vehicles (Singh, 2015). That is why switching to electric cars now would allow other transportation means such as airplanes and ships to utilise the remaining fossil fuels.

A switch to full battery power cars would have positive and some negative effects. As a result to the high number of EVs, the electricity demand and production will rise. Therefore, the carbon emissions from the energy sector would increase slightly. On the other hand, the CO_2 levels from the transport sector would decrease significantly leading to a total drop of approximately 12 per cent of total carbon emissions in the UK. This leads to the conclusion that replacing all conventional cars in Great Britain with electric cars would have overall a positive effect on the environment improving the air quality. Switching to more renewable sources of electricity with less carbon intensity would allow for a further reduction of carbon dioxide levels.

In addition, during cold weather, owners would need to use the electric heating of the car, which uses energy from the battery, this is expected to reduce the range by 28%.

This chapter has also focused on the electricity consumption in the UK, and the electricity consumption patterns. It seems that the UK is ‘trapped’ in user patterns by the ‘mouse’ shape, even during Covid-19 pandemic lockdown. This part of the research has considered the winter season before and after lockdown. The month of November was examined in more details because the ambient temperature can drop below 2°C and it was during the second lockdown in the UK. This suggests that households would use more heating, thus increasing the energy demand during that month. Whereas during the first lockdown between March and June, the weather is warmer. In the hourly demand comparison for the weekdays and weekends in November it was analysed the data between 2018 and 2021. However, the pandemic did not affect the fluctuating power demand, as show in Figure 9.6-a and 9.6-b as it followed similar trend as previous years. This current shape of a mouse creates a challenge ‘a trap’ in promoting more stable electricity. Especially when the UK electrifies the transport and heating sectors via electric vehicles and heat pumps. The strain on the grid could be severe if the same power demand is followed. For that reason, more battery storage systems combined with solar panels or wind turbines should be implemented along with thermal storage to reduce the peak load on the national grid and flatten the curve. More analysis needs to be performed in the future to analysis the reasons for such patterns and how to avoid them.

10. Discussions and Conclusion

10.1. Discussion

This research provides an extensive and multifaceted investigation into the challenges, potential, and implications of deploying air source heat pumps (ASHPs) across different housing types in the United Kingdom. The study not only addresses technical aspects of ASHP performance but also considers homeowner perceptions, grid impacts, and alternative heating solutions. Furthermore, it also looks into the competitive technology such as district heating and thermal storages as an alternative. The research also investigates the effect on the grid from the expansion of electric vehicles fleet in the UK. In this discussion, a thorough review of the research findings across multiple chapters is provided, assessing their contributions to the existing body of knowledge while highlighting limitations, addressing research gaps, and proposing avenues for future research. The discussion also engages with the broader implications of electrification on the power grid and draws comparisons with international trends.

10.1.1. Chapter 4 and 5: Experimental and Simulation-Based Analysis of ASHP Performance

The detailed experimentation in Chapter 4 offers significant insights into the real-world performance of ASHPs, focusing on the effects of frost cycles on efficiency. The test rig developed for this study allowed for close monitoring of frost accumulation and defrost cycles, providing empirical data that informs our understanding of how ASHPs behave in cold climates. Frost accumulation on the outdoor unit leads to decreased performance as the heat exchanger's ability to absorb heat diminishes. The study’s results showed that defrost cycles can impose substantial penalties on energy consumption, especially in colder regions.

This finding is critical for countries such as the UK, where cold winters may reduce ASHP efficiency. The simulated results further extend this analysis to ten cities globally, enabling a comparative understanding of how ASHPs perform in different climates. For UK policymakers, these findings are crucial because they underline the need for region-specific adaptations in ASHP technology or the introduction of hybrid systems, combining ASHPs with auxiliary heating systems during colder periods.

10.1.2. Chapter 5: Simulations of ASHP Energy Demand Based on House Type and Insulation Levels

Chapter 5 also moves beyond the mechanical operation of ASHPs to examine how external factors—particularly housing types and insulation levels—affect energy consumption and heating demand. This part of the study employed Simulink simulations, allowing for large-scale predictions of energy demand based on various combinations of house archetypes, insulation quality, and climate conditions. The study discovered that houses with poor insulation or of certain older types (such as Victorian terraced homes) consume significantly more energy when fitted with ASHPs compared to newer, well-insulated homes.

This chapter provides an important contribution to the literature by showing that ASHP performance is heavily dependent on building characteristics, a factor not deeply explored in prior research. While the environmental benefits of ASHPs are well documented, this research highlights that poorly insulated homes will see limited performance benefits and may even experience increased energy bills, especially if users resort to running their systems for longer periods to compensate for inadequate heating. This poses a policy challenge: if the government is to meet its target of widespread ASHP adoption, it will also need to support deep energy retrofits in older housing stock. Moreover, these results suggest that simply promoting heat pumps without addressing insulation quality may lead to inequitable outcomes where some homeowners experience higher energy costs.

10.1.3. Chapter 6: Case Studies and Interviews with Homeowners

The case studies in Chapter 6 complement the survey data (Chapter 7) by providing in-depth insights into the real-world experiences of ASHP users. By interviewing homeowners who have installed ASHPs, the research validated several survey findings, particularly around satisfaction levels and the need for improved insulation in homes. Most users reported satisfaction with their heat pump’s performance, especially in homes that were already well-insulated. However, homeowners in poorly insulated homes or colder areas expressed concerns about heating performance during the winter months.

The qualitative approach in this chapter allows for a deeper understanding of user satisfaction, filling a gap left by quantitative surveys. By exploring the lived experiences of ASHP owners, this research adds nuance to the understanding of the factors driving or inhibiting heat pump adoption. The interviews also provided actionable insights, such as the importance of professional installation and the need for better customer support and post-installation services to address issues like underperformance or technical difficulties.

10.1.4. Chapter 7: Homeowner Survey and Perceptions

The homeowner survey conducted in Chapter 7 provides valuable insights into the human factors that influence HP adoption, such as cost concerns, perceptions of efficiency, and comfort levels. The study found that while environmental awareness is relatively high among respondents, practical concerns about high installation costs and uncertainties about performance in cold weather limit the broader uptake of heat pumps. These findings emphasise the socio-economic barriers to HP adoption, which must be overcome for mass deployment to succeed.

A notable contribution of this chapter is its revelation of a significant knowledge gap among homeowners regarding how HPs function and their potential long-term savings. The survey showed that many homeowners were unaware of government incentives or held misconceptions about the efficiency of heat pumps in colder climates. These insights are crucial for developing targeted communication strategies to increase consumer confidence in heat pump technology.

10.1.5. Chapter 8: Case Study of Nottingham Ice Centre – Alternatives to District Heating

Chapter 8 provides a detailed case study of the Nottingham Ice Centre, exploring how heat pumps and thermal storages can be used as heat recovery methods to reduce or eliminate the reliance on district heating. The focus of this chapter is not merely on comparing district heating with other systems but on investigating innovative alternatives, particularly using ASHPs and thermal storages, to optimize energy recovery from cooling systems. This chapter is crucial because it presents a practical, real-world application of ASHP technology in a large-scale, high-energy-demand environment, such as an ice rink.

- **Heat Recovery Through Heat Pumps and Thermal Storages**

The Nottingham Ice Centre requires a significant amount of energy for refrigeration to maintain the ice, leading to excess heat production. The chapter explores how this waste heat can be recovered and reused to meet heating needs, significantly reducing the overall energy demand from district heating. By integrating thermal storage systems, the facility can effectively capture waste heat from the refrigeration process and storage it for future use, especially during peak heating periods and help reduces NIC's energy cost in winter. However, from the analysis in Chapter 8 it was revealed that heat pumps as a recovery method would not improve the cost effectiveness to supply the building with thermal energy compared to district heating.

This research contributes to the broader understanding of how heat pumps can be used not only for direct heating purposes but also for industrial-scale heat recovery, which is particularly relevant for facilities with large cooling demands. The integration of thermal storages further enhances system efficiency by allowing excess heat to be storaged and used when needed, reducing reliance on external energy sources.

- **Evaluation of Energy Efficiency and Cost Savings**

The chapter provides a thorough evaluation of the energy savings and cost-efficiency associated with using heat pumps and thermal storages for heat recovery at the Nottingham Ice Centre. The analysis reveals that reductions in energy costs and district heating dependence can be achieved through these alternative methods. The findings underscore the potential of using heat recovery systems to create more self-sufficient energy systems in industrial and commercial settings.

However further analysis on heat pumps as a recovery method in NIC revealed that energy cost would not be reduced considerably compared to district heating. The reason being that a high heat capacity heat pump would be needed to satisfy the centre demand. The price of electricity is higher than gas. Even if NIC completely eliminates district heating, their energy cost will remain relatively the same. Furthermore, in this chapter it was revealed that thermal storage will help reduce energy cost by decreasing the amount of thermal energy required by DH.

This contribution is particularly relevant for large facilities that produce significant waste heat, as it provides a clear pathway for reducing energy costs and carbon emissions by reusing otherwise wasted thermal energy. The chapter’s focus on practical, real-world applications enhances its value for energy planners and facility managers seeking to optimize their energy systems.

- **Broader Implications for Industrial and Commercial Applications**

The Nottingham Ice Centre case study has broader implications for other commercial and industrial settings with similar energy profiles. The lessons learned from this case can be applied to other facilities that generate substantial waste heat, such as data centres, manufacturing plants, and food processing facilities. Particularly, the performance and cost-effectiveness of both heat pumps and thermal storage to recover waste heat and supply it to the buildings while reducing the energy cost for the facilities. By showcasing the viability of heat recovery using HPs and thermal storages, the research demonstrates that these technologies can play a significant role in reducing reliance on external energy sources, such as district heating, and cutting operational costs in energy-intensive environments.

10.1.6. Chapter 9: The Impact of Electrification on the Grid

Finally, Chapter 9 explores the broader impact of ASHP adoption and the simultaneous rise of electric vehicles (EVs) on the UK's power grid. The chapter's analysis indicated that while the grid can handle the additional load under current conditions, a significant increase in HP and EV adoption could strain the grid, particularly during peak winter months. The analysis highlights the importance of advanced grid management solutions, such as demand-response technologies and smart grids, to mitigate potential grid instability.

This chapter provides a vital contribution to the understanding of grid dynamics in the context of widespread electrification. It highlights that while EV offer environmental benefits, their integration into the national energy system requires careful management of electricity demand. One key takeaway is the necessity for policy intervention to promote load-shifting technologies and energy storage solutions to alleviate peak demand pressures.

10.2. Limitations and Mitigations

However, certain limitations persist, primarily around the assumptions used in the simulations. For example, the reliance on an ideal control process in the simulation of frost cycles (Chapter 4) may not fully reflect the complexity of real-world heat pump operation, where factors such as hysteresis and equipment degradation over time could lead to deviations from predicted performance.

While the research provides valuable insights, several limitations warrant attention. First, the simulation models used in Chapters 4 and 5 rely on idealised assumptions about equipment performance and user behaviour. Future studies should incorporate more real-world variability to produce more granular and accurate predictions. Expanding the scope of future surveys and case studies to include more diverse populations and housing types would enhance the robustness of the conclusions.

Moreover, the study focuses predominantly on ASHPs and does not explore alternative heating solutions, such as ground source heat pumps or hybrid systems, in great depth. Future research could explore how these alternative systems compare in terms of cost, efficiency, and user satisfaction, particularly in colder climates.

In conclusion, this research offers a comprehensive analysis of ASHP deployment in the UK, providing valuable contributions to both academic knowledge and practical policy discussions. By addressing the technical, social, and grid-related challenges of heat pump adoption, it lays the groundwork for future research and policy initiatives aimed at achieving a sustainable, low-carbon heating system.

To mitigate these limitations, future research should focus on long-term monitoring of heat pumps performance in diverse real-world conditions to capture the impact of seasonal variations, equipment wear, and user behaviour over time. Expanding the survey sample size and conducting cross-national comparisons could further enhance the generalisability of the findings.

10.3. Addressing Gaps in Research

The research identifies key gaps in understanding the relationship between house types, insulation levels, and the efficiency of ASHPs. It provides a novel approach by integrating experimental results from a test rig with simulations across different housing types in the UK and ten global cities (Chapter 5). The simulations comprehensively address how variations in insulation level and ambient conditions impact air source heat pump energy consumption, which has not been thoroughly explored in previous literature. Moreover, the case studies, survey, and interviews conducted with UK homeowners (Chapter 6) offer critical qualitative insights into the social acceptance and real-world performance of heat pumps, thus bridging the gap between technical performance and user satisfaction. This dual focus on technical and behavioural aspects strengthens the robustness of the research findings.

10.4. Contributions to Knowledge

This research makes several contributions to the existing body of knowledge on the electrification of heating systems, specifically concerning the deployment of ASHPs in the UK. First, the integration of empirical and simulation data provides a detailed understanding of how different housing archetypes and insulation levels influence the efficiency and performance of heat pumps. This has direct implications for policymakers and grid operators as they seek to balance the increased electrification of heating with the stability of the power grid. Furthermore, the research sheds light on the socio-economic barriers to heat pump adoption, offering practical recommendations for improving homeowner acceptance through targeted incentives and educational campaigns (Chapters 6 and 7).

1. Integration of Empirical Testing and Simulation Modelling

One of the most notable contributions of this thesis is the integration of empirical testing with simulation-based analysis, as outlined in Chapters 4 and 5. While many studies rely solely on theoretical or simulation-based models to predict ASHP performance, this research validates those models through empirical data collected from test rig experimentation. The integration of real-world data strengthens the accuracy and reliability of the simulation models, offering a robust framework for predicting ASHP performance across diverse housing types and climate conditions.

By developing a test rig to measure the effects of frost cycles on ASHPs, this research addresses a crucial, often overlooked aspect of ASHP operation in colder climates. The empirical results not only validate the simulation but also offer practical insights into how defrost mechanisms impact overall energy consumption. This approach advances the methodology in the field by demonstrating the importance of integrating empirical data with simulation models to provide a more nuanced understanding of ASHP performance in real-world conditions.

2. Detailed Examination of the Relationship Between Housing Characteristics and ASHP Performance

Another key contribution is the in-depth analysis of how different house types and insulation levels impact the performance of ASHPs, particularly with respect to energy demand. This aspect of the research fills a significant gap in the literature, where many studies have focused on the mechanical efficiency of ASHPs without fully considering how building characteristics affect their effectiveness.

The Simulink simulations (Chapter 5) offer detailed insights into the variability of ASHP performance depending on factors such as insulation quality, house age, and structural design. The findings suggest that in poorly insulated homes, the expected efficiency gains from ASHPs may not be realised, and instead, users may experience higher energy bills due to prolonged system operation. These results provide a crucial contribution to policy discussions around energy efficiency and retrofitting, emphasizing that promoting ASHPs in isolation is insufficient—there must also be a concerted effort to upgrade the insulation and energy efficiency of older buildings.

3. Identification of socio-economic barriers to heat pump adoption

The survey and case studies (Chapters 6 and 7) provide an understanding of the socio-economic barriers that hinder the widespread adoption of HPs in the UK. By examining both the perceptions of homeowners who have adopted heat pumps and those who continue to rely on traditional gas boilers, this research uncovers important insights into the psychological, financial, and informational barriers that exist.

This contribution is crucial because it addresses a major gap in the existing literature, which often focuses on the technical and economic aspects of HP deployment without considering user behaviour and perceptions. The research highlights those high upfront costs, uncertainties about performance in cold weather, and a lack of awareness about government incentives are significant barriers to adoption. Moreover, it emphasises the importance of improving customer education and post-installation support to ensure that users fully understand how to optimise ASHP performance in their homes.

4. Contribution to Understanding ASHP Defrost Cycles and Grid Management

The detailed analysis of defrost cycles and their impact on ASHP energy consumption (Chapter 5) adds a crucial layer of understanding to the challenges of integrating ASHPs into the national energy system, particularly during winter months when energy demand is highest. The research's findings regarding the efficiency penalties imposed by defrosting offer new insights into how ASHPs operate in cold climates, where frost accumulation is common.

This contribution is particularly important for grid operators and energy planners, as it provides detailed data on how defrost cycles can lead to short-term spikes in energy consumption, potentially exacerbating grid load issues during peak demand periods. The research calls attention to the need for better defrost cycle management and the potential development of smarter ASHP systems that can minimise these inefficiencies. These insights contribute to the broader field of energy systems management by highlighting specific operational challenges that must be addressed for ASHPs to become a reliable and efficient part of the UK's decarbonised energy future.

5. Evaluation of heat pumps and thermal storages as a heat recovery method in commercial buildings.

- **Application of Heat Recovery in High-Energy Demand Facilities**

The research in Chapter 8 offers an in-depth analysis of how heat pumps and thermal storages can be applied in high-energy-demand environments, such as ice rinks. This demonstrates the versatility of HPs beyond residential settings and highlights their potential in commercial and industrial applications. The Nottingham Ice Centre case study provides real-world validation of the benefits of heat recovery, specifically in reducing energy waste and improving system efficiency.

- **Innovation in Thermal Storage for Energy Flexibility**

One of the key contributions is the examination of thermal storages as a solution for capturing and reusing excess heat. The ability to storage thermal energy for future use adds flexibility to energy management systems, allowing facilities to optimise their energy consumption during peak demand periods. This solution supports ongoing efforts to reduce reliance on district heating and improve energy self-sufficiency in large facilities.

- **Reduction of Reliance on District Heating**

This chapter explores the potential for facilities like the Nottingham Ice Centre to drastically reduce or even eliminate the need for external district heating by utilising on-site heat recovery. By capturing waste heat from refrigeration processes, these facilities can heat other parts of the building more sustainably. The findings suggest that integrating thermal storages can lead to energy and cost savings, providing a clear alternative to traditional district heating systems.

- **Scalability and Replicability for Other Industries**

The solutions outlined in this chapter are not limited to ice rinks; they can be scaled and adapted for a wide range of industries that produce excess heat. The research provides a template for other facilities to follow, potentially leading to broader applications of HPs and thermal storages in diverse industrial settings, contributing to the global effort to improve energy efficiency and reduce carbon emissions.

6. Insights into the Impact of ASHP and Electric Vehicle (EV) Adoption on the Grid

Chapter 9 makes a contribution by exploring the impact of electric vehicle (EV) adoption on the national grid. This analysis is crucial as it provides a forward-looking perspective on how the increasing electrification of both heating and transport will affect the UK’s electricity infrastructure.

The research’s findings suggest that while the grid is currently capable of the current adoption rate of heat pumps and electric cars, simultaneous growth in both ASHPs and EVs could create serious strain during peak periods, particularly in the winter. This contribution is highly relevant to current policy discussions about grid capacity and resilience, as it underscores the need for strategic investments in grid infrastructure, advanced demand-response technologies, and renewable energy integration to ensure that the UK’s energy system can support widespread electrification. By identifying specific risks and potential bottlenecks, this research provides essential guidance for future grid planning and the development of smarter, more flexible energy systems.

7. Cross-National Relevance and Scalability

While the research focuses on the UK, its findings have broader implications for countries with similar climates and housing stocks. The analysis of ASHP performance in different global cities, as well as the insights into grid management, provide a framework that can be adapted to other regions considering ASHP adoption as part of their decarbonisation strategies.

The scalability of the research findings is a key contribution, as it offers a model for other countries to follow when integrating ASHPs into their national energy plans. The use of both empirical and simulated data makes the results adaptable to various geographical contexts, allowing other nations to draw on this research to develop region-specific strategies for ASHP deployment. This cross-national relevance enhances the impact of the research, positioning it as a valuable resource for global discussions on sustainable heating solutions.

Overall, this research significantly advances our understanding of heat pump deployment in the UK, offering both theoretical and practical contributions to the fields of energy efficiency, grid management, and sustainable heating. By addressing technical, socio-economic, and policy-related challenges, the research provides a comprehensive framework for promoting the effective integration of ASHPs into the UK’s housing stock and national energy system. These contributions are not only relevant for academic discussions but also have immediate applicability for policymakers, industry stakeholders, and homeowners, guiding future efforts to decarbonise residential heating and meet the UK’s net-zero targets.

10.5. Conclusions

The findings of this thesis, spread across Chapters 4 to 9, offer comprehensive insights into the role of heat pumps and EVs in the UK's transition to a low-carbon heating sector. Key findings from each chapter can be summarised as follows:

- **Chapter 4**: The development and testing of the ASHP test rig demonstrated the critical role that frost cycles and defrost mechanisms play in the overall efficiency of heat pumps. The findings showed that even short defrost cycles could significantly affect power consumption, especially in colder climates, validating the need for robust defrost cycle control mechanisms in ASHPs.
- **Chapter 5**: The conclusions drawn from the simulation model confirmed that insulation levels and house types significantly impact the energy demand of ASHPs. These insights are particularly important for policymakers who are planning the mass deployment of heat pumps in diverse housing stocks across the UK.
- **Chapter 6 and 7**: The survey and case studies revealed the high level of environmental awareness among current ASHP users, but also highlighted the significant barriers to wider adoption, such as high upfront installation costs and performance concerns in cold weather. These findings suggest that government interventions, such as subsidies and better consumer education, are critical to accelerating ASHP adoption.

The comparison of survey findings with real-world case studies highlighted the importance of proper insulation and appropriate sizing of HPs. Homeowners with well-insulated homes were more likely to experience satisfactory performance, emphasising the need for an integrated approach that combines heat pump installation with home retrofitting programs.

- **Chapter 8**: Chapter 8 offered an in-depth case study of the Nottingham Ice Centre, focusing on how heat pumps and thermal storages can be employed as heat recovery methods to reduce or eliminate reliance on district heating. The study demonstrated that integrating thermal storages to capture and storage waste heat from the refrigeration system reduces the energy demand for heating. This not only could improve the facility's energy efficiency, but it could also provide substantial cost savings by minimising the need for external district heating.
- The Nottingham Ice Centre case study serves as an exemplary model of how thermal storage or heat pumps can be deployed in industrial and commercial settings where waste heat is available. It further highlights the scalability of such technology beyond residential applications, particularly in high-energy-demand environments. The findings emphasise the potential for heat recovery systems, combined with thermal storage to enhance energy self-sufficiency in facilities like ice rinks, data centres, and industrial plants, contributing to broader energy efficiency and carbon reduction goals.
- **Chapter 9**: The final chapter explored the effect of electric vehicles (EVs) on the power grid. The results indicated that, while manageable at current adoption rate, the simultaneous rise in EV and HP implementation could strain the grid during peak times, particularly in winter. This highlights the importance of developing advanced grid management solutions and demand-response technologies to mitigate potential grid imbalances.

In conclusion, this research has provided a comprehensive analysis of the factors influencing the adoption and performance of HPs in the UK, contributing valuable knowledge to the ongoing efforts to decarbonise residential heating. While the findings underscore the significant potential of heat pumps to reduce carbon emissions, they also highlight the critical challenges that need to be addressed, particularly concerning cost, performance in cold weather, and grid stability. By addressing these challenges through continued research and policy innovation, the UK can accelerate its transition to a sustainable, low-carbon future.

10.6. Future research

Future work will focus on the innovative development of the technology to enhance the performance during the defrost cycle and also to assess the best heating options depending on the type of house and its insulation level.

Future research in the domain of air source heat pumps (ASHPs) and electrification should build on the current findings by addressing several key areas that remain underexplored. Expanding the scope beyond the technical and economic analyses of ASHP performance, future investigations could incorporate advanced technological innovations, comprehensive real-world testing, and broader social and policy considerations.

- **Integration of Alternative Heating Technologies**

While this study focused primarily on ASHPs, future research should explore a more diverse set of low-carbon heating technologies. Investigating **ground source heat pumps (GSHPs)**, **hybrid systems** (combining heat pumps with traditional boilers or electric resistance heaters), and **solar thermal heating** could provide valuable insights into how these technologies perform in comparison with ASHPs, especially in colder climates.

- **Advanced Controls and Smart Grid Integration**

The increasing strain on the power grid, driven by electrification through ASHPs and electric vehicles (EVs), emphasizes the need for intelligent energy management solutions. Future research could focus on developing and testing advanced control systems that optimize heat pump operation based on real-time energy demand, weather conditions, and electricity prices. Integration with smart grids, demand-response technologies, and energy storage systems could further alleviate grid pressures during peak periods.

- **Long-Term Performance Monitoring**

One of the main limitations identified in the study is the reliance on idealized models and short-term experiments. Future research should prioritize long-term performance monitoring of ASHPs in real-world conditions, capturing data on seasonal variations, equipment wear, user behaviour, and maintenance needs. This data could lead to more accurate models that reflect actual performance over the lifespan of the heat pump system.

- **Building Retrofit Strategies**

The findings on the dependency of ASHP efficiency on building characteristics highlight the critical role of building retrofits in maximizing heat pump performance. Future research should delve deeper into cost-effective strategies for improving insulation and building envelope upgrades in older housing stocks, particularly Victorian and pre-20th century homes. Research could also focus on the policy frameworks and financing models necessary to support large-scale retrofit initiatives.

- **Cross-National Comparisons and Global Adaptation**

While this research focused on the UK, the global deployment of ASHPs presents varying challenges and opportunities based on regional climate, building standards, and grid infrastructure. Conducting cross-national comparisons would offer valuable insights into how ASHP technologies can be adapted to different climatic zones, regulatory environments, and grid conditions. Comparative studies across countries could help identify best practices and lessons for policy frameworks.

- **Decentralized Energy Systems and Heat Recovery**

The Nottingham Ice Centre case study highlights the potential for **heat recovery systems** to reuse waste heat, offering opportunities to further explore decentralized energy systems. Future research could focus on scaling these systems for other commercial, industrial, and even residential applications, where substantial waste heat is produced. Investigating new technologies like low-temperature district heating or modular heat recovery units for homes could expand the range of ASHP applications.

Future research on ASHPs should broaden its scope to incorporate emerging technologies, real-world monitoring, and cross-national perspectives, while addressing socio-economic challenges and user behaviour. By focusing on these key areas, future studies can contribute to more effective and equitable low-carbon heating solutions that will be essential to meeting global climate goals.

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Appendices

Appendix I

Acquired components for the test rig of the air source heat pump:

***Table A 1** – List of purchased components for the air source heat pump test rig*

Description	Supplier / Maker	Qty	Unit Price	Total
DMHT4 Din Rail Meter Enclosure	Meters UK ltd.	4.00	19.00	76.00
Heat Meter	Meters UK ltd.	1.00	235.00	235.00
Single Phase Meter DIN Rail M-Bus kWh	Meters UK ltd.	4.00	39.00	156.00
Evaporator output to suction hose	Buckley Engineering	1.00	105.01	105.01
Evaporator intput from expansion valve hose	Buckley Engineering	1.00	119.36	119.36
Thermal storage refrigerant connection hoses	Buckley Engineering	2.00	103.76	207.52
Compressor suction anti vibration hose	Buckley Engineering	1.00	52.88	52.88
Compressor discharge anti vibration hose	Buckley Engineering	1.00	49.48	49.48
Aeroquip male fittings to mate with aeroqip ended hoses	Buckley Engineering	3.00	63.75	191.25
Additional I/O module.	Technische Alternativ	2.00	129.00	139.32
CAN bus converter	Technische Alternativ	1.00	158.00	85.32
Communications module	Technische Alternativ	1.00	184.00	99.36
Freely programmable controller	Technische Alternativ	1.00	484.00	261.36
Profibus / M bus card	Technische Alternativ	1.00	39.00	21.06
PT1000 sensor	Technische Alternativ	15.00	12.60	102.06
1/4" Schrader valve for brazing.	Derbyshire Refrigeration	8.00	1.20	9.60
1/4″ 36″ Charging Hoses	Derbyshire Refrigeration	1.00	44.00	44.00
12 litre liquid receiver with Rotalok valve.	Derbyshire Refrigeration	1.00	80.83	80.83
15 m coil 1/2" copper tube annealed.	Derbyshire Refrigeration	1.00	27.22	27.22
15 m coil 1/4" copper tube annealed.	Derbyshire Refrigeration	1.00	11.51	11.51
15 m coil 3/8" copper tube annealed.	Derbyshire Refrigeration	1.00	20.68	20.68
15 m coil 5/8" copper tube annealed.	Derbyshire Refrigeration	1.00	39.24	39.24

Digital Vacuum Gauge	Derbyshire Refrigeration	1.00	130.53	130.53
Hand Valve with 1/2" braze connections.	Derbyshire Refrigeration	1.00	12.00	12.00
Hand Valve with 1/4" braze connections.	Derbyshire Refrigeration	1.00	12.00	12.00
Hand Valve with 3/8" braze connections.	Derbyshire Refrigeration	4.00	12.00	48.00
Javac Ratchet Wrench	Derbyshire Refrigeration	1.00	7.00	7.00
Vacuum Pump 4CFM – 230V	Derbyshire Refrigeration	1.00	169.00	169.00
Steel for main unit frame	Eggleston Steel	4.00	23.75	95.00
Carriage charge for the raw material for the frame	Eggleston Steel	1.00	18.50	18.50
Evaporator	SPC House	1.00	1,275.00	1,275.00
0.75mm² 3 Core Butyl Flex White 50M	TLC Electrical Supplies	1.00	36.00	36.00
0.75mm² Tri Rated Cable - Brown	TLC Electrical Supplies	1.00	11.40	11.40
1.5mm² Tri Rated Cable - Green/Yellow	TLC Electrical Supplies	1.00	18.00	18.00
2.5mm² Tri Rated Cable - Black	TLC Electrical Supplies	1.00	27.60	27.60
32 Amp TP&N Rotary Switch - IP65	RS Components	1.00	16.20	16.20
Aluminium Foil Paper Backed Adhesive Tape 50 x 0.075 mm	RS Components	1.00	13.86	13.86
Bootlace Ferrule Crimp terminal Kit	Cablecraft	1.00	14.61	14.61
Compressor Potential Relay	Dawmec / Copland (Emerson)	1.00	24.91	24.91
Compressor Run Capacitor (50mFd/475V)	Dawmec / Copland (Emerson)	1.00	23.50	23.50
Compressor Start Capacitor (88-108mFd/330V)	Dawmec / Copland (Emerson)	1.00	19.74	19.74
R134a scroll compressor.	Dawmec / Copland (Emerson)	1.00	1,343.00	631.21
Cable assembly - 3 metres - for SV1	Dawmec / Copland (Emerson)	1.00	4.46	4.46
Coil 230 V / 50 Hz for SV1	Dawmec / Copland (Emerson)	1.00	15.69	15.69
EEV cable assembly - 3 metres	Dawmec / Copland (Emerson)	2.00	6.23	12.46
EEV Universal Driver Module	Dawmec / Copland (Emerson)	2.00	163.61	327.22
Expansion Valve & Oil control valve	Dawmec / Copland (Emerson)	2.00	108.30	216.60

Hot gas bypass	Dawmec / Copland (Emerson)	1.00	18.41	18.41
Liquid filter / drier	Dawmec / Copland (Emerson)	1.00	8.06	8.06
Oil return sight glass	Dawmec / Copland (Emerson)	1.00	9.32	9.32
Receiver outlet sight glass	Dawmec / Copland (Emerson)	1.00	9.28	9.28
Universal Driver Module Terminal Kit	Dawmec / Copland (Emerson)	2.00	4.43	8.86
Condenser	(Alfa Laval) BSS	1.00	458.50	458.50
C.K Automatic Wire Stripper	TLC Electrical Supplies	1.00	17.16	17.16
Cutting Pliers Cable Cutter	RS Components	1.00	12.88	12.88
Purple Tri-rated Cable, 0.5 mm²	RS Components	1.00	11.69	11.69
Discharge pressure transmitter, 0 - 40 barg	RS Components	1.00	95.88	95.88
Insulated Crimp Tool	TLC Electrical Supplies	1.00	14.28	14.28
Blue Tri-rated Cable, 0.75 mm²	RS Components	1.00	15.05	15.05
Power Supply, 12V dc	RS Components	1.00	12.36	12.36
Ratchet Tool for Boot Lace Ferrules	TLC Electrical Supplies	1.00	23.94	23.94
Bootlace Ferrule Crimps 0.5 mm²	TLC Electrical Supplies	2.00	1.20	2.40
Bootlace Ferrule Crimps 0.75 mm²	TLC Electrical Supplies	1.00	1.20	1.20
Bootlace Ferrule Crimps 1.0 mm²	TLC Electrical Supplies	1.00	1.20	1.20
Bootlace Ferrule Crimps 1.5 mm²	TLC Electrical Supplies	1.00	1.20	1.20
Side Cable Cutter	RS Components	1.00	9.72	9.72
Suction pressure transmitter, 0 - 16 barg	RS Components	1.00	95.88	95.88
Screw Driver Set - 6 Piece	TLC Electrical Supplies	1.00	7.30	7.30
6 inch Combi Pliers	TLC Electrical Supplies	1.00	9.74	9.74
Block 63VA Isolating Transformer, 230/400V : 2 x 24V	RS Components	1.00	35.53	35.53
3/8″ Charging Hose 72″ (One for oil return line)	Derbyshire Refrigeration	2.00	39.00	78.00
3m length 3/4" copper tube hard drawn.	Derbyshire Refrigeration	1.00	14.38	14.38
3m length 7/8" copper tube hard drawn.	Derbyshire Refrigeration	1.00	15.41	15.41

4-Valve Test & Charging Manifold	Derbyshire Refrigeration	1.00	135.00	135.00
Plastic sheet for frame.	Graingate Ltd.	6.00		763.00
RS PRO 1 piece Automatic Punch	Rs Components	1	22.40	22.40
13" 330MM Blind Rivet Nut Gun	Amazon	1.00	28.61	28.61
Swivel Wheel with Brake Castor 50mm 50kg	ToolStation	4.00	2.12	8.48
M6 Countersunk Head, 25 mm Steel Pozidriv Bright Zinc Plated	Rs Components	1.00	8.16	8.16
M6 Countersunk Head, 20mm Steel Pozidriv Bright Zinc Plated	Rs Components	1.00	7.21	7.21
Fan Coil Heater - control	Puravent	1.00	222.30	222.30
Fan Coil Heater for removing pumped heat.	Puravent	1.00	910.29	910.29
Frame powder coating				
Bosch 10 piece Metal Twist Drill Bit Set, 1mm to 10mm	RS Components	1.00	8.18	
7/8 inch full bore ball valves.		2.00		
7/8 inch full bore threaded connector		1.00		
Evaporator fan	ELTA FANS LTD	1.00	566.00	566.00
Electrical enclosure(s)		1.00	230.00	230.00
Open slot trunking 60mm x 40mm x 2m	CPC	4.00		39.90
DIN Rail, Slotted Top Hat, 35mm, 2m	CPC	2.00		6.18
2 Pole Modular DIN Rail Contactor, 25A, N/O, 230V	CPC	1.00	19.79	19.79
Seal-Lok ORFS Nut, Sleeve, Locknut TL	Parts Gopher	3.00		
Seal-Lok ORFS Nut, Sleeve, Locknut TL	Parts Gopher	2.00		
Seal-Lok ORFS Nut, Sleeve, Locknut BL	Parts Gopher	4.00		
Seal-Lok ORFS Straight LOHB3	Parts Gopher	4.00		140.61
Parts Gopher parts delivery fee	Carla Bay/Parts Gopher	1.00	76.18	76.18
Parts Gopher parts service fee	Carla Bay/Parts Gopher	1.00	107.31	107.31
KEMET Capacitor Clip	RS Components	2.00		

Wurth Electronik Steel Hex Threaded Standoff, Male/Female 971899611, 80mm, M6	RS Components	10.00		
RS PRO Heat Shrink Tubing, Black 6.4mm Sleeve Dia. x 1.2m Length 2:1 Ratio	RS Components	5.00		
Evaporator Fan Box	Graingate Limited	1.00	760.00	760.00
Test rig top frame ligts panel	Graingate Limited	1.00	110.00	110.00
Ology Services Ltd. - Initial brazing and assembly	Ology Services Ltd	1.00	2,334.00	2,334.00
Ology Services Ltd. - Additional works & refrigerant	Ology Services Ltd	1.00	708.94	708.94
Universal three-way valve	Technische Alternative	2.00	76.82	153.64
Circulating pump	Amazon	1.00	64.90	64.90

SUBTOTAL (Excl VAT)				13,725.08
VAT				2,745.02

GRAND TOTAL (Excl VAT)				16,470.10
				==========

Appendix II – Data sheet of the fin coil heat exchanger used as an evaporator

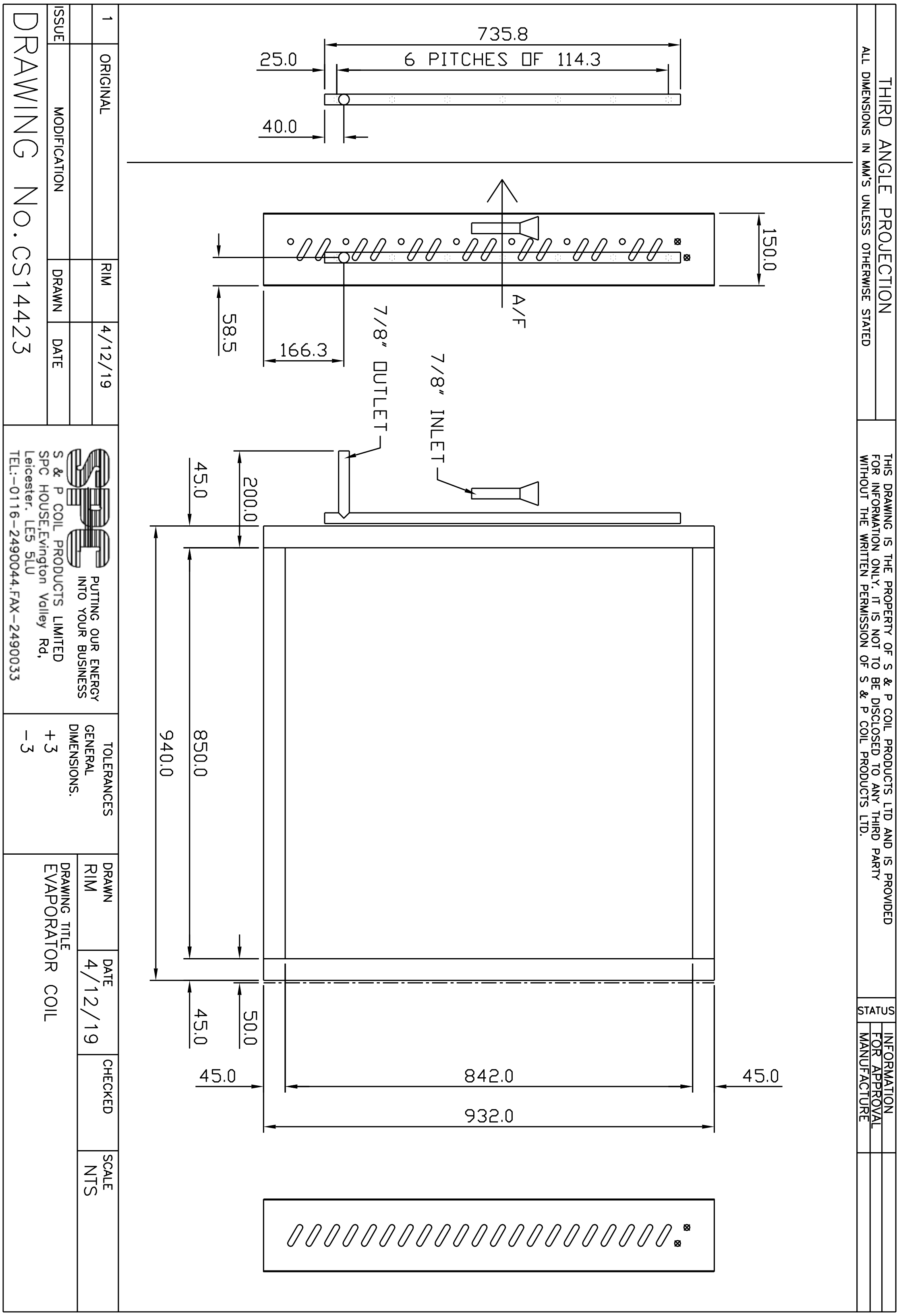

Figure A 1 *- Technical drawing of the fin coil heat exchanger used as an evaporator in the test rig.*

Appendix III – Data sheet of the plate heat exchanger used as a condenser

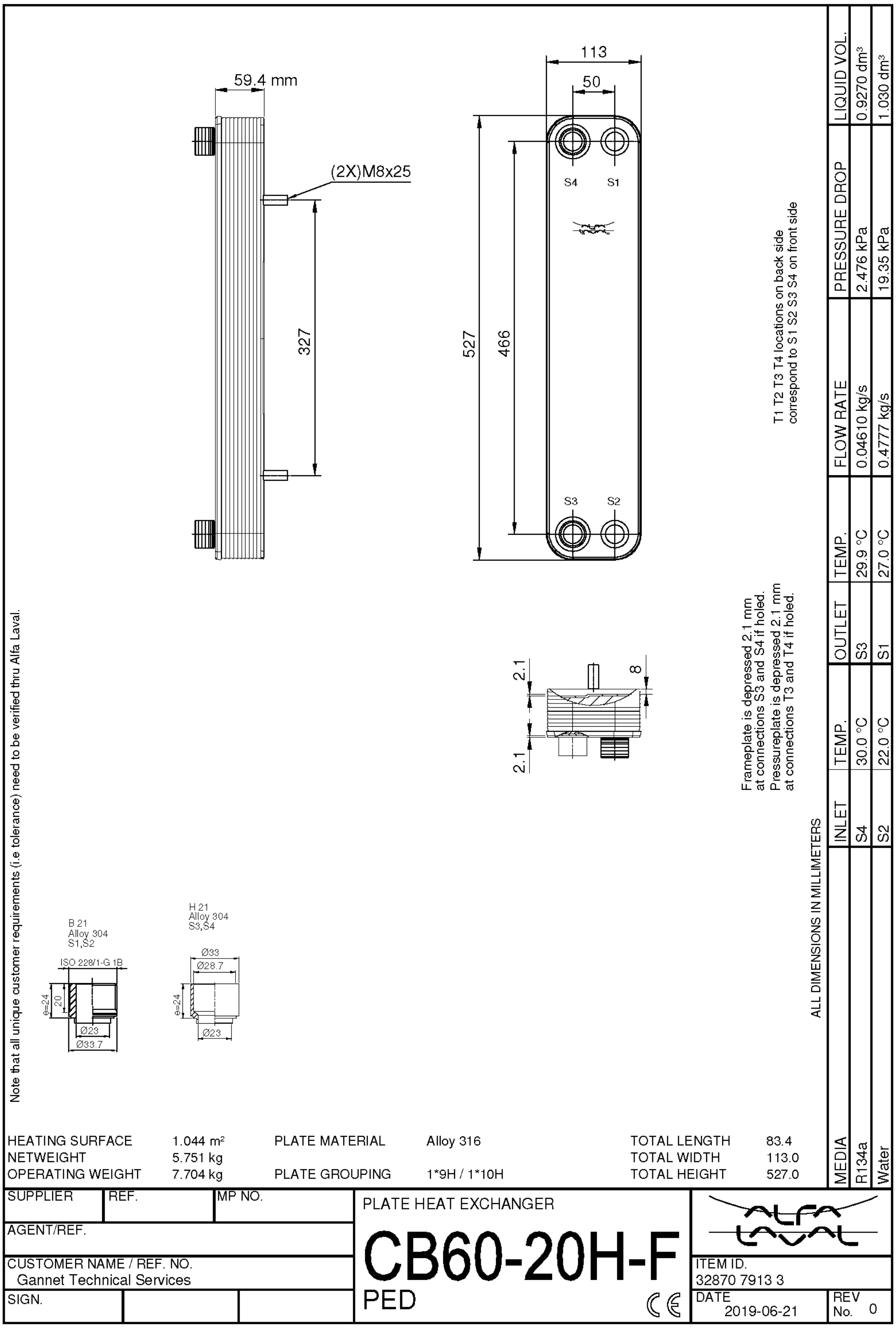

Figure A 2 *- Technical drawing of the plate heat exchanger used as a condenser in the test rig.*

Appendix IV – Scroll compressor technical drawing

A: 386,5 mm
B: 361 mm
C: 264,5 mm
D: 222,4 mm

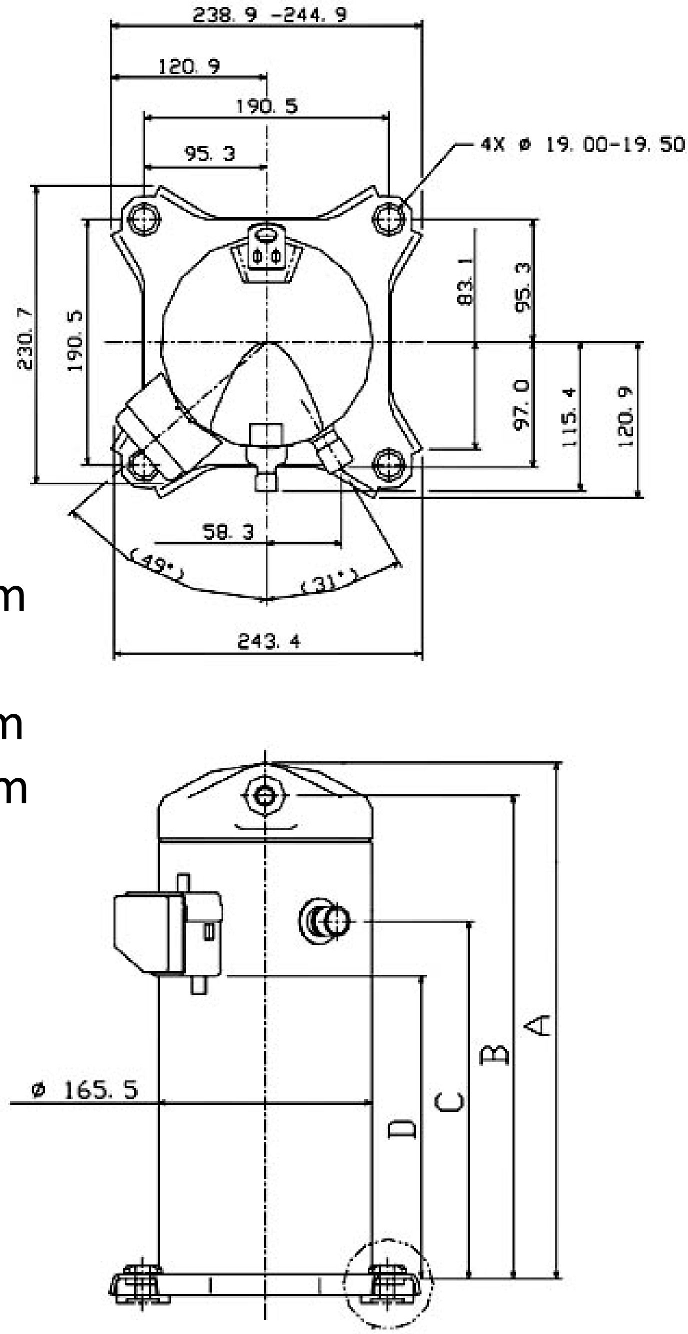

Figure A 3 *- Technical drawing of the compressor used in the test rig.*

Appendix V – Scroll compressor technical data

Table A 2 *- Scroll compressor technical data*

Model: ZH21K4E-PFJ	
Technical data	
Nominal motor power (HP)	3
Displacement (m^3/h)	8
Sound pressure level	62
Weight (kg)	30
Oil charge (dm^3)	1.45
Electrical data	
Power supply (V/~/Hz)	220-240V/1/50Hz
Locked rotor current (A)	76
Maximum operating current (A)	18.5
Winding resistance (Ω)	0.937
Connections	
Suction line (inch)	¾ “
Discharge line (inch)	½ “

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Appendix VI – Technical drawing of the evaporator-fan frame.

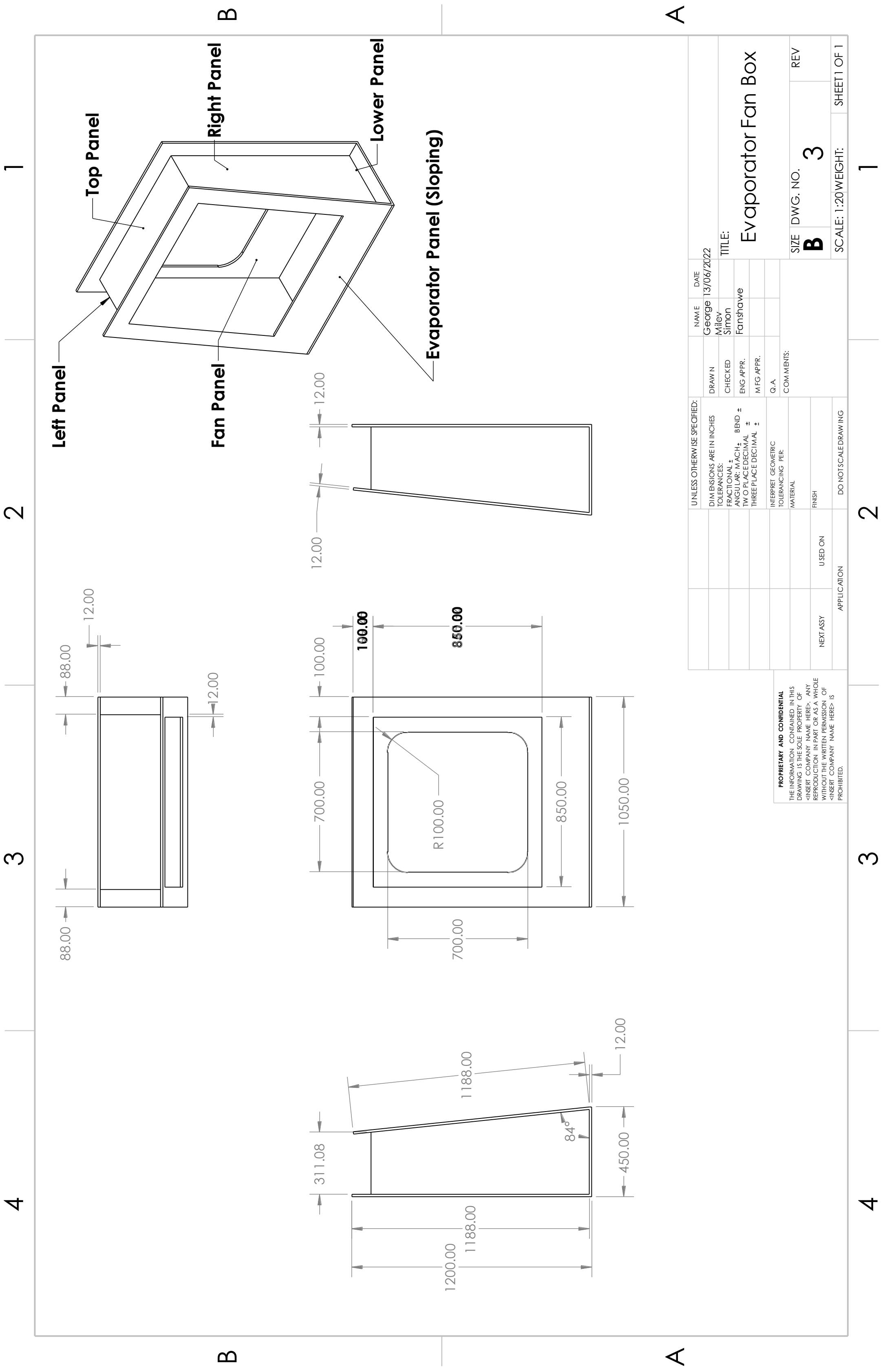


Figure A 4 *- Technical drawing of the evaporator-fan frame*

Appendix VII – Technical drawing of the evaporator-fan assembly

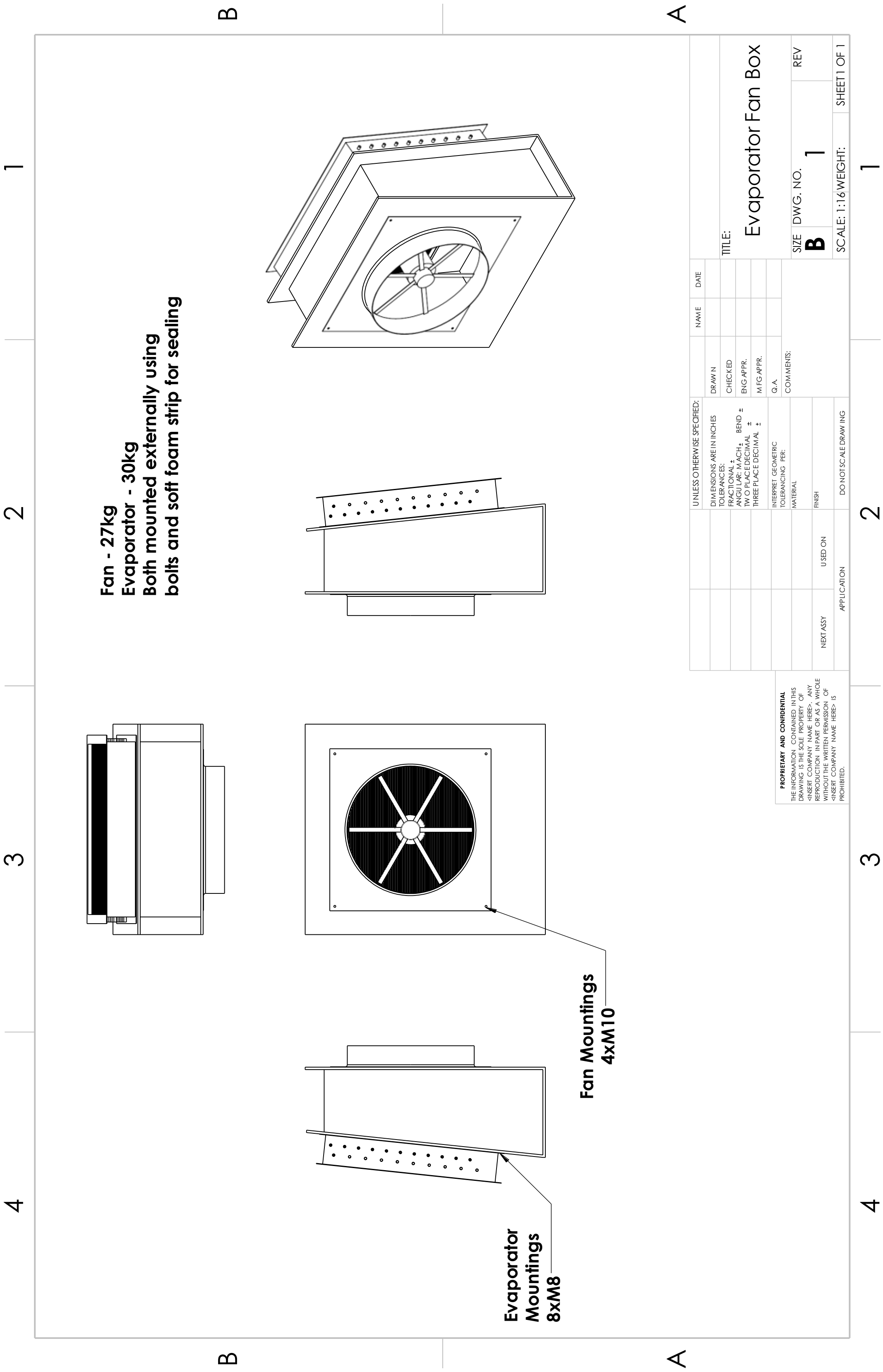


***Figure A 5** – Technical drawing of the evaporator-fan assembly.*

Appendix VIII – Fan specification data

Technical Data - Fan Model SCP630-1EC (10 speed)

Location: **Designation:**

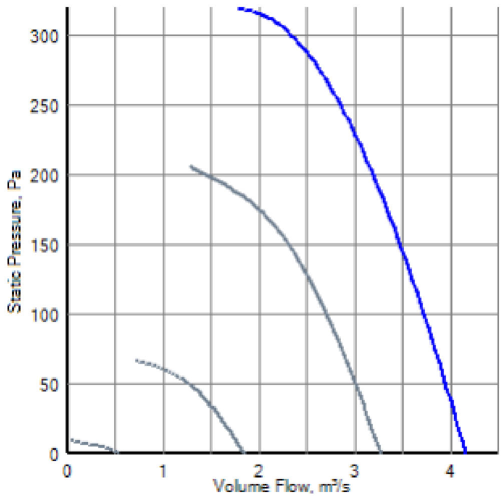
Please Note: Data shown is nominal - enter more criteria for accurate detail.

Performance - Required

Air Flow : 0.00 m³/s
Static Pressure : 0 Pa
Selection Pressure: 0 Pa
Installation Type: n/a
Air Density: 1.204 kg/m³
- Atmos. Temp: 20 °C
- Altitude: 0 m
- Humidity: 0.0 %

Actual

Air Flow: 0.00 m³/s
Static Pressure: 0 Pa
Total Pressure: 0 Pa



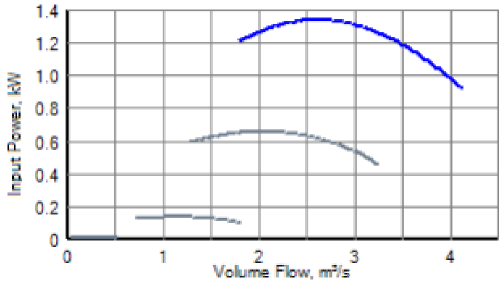
Fan Data

Catalogue Code: SCP630-1EC (10 speed)
Description: Axial Plate

Diameter: 630 mm
Impeller Type: Axial
Blade Material: -
Speed: 1800 r/min @50 Hz
Power, Abs: - Peak: 1.17 kW
Input Power: 0.60 kW
Efficiency Total: - Static: -
SFP: -
Fan Weight: 27.0 kg

Motor Data (at STP)

Motor Type:
Electrical Supply: 230V 1ph 50Hz
Motor Frame: 80
Motor Power: 1.12kW
FLC/Start (DOL): 9.30A / 9.30A
Motor Speed: 4 pole
Motor Efficiency: 81.0%



Sound Data

Spectrum (Hz):	63	125	250	500	1K	2K	4K	8K	dBW	dB(A) @ 3m
Inlet (dB):	65	84	82	84	81	79	76	75	90	66
Outlet (dB):	71	77	84	87	84	82	79	79	91	69

Sound levels are quoted as in-duct values. dB(A) values are average spherical free-field for comparative use only.

Figure A 6 *– Technical data of the evaporator fan.*

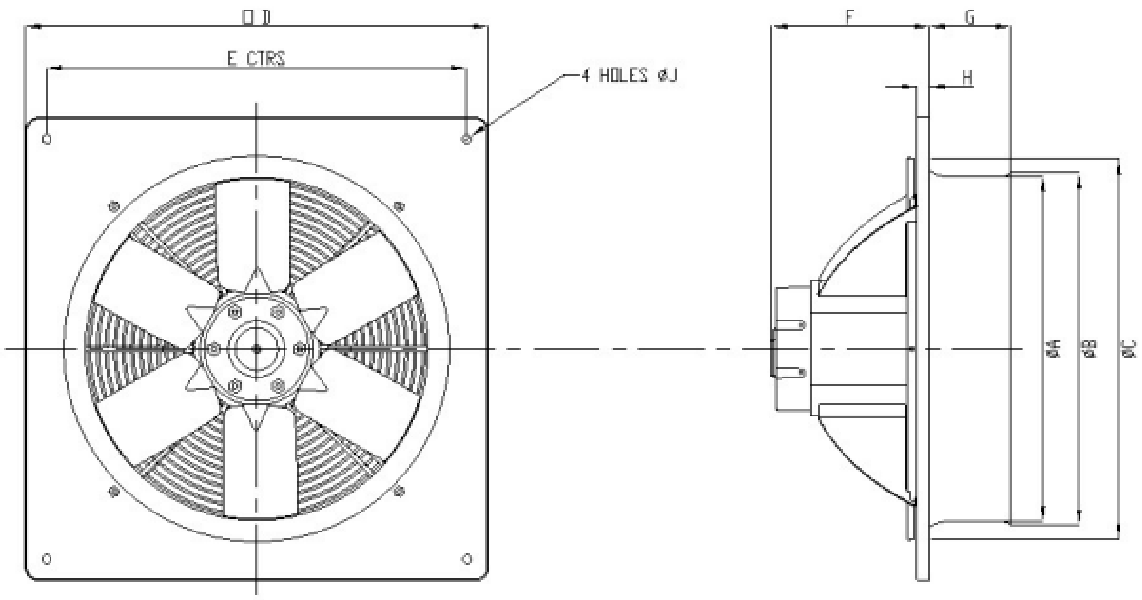
Technical Data - Fan Model SCP630-1EC (10 speed)

Location: **Designation:**

Energy Related Product Data

		At Maximum Efficiency Point	
Overall Efficiency:	54.2%	Input Power:	0.14 kW
Measurement Category:	A	Air Flow:	1.20 m^3/s
Efficiency Category:	Static	Pressure:	54 Pa
FMEG:	66 (Integrated)	Speed:	805 r/min
Specific Ratio:	1		

Drawing for Fan Model SCP630-1EC



PRODUCT CODE	A	B	C	D	E	F	G	H	J
SCP250-1EC	250	261	275	370	320	197	75	15	7
SCP315-1EC	315	326	360	430	380	201	75	15	10
SCP350-1EC	350	361	395	485	435	194	75	15	10
SCP400-1EC	400	411	450	540	490	170	95	15	10
SCP450-1EC	450	461	500	575	535	198	95	15	10
SCP500-1EC	500	512	560	655	615	231	100	15	10
SCP560-1EC	560	577	620	725	670	247	100	15	10
SCP630-1EC	630	647	700	805	750	251	105	20	10
SCP710-1EC	710	725	765	850	810	241	103	27	10

Figure A 7 *- Technical data of the evaporator fan.*

Appendix IX – Ethical approval and consent forms for interviews and questionnaire

Nottingham Trent University

Investigating the performance of an air source heat pump in a residential building
CONSENT FORM

	Consent Statement	Yes	No
1.	I confirm that I'm 18 years of age or older.	Y	
2.	I confirm that the purpose of the research has been explained to me, that I have been given information about it in writing, and that I have had the opportunity to ask questions about the research.	Y	
3.	I understand that my participation is voluntary and that I can ask to withdraw without giving a reason up until 14 days after collecting my data.	Y	
4.	I understand my part in the research. I understand that my participation is voluntary, and that I am free to withdraw my consent and ask for the temperature sensors to be removed, without giving any reasons.	Y	
5.	I understand that data collected during this study will be processed in accordance with data protection law as explained in the Participant Information Sheet.	Y	
6.	I understand and consent to the methods of data collection and particularly to any electronic recording that will take place and confirm that I know how long their data will be retained.	Y	
7.	I agree to take part in the study.	Y	

Participant's signature

[redacted]

Researcher's signature

[redacted]

Page 1 of 1

Figure A 8 - *Consent form for both case studies*

Ethics Application: Investigating the performance of an air source heat pump in a residential building

Risk	Medium
Applicant	George Milev
Org Unit	Doctoral School - Studentships
Supervisor	Amin Al-Habaibeh
Status	Favourable Opinion

Ethics Application: Heat pumps as an alternative to reduce energy consumption and carbon emissions

Risk	Medium
Applicant	George Milev
Org Unit	Doctoral School - Studentships
Supervisor	Amin Al-Habaibeh
Status	Favourable Opinion

Figure A 9 *- Ethical approval for case studies and questionnaire*

Appendix X – Control system elements

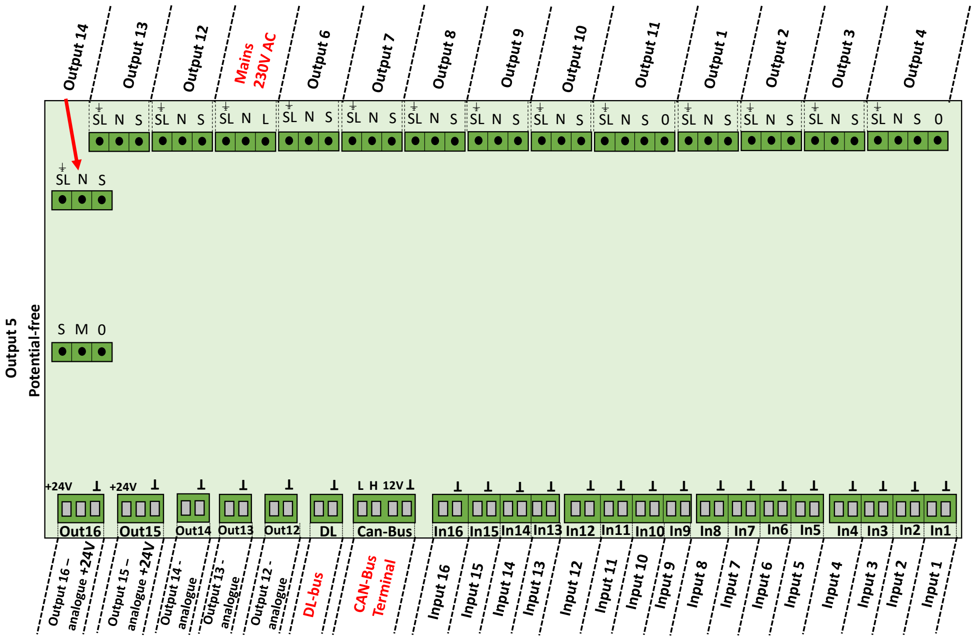


Figure A 10 *- Universal Controller UVR16x2 Diagram*

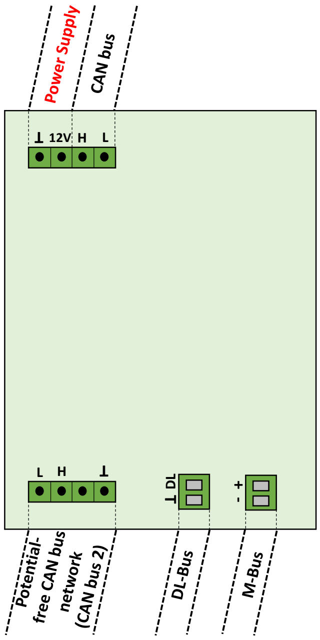


Figure A 11 *- Diagram of CAN-BC2*

Figure A 11 shows the CAN-bus converter diagram, highlighting the slots and their functions. The top slot provides 12V power, while other slots are available for potential-free CAN bus networks, DL-Bus, and M-Bus if needed.

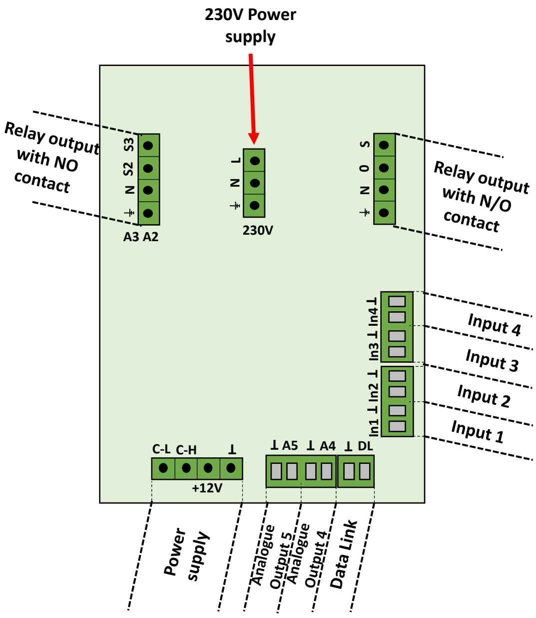


Figure A 12 *- Diagram of CAN I/O45*

Figure A 12 displays the CAN I/O45 configuration, including the slots for inputs, relay outputs, and power supply. It includes four inputs programmable as analogue or digital, two analogue outputs, and additional relay outputs for specific needs.