HOW BUILDING CHARACTERISTICS AFFECT HEAT PUMP CONSUMPTION – A UNITED KINGDOM CASE STUDY

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ABSTRACT

Heat pumps are a promising technology to decarbonise residential heating in the UK, which is responsible for around 21% of the country's CO_2 emissions *(BEIS 2018)*. This thesis investigates the impact of different building characteristics on heat pump operation over the day and its contribution to peak electricity demand. This dissertation uses the recent Electrification of Heat trial data, revisiting and extending the published interim analysis. The findings show that Efficiency Performance Certificate (EPC) is an ineffective indicator for heat pump consumption, and that MCS Space Heat Load (SHL), which measures the estimated heating need of a property, is strongly correlated to heat pump consumption. Findings demonstrate that a house with low MCS SHL makes it more convenient to install a heat pump. Assuming that the data sample of the trial is representative of the UK building stock, the study shows that if the average UK property were able to decrease its MCS SHL by 28% through home efficiency measures, this would save 1.8kWh/day and reduce the peak power demand by 0.35kW when installing a heat pump. In a 2050 UK scenario with 100% deployment of heat pumps, this would lead to a reduction in electricity use in excess of 19TWh/year and a reduction in peak demand of over 10GW. This translates to an estimated saving of £0.57–3.62bn in yearly electricity bills, and over £33bn in avoided network upgrades requirements. To achieve these savings, properties must be refurbished to improve their insulation and building fabric. The results presented in this thesis are relevant to policymakers and can inform data-grounded decisions on the strategy to decarbonise residential heating, on the road to achieving the UK 2050 net zero commitment.

Acronyms

Acronym	Full form
ADMD	After Diversity Maximum Demand
ASHP	Air Source Heat Pump
bn	billion
CAPEX	Capital Expenditure
DC	Delivery Contractor
CD	Coldest Day
COP	Coefficient of Performance
DESNZ	Department for Energy Security and Net Zero
DHW	Domestic Hot Water
DR	Demand Response
DSR	Demand Side Response
EoH	Electrification of Heat
EPC	Energy Performance Certificate
ESC	Energy Systems Catapult
ETS	Energy Saving Trust
GSHP	Ground Source Heat Pump
HL	Heat Loss
HP	Heat Pump
HPRI	Heat Pump Readiness Index
HT	High Temperature
HWT	Hot Water Tank
LT	Low Temperature
MCS	Microgeneration Certification Scheme
PCM	Phase Change Material
RHPP	Renewable Heat Premium Payment
SHL	Space Heat Load
SPF	Seasonal Performance Factor
TES	Thermal Energy Storage
UK	United Kingdom
WSHP	Water Source Heat Pump

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INTRODUCTION

MOTIVATION

The UK Government has committed to a net zero carbon emissions target by 2050. Residential space heating and domestic water accounts for around 21% of CO_2 emissions in the UK *(BEIS 2018)*. Decarbonising heat is a challenge: according to the *Ministry of Housing, Communities & Local Government (2020)*, today 90% of households use gas boiler systems. Additionally, large parts of the UK building stock are poorly insulated and inefficiently heated *(Eyre and Baruah 2015)*. As noted by the *National Institute for Clinical Excellence (2019),* and *Gasparrini, et al. (2015),* excess deaths during cold spells are higher than in comparable countries, so policies to decarbonise heating also need to ensure that adequate heat is available to all.

There are two key strategies for decarbonising heat: through efficiency measures (such as refurbishment, better insulation, and more efficient heating appliances) and switching to less carbon intensive fuels. Heat pumps allow to incorporate both strategies at the same time. Heat pumps are more efficient than conventional boilers, and they run on electricity, which can be potentially zero emission if the grid or local generation source is renewable. Therefore, they are identified as a promising candidate for decarbonising residential heating.

Despite the advantages of heat pumps, there are challenges ahead for their market penetration. Firstly, heat pumps have a high up-front cost (£8,000-15,000 for ASHP, and £18,000-25,000 for GSHP compared to £1,500-3,000 for conventional boilers *(Heatable 2023))* and medium-high running costs due to electricity prices. Secondly, since heat pumps work more efficiently at lower temperatures, they are better suited for heating systems that have large areas for heat exchange, such as houses with underfloor heating rather than radiators. The work to switch from radiators to underfloor heating is expensive and disruptive, both of which are factors driving away potential customers. The alternative would be to install a high-temperature heat pump, which is compatible with a small radiator size but typically more expensive, or to increase the radiator area. Thirdly, heat pumps add to electricity demand and may overload local electricity networks, especially during cold winter periods, when demand is already high. To reach 100% heat pump penetration *Eyre and Baruah (2015)* estimate that 40GW of new capacity would need to be installed and that the investment cost would be around £70bn by 2050. Due to the above limitations, in addition to heat pumps, biofuels and district heating will also be important technologies to diversify supply and reduce the risk of electricity shortages *(Eyre and Baruah 2015).*

Compared to other European countries, the UK is lagging behind in terms of heat pump installations and performance, *(Carroll, Chesser and Lyons 2020).* The literature suggests several reasons for the performance gap. *Bergman (2012)* highlights technical problems, poor installation, lack of grants and government involvement, poor information to users, improper use, and lack of skills and installers. *Gleeson and Lowe (2013)* attribute the lower UK performance relative to other European countries to high back-up heating and DHW (domestic hot water) use, the lack of compensating heating control, the low-quality components and control of heating systems and the lower insulation standards. When comparing the data between heat pumps installed in European countries, *Ruhnau, Hirth and Praktiknjo (2019)* show that the UK has average U-values of $1.8 W/m^2K$, compared to $1.15 W/m^2K$ in Germany, which contributes to the performance gap.

A study on building stock found that around 80% of current standing buildings will be in use in 2050 and that 40% of UK buildings are 'hard-to-treat', with either solid walls, no loft space, no gas connection or they are high rise *(Dowson, Poole and Susman 2012)*. According to *(Beaumont 2007)*, 66% of 'hard to treat homes' live in fuel poverty, spending over 10% of their income to afford adequate residential energy services. To make these houses heat pump ready, the barriers to retrofit, such as lack of government incentives, high costs, disruption of work and uncertainty on payback, would need to be resolved.

Homes with the greatest potential to reduce energy consumption and carbon emissions, and to improve welfare and living standards, also face some of the greatest challenges for a widespread uptake of heat pumps. This thesis therefore seeks to investigate the relationship between building fabric and heat pump consumption and performance.

The motivation for this dissertation is to test the hypothesis that building characteristics (including insulation, heat loss, building area) have a relevant impact on the energy consumption of heat pumps and, if this is confirmed, to attempt to quantify the impact on the UK house stock through trial data.

The research question is timely and relevant because it can help to guide the roll out of insulation measures in a targeted and effective manner, such that the roll out of heat pumps can be achieved faster, at lower cost and with less impact on the electricity system.

OBJECTIVES

The primary objectives of this dissertation are to:

- Test the hypothesis that building characteristics (such as construction material, glazing, wall insulation, building heat loss and floor area) strongly impact heat pump consumption.
- Identify which building indicators are most meaningful as predictors of heat pump consumption. Examples of possible indicators include EPC, MCS building heat loss and MCS space heat load.
- Understand the impact of building characteristics on indoor temperatures and energy consumption for heating on the coldest day of the year.

The secondary objectives are to:

- Observe the daily heat pump energy consumption pattern over the year, in winter, and on the coldest day in the UK.
- Quantify the decrease in heat pump efficiency when there are low outdoor temperatures.
- Estimate how better building characteristics can decrease the required electricity generation and infrastructure capacity, and the associated cost savings.

LITERATURE REVIEW

This chapter provides an overview of the literature on heat pump operating principles and previous studies exploring the impact of building fabric with a particular focus on UK field trials.

HEAT PUMP OPERATION AND SIZING

Heat pumps work to transport heat from one reservoir to another. This is unlike a boiler, which releases previously stored energy by burning a fuel.

Three main types of heat pumps are in use in the UK: air source heat pumps (ASHP), water source heat pumps (WSHP), and ground source heat pumps (GSHP). Heat is extracted from the source and moved, typically via a wet system, throughout the building to heat exchanges, such as radiators or underfloor systems.

Heat pumps are reverse heat engines. On the decompressed side of the cycle, heat is extracted from the environment, heating up the refrigerant, which is compressed to increase its temperature and release it to its environment on the other side of the circuit. Multi-step heat pumps contain more than one compressor, stepping up the temperature in two or more cycles, while maintaining a relatively high efficiency and reaching higher temperatures. Figure 1 illustrates the thermodynamic processes of heat pumps.

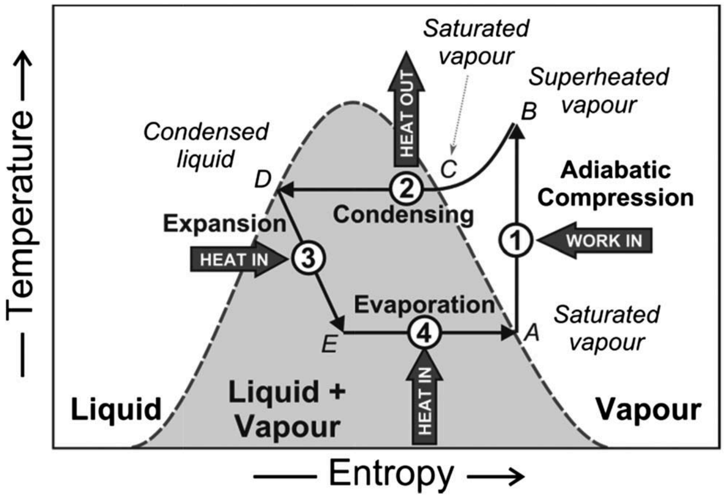

Figure 1. Thermodynamic process of a heat pump ***(Staffell, et al. 2012).***

In normal operation, energy consumption of a heat pump merely serves to drive the electric compressor, the fan, the auxiliary systems, and the circulation pump. For start-up and under extreme conditions a defrosting cycle may use resistive heat. Otherwise, heat pumps do not 'generate heat' from their electrical input and merely 'move heat'.

As a result, the coefficient of performance (COP), which measures the ratio of heat output and electrical input exceeds 3 for most well installed systems. Another indicator is the seasonal performance factor (SPF), which measures the system performance over an extended period (over a year or a season). Three types of SPF are in use:

SPFH2 The ratio of heat delivered and the electricity input from the compressor, fan, and defrosting cycle.

SPFH3 Including also the electricity used from the auxiliary heaters (immersion heater or backup heating system).

SPFH4 Including also the electricity needed by the circulation pump.

SPFH4 is therefore always lower than SPFH3 and SPFH2.

The temperature difference between the source and the desired output (indoor temperature set point) influences the COP of heat pumps. Due to Carnot's relationship, the larger the difference between source and sink temperature, the lower the COP, as illustrated in Figure 2. This sheds light on a major challenge for heat pumps: their efficiency decreases with lower surrounding temperatures, corresponding to the moment when they are most needed.

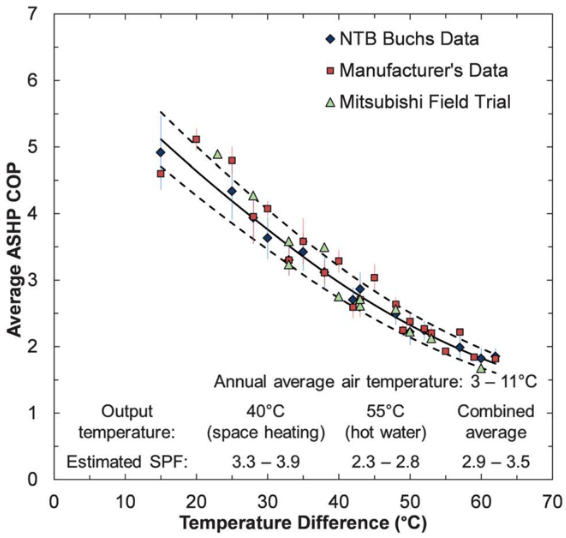

Figure 2. Average ASHP COP compared to the temperature difference between the source and sink *(Staffell, et al. 2012).*

Larger radiator areas and underfloor heating can maintain adequate indoor temperatures from lower flow temperatures and thus, more efficient heat pump operation *(Staffell, et al. 2012).* Heat pumps can also provide domestic hot water (DHW) up to 55°C, which is the minimum requirement for most hygiene standards *(K. X. Le, et al. 2019).*

Sizing heat pumps correctly affects heat pump performance and consumption. Heat pumps are often combined with other heating systems, such as resistive electric backups heaters, which – when used – can reduce the COP from over 3 to below 1. The sizing of heat pumps consists of a trade-off between higher capital expenditure (CAPEX) on a larger heat pump size and lower running costs due to higher efficiency, or lower CAPEX due to a smaller heat pump size combined with higher utilisation of auxiliary systems and thus higher running electricity costs.

In the UK, best practice for heat pump sizing is overseen by the Microgeneration Certification Scheme (MCS). In addition to certifying competent installers and appropriate manufacturers, the MCS has published a tool that allows calculating the recommended minimum heat pump size, by inputting information on building heat demand and losses, distribution systems and climate data *(MCS 2020), (MCS 2021)*.

Undersized heat pumps are particularly problematic for the electricity network since they need more auxiliary heating, increasing electricity consumption and the risk of grid overload at critical times during cold spells. Hence, the minimum set by the MCS calculation tool is often used to make heat pump installations eligible for UK renewable heat incentives.

EFFECTS OF INSULATION ON HEAT PUMP ELECTRICITY DEMAND

Insulation levels are important for heat pumps since better-insulated houses lose heat at a slower rate, thus enabling heat pump systems with lower capacities to meet thermal comfort requirements. BEUC (the European consumer organisation) estimates that after switching the heating off, the temperature drop is around 1.6°C/hour in non-retrofitted buildings, and 0.7°C/hour in retrofitted ones (with improved U-values for walls, windows, floors, and roofs) in Northern European climates *(BEUC 2023)*. Additionally, it is estimated that the heating load is often more than halved in highly insulated buildings in cold environments, as seen in Figure 3 (top). Hence, many European countries have set mandatory minimum insulation performance levels to access grants for heat pump installation *(BEUC 2023).*

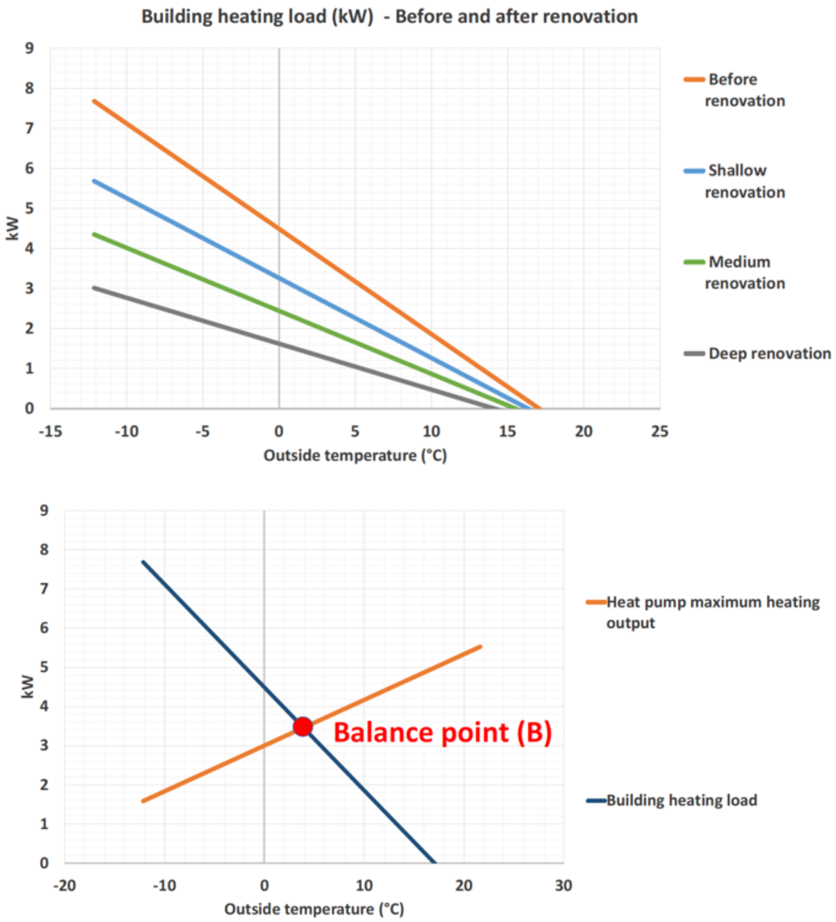

Figure 3. Top: building heating load depending on renovation status. Bottom: heat pump maximum heating output and building heating load at different outside temperatures *(BEUC 2023).*

BEUC proposes to add to EPCs a Heat Pump Readiness Indicator (HPRI). BEUC envisions the HPRI to give an indication of the share of a building's annual space that can be covered by energy extracted from outside air using a reference heat pump. The method to calculate this involves assessing three characteristics: the building envelope, the climate, and the reference heat pump. If the building heating load is above the maximum heating output of the heat pump, auxiliary systems are then used. Overall, the study demonstrates that insulation is fundamental to decreasing the required heat pump electricity demand.

The fact that building stock, thermal mass and insulation have the potential to decrease heating demand and to make heat pumps a cost-effective solution is widely supported in literature, including studies by *Fischer and Hatef (2017), Feldhofer and Healy (2021), Eggimann, Hall and Eyre (2019), Patteeuw, Henze and Helsen (2016),* and *Pruggler (2013)*. For example, *Kreuder and Spataru (2015)* note that decreasing building loss from 350W/K to 100W/K halves the winter peak load. Quality insulation is so relevant to heat pump performance that *Patteeuw, Reynders, et al.* (2015) discard all buildings that are not well insulated since otherwise the heat demand and water temperature requirement would be unsuitable for heat pumps. *Gaur, Fitiwi and Curtis* (2021) also find that heat pumps can only efficiently replace conventional heating systems in old buildings if they are well insulated. *ProgRESs Heat* (2017) highlights that insulation levels (and underfloor heating) are rarely talked about despite being a key determinant for heat pump success when trying to identify barriers to heat pump uptake.

Overall, there seems to be a literature gap for quantifying different insulation levels and their effect on heat pump consumption. In addition, most of the studies that investigated the intersection of insulation levels and heat pumps are simulation-based (with no real trial data) and do not specifically address the UK market. Of the publications cited above, the only study containing trial data is the one by *ProgRESs Heat* (2017), and the only one focussing on the UK market is by *Eggimann, Hall and Eyre* (2019). This dissertation will assess the impact of insulation on heat pump operation through trial data in the UK, hence contributing to fill the identified literature gaps.

DEMAND FLEXIBILITY

The demand for electricity presents a clear daily pattern, following social behaviour, referred to as the 'Duck Curve'*(Pandey, Kumar and Mandal 2023)*. This is a reference to the distinctive shape of daily electricity demand, bearing resemblance to a duck, with a pronounced peak demand typically observed between 5pm and 9pm. This peak presents challenges for both the network and the supply system, because it increases the possibility that the electricity lines won't have enough capacity and because there may not be enough electricity generation to satisfy demand at that specific time *(Pandey, Kumar and Mandal 2023).* Demand flexibility is a possible way to mitigate this issue, helping to match demand and supply patterns.

By delaying or anticipating heating schedules by a relatively short time without strongly impacting thermal comfort, heat pumps have shown to be promising candidates for providing demand flexibility *(Pallonetto, et al. 2019)*. Flexible heating demand is enabled by two key factors: by passive storage using the existing thermal inertia of buildings, and by active storage such as hot water tanks (HWT) or phase change materials (PCM). Despite the potential advantages, demand response (DR) in heating still faces major challenges. Flexibility requires the active participation of consumers or automated control. Furthermore, when HWT or PCM are used, heat is lost in the environment, and the COP decreases. Below, a summary of relevant studies that assess the potential of heat pumps to provide demand flexibility services in different heating configurations is presented.

Eggimann, Hall and Eyre (2019) simulate a 50% uptake of heat pumps in a 2050 UK scenario. They find that this would cause an increase in peak demand of 31.2GW, and that heat pump demand response would enable a peak reduction of a maximum of 5.8GW (19% reduction). This is roughly coherent with the simulation by *Feldhofer and Healy (2021)*, estimating a peak reduction of 21-36% thanks to heat pump demand flexibility. The study also highlights that better insulation can help reduce heating demand and the electricity peak, but this was not quantified in the study. Other publications that positively support the potential of heat pumps for demand response include the ones by *Magni, et al. (2020)* and *(Patteeuw, Reynders, et al. (2015).* As noted by *Ambrald (2021)*, heat pumps must have an aggregator (1-5 MW) to participate in balancing markets, concluding that the coupling of batteries might be a requirement to provide reliable participation. *Lee, et al. (2020)* propose to use variable-speed heat pumps for frequency regulation, showing that heat pumps are good candidates for providing ancillary services at cost-competitive rates.

The importance of an external thermal energy storage system such as HWT or PCM as opposed to using building inertia for demand flexibility is investigated in many literature studies. After performing a heat pump simulation, *Arteconi, Hewitt and Polonara (2013)* find that HWT are fundamental to allow for demand flexibility of up to 3 hours in buildings with radiator systems and low thermal inertia. After simulating flexible heat pump operation in the UK, *Kelly, Tuhoy and Hawkes (2014)* find that 1000L HWT or 500L + PMC are required to shift demand while avoiding impacting comfort. However, the authors estimate that active storage increases electricity use by 60% due to thermal losses and sub-optimal heat pump operation. *Hong, et al. (2013)* argue that the existing UK stock has a 'limited' flexibility potential, of 1-2 hours before impacting thermal comfort. Instead, flexibility reaches 6 hours when the combination of the improved building stock and HWT up to 500 L is implemented. *Renaldi, Kiprakis and Friedrich (2017)* conclude that in the UK, heat pumps are only profitable compared to boilers if they include a TES, to reduce operational costs with variable tariffs.

In contrast with the above studies, *Hedegaard, et al. (2012)* find that using building thermal mass as passive heat storage is the most cost-effective solution for demand response, while also allowing to absorb renewable excess energy. The study by *Pruggler (2013)* also shows that passive demand response allows to shift load by 15-50%, but only in well-insulated buildings. This agrees with the simulation performed by *Hong, et al. (2012)*, confirming that DR with thermal mass is helpful for reducing renewable curtailment, while also highlighting that heavy-weight buildings perform better at matching energy supply than lightweight ones due to their inertia. *Sperber, Frey and Bertsch (2020)* show that demand flexibility is strongly dependent on building insulation levels and that it is achievable using building thermal inertia. In a UK simulation, *K. Le, et al. (2019)* demonstrate that by using thermal mass and direct heating the COP achieved is 2.12 as compared to 1.88 with a hot water tank (HWT) as a demand response strategy (or as low as 1.41 depending on the operation mode). In real life, the ability of thermal mass to be used as a demand response strategy was proved in a field trial with over 300 heat pumps reported by *Müller and Jansen (2019).* By setting incentives, users decreased the electricity peak by 40-65% for one hour, when demand flexibility was requested. Finally, the DR simulation run by *Zhang, Good and Mancarella (2019)* leads to mixed results: although buildings with higher thermal inertia achieve higher comfort levels, the energy payback of flexibility is reached earlier in ones with lower thermal inertia. This last result is seemingly contradictory, highlighting that merely simulated scenarios might not reflect real-world applications successfully.

UK FIELD TRIALS

Field tests are a helpful way to validate simulations of how heat pumps are used in real-world situations. Unvalidated simulations run the danger of misrepresenting heat pump performance due to erroneous assumptions and modelling techniques. The primary field tests that have been conducted this far in the UK are outlined here.

In 2008 the Energy Saving Trust (EST) collected data on the operation of 83 heat pumps (both ASHP and GSHP), as part of one of the first large scale heat pump trials in the UK. After monitoring performance for several years, authors report an achieved average heat pump SPF between 1.5-2.1 for ASHP and 2.0-2.8 for GSHP, showing an underperformance of 40-50% with respect to expectations based on manufacturer data *(Department of Energy and Climate Change 2012)*. According to *Staffell, et al*. *(2012)*, inaccurate size, improper setup and installation, and subpar operation were likely causes of the trial's low achieved efficiency. After surveying the trial's heat pump users, *Carid, Roy and Potter (2012)* discovered that thermal comfort levels had been generally satisfactory, and that greater system efficiency was associated with better user comprehension of heat pump technology, more continuous heat pump use, and more energy-efficient homes (better EPC) with underfloor heating.

ETS conducted another trial from 2013 to 2015 under the Renewable Heat Premium Payment scheme (RHPP), where data from 689 heat pumps complying with the MCS standards was *collected (UK Data Service 2015).* Results show a 2.64 mean SPFH2 for ASHP and 2.93 for GSHP, respectively resulting in only 62% and 80% of heat pumps being compliant with the EU Renewable Energy Directive standard of an SPFH2 above or equal to 2.5 *(UCL Energy Institute 2017)*. The study finds that consumers were generally satisfied with the heating system and that heat pumps enable emissions reduction compared to any other conventional heating technology, but on the other hand they are more expensive. Even though GSHP, underfloor heating and attached houses seem to be correlated with higher heat pump performance, the study admits struggling to identify the main characteristic affecting heat pump efficiency. Moreover, results show that there is a discrepancy between EPC and yearly energy use for heating. Starting from the RHPP scheme data, *Love (2017)* observed that heat pumps create a morning and evening peak, with an overnight plateau at 40% of the peak, estimating an after diversity maximum demand (ADMD) of around 1.7kWe per heat pump. Finally, the study suggests that a 20% uptake of HP would lead to an increase in UK peak electricity demand to 60GW, from the current 52.5GW.

A focus on demand response within UK trials is reported by *Sweetnam, et al. (2018)* and *Allison, et al. (2017).* 76 heat pumps were engaged in the 2017 trial led by *Sweetnam, et al. (2018).* Of these, around half were controlled by an autonomous heat pump control system that used a cost-minimization algorithm to operate heat pumps within temperature comfort constraints, and the rest were used as a baseline without demand response. Results show an increase in the average power consumption for heat pumps in the DR group due to pre-heating activities that avoid forming a morning peak. This leads to an increase in the average household temperature and the smoothing of power consumption, but only a 0.012kW peak reduction per heat pump. The study concludes that, unless additional storage is installed, a limited amount of pre-heating and thus demand flexibility can be achieved. In the *Allison, et al. (2017)* trial, users were able to successfully shift demand without impacting thermal comfort, but heat pump efficiency turned out to be very poor. This was related to a very high auxiliary immersion heater utilisation rate, demonstrating the negative effects of heat pump under sizing on consumption.

It is worth mentioning additional trails are still ongoing, monitoring and testing several areas for heat pump roll out. For example, Clean Heat Streets is an ongoing project aiming to demonstrate that significant numbers of heat pump installations can be implemented in the same neighbourhood without causing problems to the electricity network *(Clean Heat Streets 2023).*

The most recent large-scale heat pump trial in the UK is the one led by Energy Systems Catapult (ESC) that started in 2020 and is running until September 2023, for the Electrification of Heat Project (EoH) funded by the Department for Energy Security and Net Zero (DESNZ) *(Energy Systems Catapult 2023 a).* Thanks to the publicly available data and the rigorous documentation of the field trial, this dissertation will use this trial's data to try filling the literature gaps that have been previously identified. Hence, a detailed description of the trial is presented in the method section of this dissertation. Overall, 742 heat pumps were installed in several UK locations, and interim data from 352 of these was analysed and discussed in the report by *Energy Systems Catapult (2023 a).* A '*summary of heat pump performance'* file was also published *(Energy Systems Catapult 2023 b)*, containing each house's trial ID, the consumption of the heat pump and its other components (circulation pump, immersion heater, backup system etc), the date of the coldest day, and the calculated SPFH2, SPFH3, SPFH4. The focus of the interim report is understanding heat pump efficiency: results show that the median ASHP SPFH2 and SPFH4 were 2.94 and 2.80 respectively. This decreases to 2.54 and 2.37 in hybrid systems, which were operated on a cost-optimising mode (a mean of 41.7% of heat was provided by the heat pump, the rest by the boiler). The study finds that refrigerant type affects the SPF, with R32 performing best, and that detached houses have higher mean SPFH2 than the rest. According to the study, household income and house age does not have a statistically significant impact on SPF. Furthermore, a comparison between the coldest day COP and average SPF finds that efficiency decreases, but not significantly. As is illustrated in Table 1, the interim report also presents a comparison of the present EoH SPF results with the previous RHPP one, showing an improvement in heat pump performance, possibly due to the learning curve. The Appendix provides a more complete set of results published by ESC.

Table 1. Comparison of the interim EoH ASHP performance and the RHPP scheme (Energy Systems Catapult 2023 a).

SPF Value	Interim EoH Sample	EoH Median SPF	EoH SPF [Q1, Q3], IQR	RHPP Sample	RHPP Median SPF	RHPP SPF [Q1, Q3], IQR
SPF_{H2}	291	2.94	[2.66, 3.20], 0.54	292	2.65	[2.33, 2.95], 0.62
SPF_{H4}	291	2.80	[2.53, 3.09], 0.56	292	2.44	[2.15, 2.67], 0.52

Previous government-funded research on heat pump trials has a flaw in that it merely assesses the SPF of the heat pumps, and not the daily profiles of energy consumption or indoor temperatures. As heat pumps become more widely used, electrical distribution networks will become more congested, especially between the hours of 5pm and 9pm, at peak electricity demand. SPF is a critical element, but heat pump power consumption over the time of the day must also be explored. This thesis aims to address this gap by drawing on the latest data available and specifically focus on the daily profiles of heat pump usage as a function of building characteristics.

RESEARCH QUESTION

The gaps in the literature result in the following research questions, which this dissertation aims to address:

How do building characteristics affect the operating patterns of heat pumps?

This overarching question is broken down into three sub-questions:

1) Can better insulated buildings reduce the additional peak loads from heat pumps?
2) Which building metrics best capture the potential peak demand impact of heat pumps?
3) How critical is the coldest day in the UK in terms of electrical consumption, heat pump efficiency and indoor temperatures reached?

Answering these questions will close the identified analysis gap. This will help policymakers target their initiatives and take decisions grounded on up-to-date and high-quality empirical data.

METHOD

To address the above questions, this thesis uses the latest available operational heat pump data from the Electrification of Heat (EoH) trial published by *Energy Systems Catapult (2023 b)*. These data give an unprecedented insight into heat pump usage patterns and associated building characteristics.

The EoH trial, which was initiated in 2020, aims at deepening the understanding of heat pumps for their increased rollout in the UK. In March 2023, the interim data was published together with a report exposing key insights from the study *(Energy Systems Catapult 2023 a).* The present chapter describes how data was collected during the EoH trial, it then illustrates how data was cleaned and how houses were selected for the interim report data analysis. Lastly, building on the EoH data cleaning and preliminary analysis, this section describes how data was independently analysed for the purpose of the dissertation.

TRIAL AND DATA DESCRIPTION

In the EoH trial 742 heat pumps were installed between September 2020 and November 2021. The project was led by management contractor Energy Systems Catapult, with the participation of E.ON (for North-East England), OVO Energy (For South East England) and Warmworks (for Scotland) as delivery contractors (DCs). DCs oversaw participant recruitment, surveys, design and installation of heat pumps. The evaluation contractor that was responsible for data analysis and reporting was ICF.

Delivery contractors recruited trial participants with several marketing strategies, and overall, more than 3,000 households applied to the trial. In exchange for agreeing to share monitoring of their heating systems, selected participants received a free heat pump and house efficiency measures if required. The Participant Recruitment Report *(Energy Systems Catapult 2023 c)* acknowledges that the main reasons for interest in the project were sustainability and low-carbon heating, followed by the interest in new technology, the opportunity to receive a free heat pump and futureproofing of the home.

After applying to the trial, surveys and discussions between the applicant and DC took place. The main 'applicant-led' barrier to deciding to not participate in the trial appeared to be disruption. The key 'non-participant' barriers encountered are listed below.

1. **Practical barriers**. Properties were excluded due to a lack of space for external, and internal heat pump systems, and space for thermal storage in proportions of 8%, 5% and 2% respectively.
2. **Technical barriers**. 7% of properties were excluded due to the size of the heat pump required (not within the trial budget), and 4% because installers were worried about the fact that the heat pump capacity would not compensate for heat losses of the house or because radiator areas were too small.
3. **Economic barriers**. 4% of properties were excluded because the cost of installation of heat pumps and efficiency measures was not within the DC's budget.

DCs filtered the applications based on the study's targets, timescale, budget, and home suitability to heat pumps. As part of the trial, the DENZE set some targets to mimic as much as possible the house types present in the UK and to include various heat pump types. Table 2 shows the distribution of house and heat pump types, and it indicates which targets were met.

Table 2. Trial target quota for heat pump type, property form and property age, compared to achievements *(Energy Systems Catapult 2023 a).*

Criteria	Group	Target Quota	Achieved (%)	Achieved (No.)
Heat Pump Type	Low Temperature Air Source	-	41.2%	306
	High Temperature Air Source	*min 6%*	32.7%	243
	Ground Source	*min 6%*	5.1%	38
	Hybrid	*20-60%*	20.9%	155
Property Form	Detached	*40%*	40.6%	301
	Semi-detached	*40%*	42.8%	261
	End-terrace			57
	Mid-terrace	*15%*	11.1%	82
	Flats	*5%*	5.5%	41
Property Age	Pre-1919	*10%*	7.8%	58
	1919 to 1944	*20%*	14.2%	105
	1945 to 1964	*20%*	24.0%	178
	1965 to 1980	*20%*	22.2%	165
	1981 to 1990	*10%*	9.2%	68
	1991 to 2000	*10%*	9.6%	71
	2001+	*10%*	13.1%	97

As reported by ESC, 15% of the households finally selected in the trial received efficiency improvements before installing the heat pumps *(Energy Systems Catapult 2022)*. The most popular efficiency measures were loft insulation followed by cavity wall insulation and door replacements. Furthermore, 93% of the trial properties received new heat emitters (larger radiators) due to lower water temperatures reached by heat pumps. Most new heat emitters were low-temperature radiators (54%), followed by standard radiators (33%). New thermal stores were also installed in 81% of properties: many existing DHW thermal stores were replaced due to the requirement for a larger size of immersion coils. The trial had a fixed budget, resulting in an average total cost of £14,800 per property. Data shows that hybrid systems were cheaper (also due to their smaller HP size), followed by low-temperature ASHP and HT (high temperature) ASHP and shared GSHP. Excluding time for efficiency interventions, the installation of HP, TES, heat emitters, pipelines etc. typically took around 2-4 days, with two engineers and an electrician. For GSHP, the installation time was higher, on average 84 days.

The published data includes a *csv* file named '*BEIS Electrification of Heat Project - Property, Design and Installation Information*'. It contains information of the initial 3,000 applicants. For each household, the file contains:

- **Participant information** – address, occupant income, occupation, age etc.
- **Recruitment information** – reason for interest in the trial, social group etc.
- **Home information** – house type, age, floor area, existing heating system (radiator, underfloor heating, TES etc.), house EPC etc.
- **System design and installation information** – MCS calculation for heat loss (HL) and space heat load (SHL), installed heat pump power rating, heat pump type, cost etc.

The setting of electricity and temperature sensors in the households of the trial is illustrated in Figure 4, Figure 5 and Figure 6 for ASHP, GSHP and hybrid systems respectively. For monitoring electricity, each home contained metering for the circulation pump, backup and/or immersion heater (if installed), and whole system energy consumption. An indoor temperature sensor was located centrally in a shaded area within the property, but no standard room type was specified. The outdoor temperature was retrieved from local MET weather station. A single heat meter was installed to record the flow rate, flow temperature, and return temperature for estimating the heat pump energy output. Since in all non-hybrid systems, the heat pump provided both space heating and DHW, the location of the heated water diverter valve was recorded. Based on the diverter valve direction, the temperature of the flowing water was recorded in the space heating or hot water flow temperature data mode. In ground source heat pump setups, brine temperature sensors were recorded, and in hybrid settings, the boiler consumption was also recorded. In contrast to ASHP and GSHP systems, heat pumps in hybrid systems only provided space heating since DHW was produced directly by the boiler.

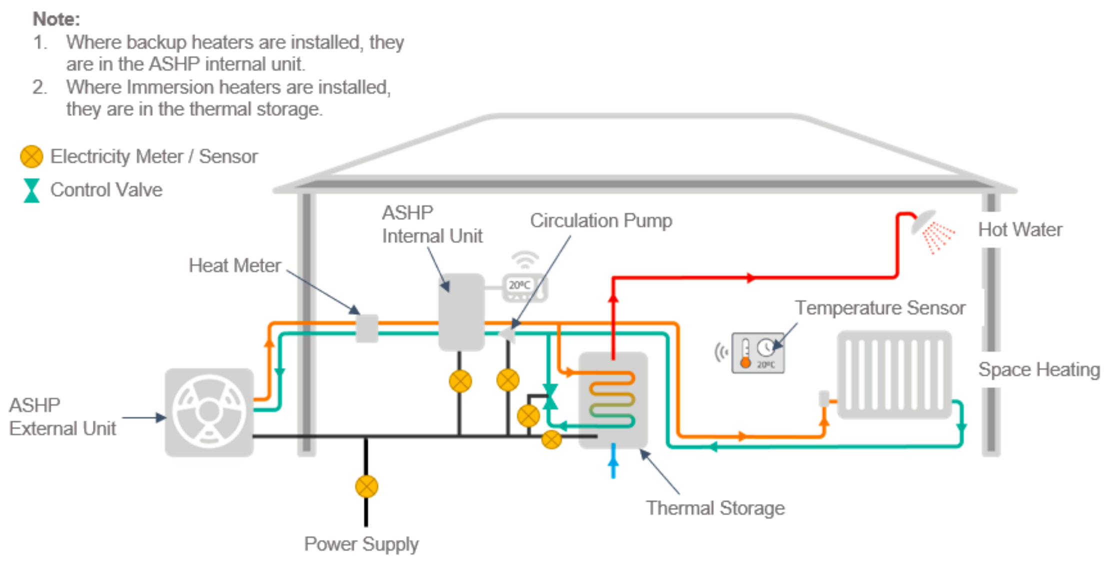

Figure 4. ASHP typical metering setting *(Energy Systems Catapult 2023 a).*

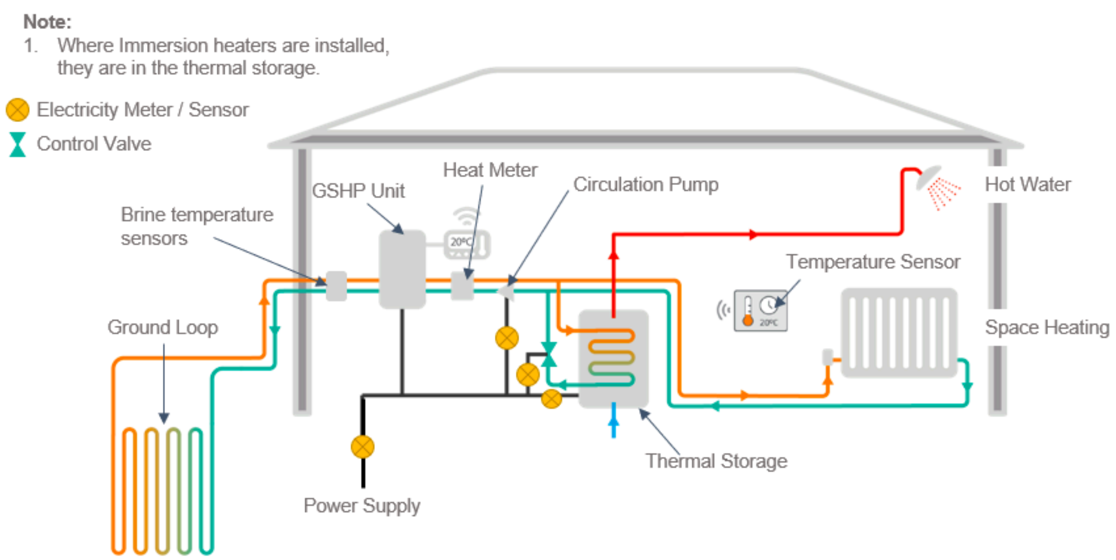

Figure 5. GSHP typical metering setting *(Energy Systems Catapult 2023 a).*

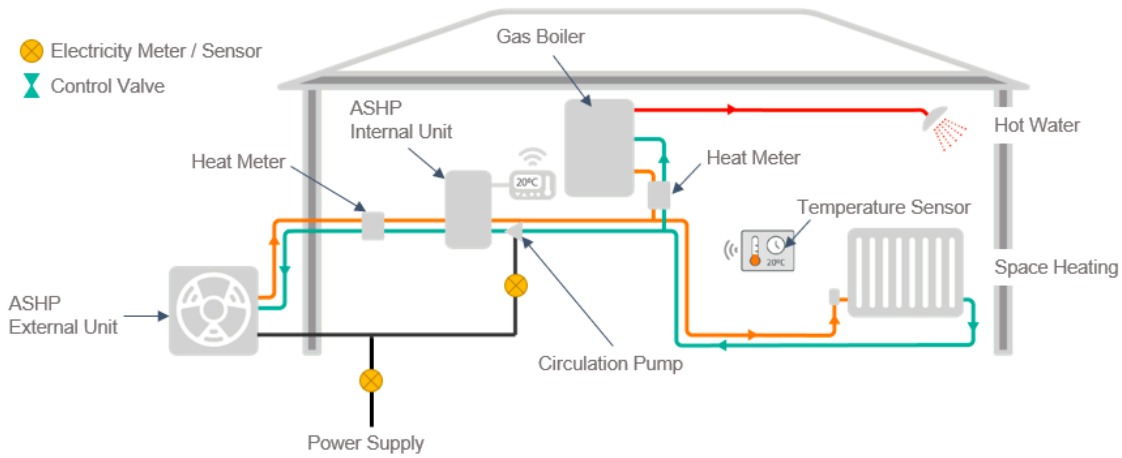

Figure 6. Hybrid system typical metering setting *(Energy Systems Catapult 2023 a).*

PassivSystems metering equipment was used by all delivery contractors, collecting 2-minute data from each sensor. Meters complied with the MCS Domestic RHI Metering Guidance Document. All heat and electricity meters were cumulative, and the temperature ones were instantaneous at the time of the reading. All sensors were wired or used Z-waves and they sent data to the Collection Hub. In addition to storing the recorded 2-minute property data in a local database, metering data was then transmitted through the internet to the general storage database containing information of all trial households. During the trial, two possible monitoring issues recurred: transmission issues or problems with monitoring equipment. Data was lost when the transmission between the sensors and the local data hub was lost, in which case gaps in the data became apparent. In cases in which the local database storage hub disconnected from the internet, measurements could be recovered as soon as the internet connection was restored. Monitoring equipment problems happened due to equipment installation issues and in-situ failures or partial failures. In case of monitoring equipment failures, engineers or installers were sent to the property to fix the design, to replace or re-calibre the sensors *(Energy Systems Catapult 2023 a).*

METHOD FOR CLEANING AND SELECTING APPROPRIATE HOUSEHOLDS FOR ANALYSIS

As part of the EoH trial, data quality checking, cleansing and process analysis was performed. The interim data that was published includes monitoring between September 2020 and August 2022. The method used by the monitoring contractor for cleaning the data is summarised here.

Data cleaning consisted of aligning timestamps, eliminating anomalies, and correcting them. Specific interventions are listed below:

- Aligning timestamp to 2-minute data.
- Managing cumulative meter data reversals.
- Removing anomalous single point or extended period anomalies in the cumulative data.
- Relevelling data after the meter reset itself.
- Removing out-of-range temperatures.
- Amending spelling mistakes and aligning property age in the correct category.

A score was assigned for each cleaning intervention, indicating the quality of the data. The weight of penalisation for each intervention was assigned arbitrarily by contractors and the rationale is explained in a report by ESC *(Energy Systems Catapult 2023 a).* The data quality score was used to decide whether a house had sufficient data for the analysis and to select the highest quality yearly data window of each property for the SPF analysis.

In addition to the previously listed 'standard' cleansing interventions on the data, other more 'conceptual' cleansing was performed. Overall, the data quality was penalised in the following cases:

- The cumulative data for different components of the heating system was flat – indicating no operation or no monitoring.
- The monthly electricity consumption was below 1kWh – indicating likely an unoccupied house.
- The 30-minute COPH2 was below or above 0.75 and 7.5 – indicating problems with cumulative readings.
- The SPFH2 or SPFH4 was below or above 1.5 and 4.5 respectively – indicating problems with cumulative readings.

- The percentage of available data over the monitoring period was below 50% – indicating insufficient data.
- The energy output was in an unacceptable range – indicating unlikely scenarios and monitoring issues.

Figure 7 shows the shortlisting of households for the data analysis. As illustrated, a substantial number of households (261) were excluded because there was data for less time than a year. A smaller number of houses was excluded due to monitoring issues, data quality, gaps, and SPF out of range. This led to 353 households being considered appropriate for further analysis, out of the 742 heat pumps installed at the time. It is worth noting that the monitoring will end in September 2023, by which time all heat pumps installed are expected to have at least a year of monitored data up to the quality required for analysis.

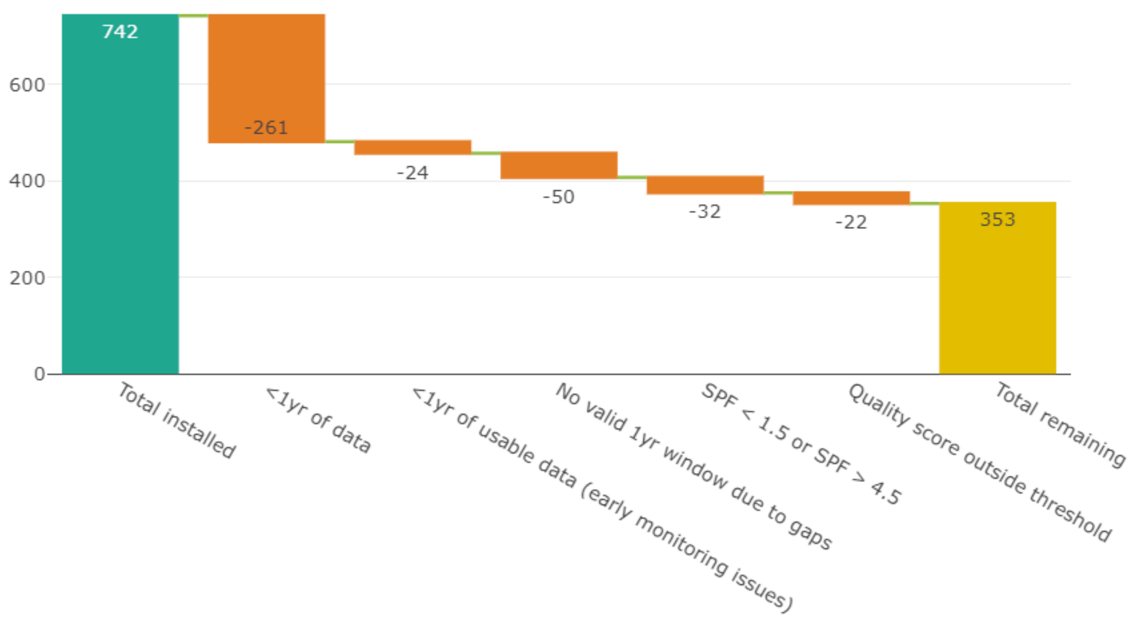

Figure 7. Shortlisting of households for analysis after data cleaning (Energy Systems Catapult 2023 a).

METHOD FOR ANALYSING THE DATA

Given the overview of the trial data above, this section outlines the new method used in this study to answer the research questions.

Python was chosen for analysing the data for three main reasons: it is one of the most used data-analysis programming languages, it contains useful libraries for processing large amounts of time-data, and it is the language already picked by the Energy Systems Catapult for its analysis. The original Python code used in this dissertation is available at this GitHub repository *(Perelli-Rocco 2023).*

The code accesses a folder containing the cleaned 2-minute data files collected for every house in the trial, and the EoH interim results file '*heat_pump_performance_summary_v1-0' (Energy Systems Catapult 2023 b).* The latter includes the property ID of each house, yearly consumption data, the date of the coldest day, whether the house had high enough quality data to be useful in the SPF analysis and, if so, the calculated performance (SPF) in the year date window. For coherence and comparability, the dissertation takes the already clean data and considers only the same houses that had already been included in the EoH SPF analysis, with the same year date window. Hence, for every house ID, the code checks whether the house was included in the analysis, and if so, it proceeds with the calculations below.

For each valid house, by verifying the match of the property ID, the code retrieves and reads the file containing the raw 2-minute data of the selected house, placing the consumption data in a dataframe.

A function is used to fill the rows of data where the meter did not upload the data immediately: if the cumulative energy measurement does not change between the last available measurement and the next one, then it can be filled in (since the cumulative value was unchanged).

As previously introduced, the house's data does not contain a separate meter for monitoring the heat pump consumption itself. To obtain this, the backup, immersion heater and circulation pump electricity consumption is subtracted from the whole system's energy consumption.

The time difference between one measurement and another is used to convert the cumulative energy consumption to an average power consumption over the timeframe. Hence, a new column is added in the dataframe, containing the average power of each heating system component at the recorded time.

As introduced above, the summary performance file published by ESC contains the start and end dates indicating the window of time with the best 1-year data for each property ID. In this study, the same dates are selected for in each house. Thus, the dataframe is filtered by time so that it only contains the measurements of the property within the specified year, making up the house's 'window dataframe'.

The SPFH2, SPFH3 and SPFH4 are then calculated for each house. To calculate the SPF, the first and last row of the year window that have non-empty values in the relevant cumulative energy consumption and heat output columns are subtracted, resulting in the total electricity consumption and heat output of each component over the year. The typical definitions for SPF over a year are applied, such as:

$$SPFH2 = \frac{\Delta Q_{output}}{\Delta E_{HP}} \tag{1}$$

$$SPFH3 = \frac{\Delta Q_{output}}{\Delta E_{HP} + \Delta E_{immersion\_coil} + \Delta E_{back-up}} \tag{2}$$

$$SPFH4 = \frac{\Delta Q_{output}}{\Delta E_{HP} + \Delta E_{immersion\_coil} + \Delta E_{back-up} + \Delta E_{circulation\_pump}} \tag{3}$$

where $\Delta Q_{\_output}$ is the heat output, $\Delta E_{\_HP}$ is the electricity used by the heat pump, $\Delta E_{\_immersion\_coil}$ and $\Delta E_{\_back-up}$ are the immersion coil and backup energy used, and $\Delta E_{\_circulation\_pump}$ is the circulation pump energy. A schematic boundary diagram is presented in Figure 8.

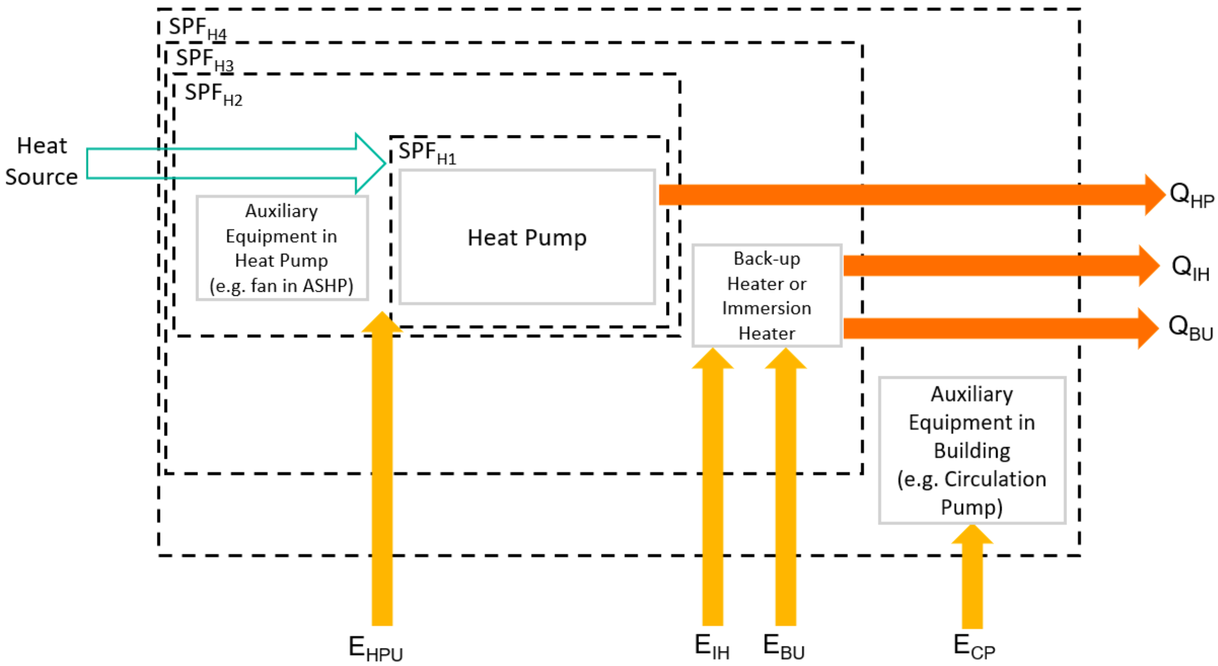

Figure 8. Schematic diagram of SPF boundaries *(Energy Systems Catapult 2023 a).*

The SPFs derived from the raw data were all consistent with the ones previously calculated by ESC and published in the summary performance file *(Energy Systems Catapult 2023 b).* This served as a useful consistency sanity check.

After having extracted the SPF over the year, it is considered unnecessary to have the data in a 2-minutes resolution. A high resolution creates problems when meters don't all update their consumption values at the same time: a mismatch between different meters causes the presence of some 'fictitious' negative readings for the heat pump consumption. To reduce the impact of these unsynchronised updates, a 30-minute resolution is chosen. Hence, the code reshapes and groups the data over half an hour timestamp. When performing this operation, the mean values every 30 minutes are taken for electricity consumption and temperature sensors. This lower resolution does not impact the results since the study is interested in finding general heat pump consumption profiles over time.

To assess heat pump consumption in different seasons, new dataframes are created which group the data according to their season. The 'winter' dataframe takes data collected in December, January, and February of the yearly window dataframe. 'Spring' includes data from March, April and May, 'Summer' includes June, July and August, and 'Autumn' includes September, October, and November.

For each of the seasonal dataframe and the yearly 'window' dataframe, the code groups the data by time, and it calculates the mean consumption of each component and mean temperature for every half an hour of the day averaged over the season. For example, a mean winter dataframe is created which contains the indoor and outdoor temperature every half-an-hour, and the average winter heat pump consumption, backup, immersion heater, and pump consumption averaged over half-an-hour intervals from the winter data. Relevant information regarding the house ID, SPFH, heat pump type and size, MCS heat loss, MCS space heat load, house area and EPC are also appended to the dataframes for future analysis.

The summary performance data file provided by ESC contains the date of the coldest day identified for every property, which is useful for the coldest day analysis of the dissertation. Hence, a new 'coldest day' dataframe containing the half-hour consumption and temperature data is filtered and extracted. The function that finds the average COPH2, COPH3 and COPH4 is used again so that the heat pump performance on the coldest day can be compared to the rest of the year. Columns containing house information and COP values are added to the coldest day dataframe of the property, including the temperature recorded on the day at 6pm.

Then, a new function is used to create a dataframe containing information on the total energy consumption of the year, winter, and coldest day for each heating system item of the property. This is useful for later analysis.

After having created all the dataframes for the mean half hour resolution daily profile averaged over the year, over each season, for the coldest day, and for the total consumption, each dataframe is appended outside of the 'for loop' that runs for each house. To save the processed data of each house, files containing all properties mean consumption dataframes are created.

The file that contains the 30-minute resolution day profile averaged over the year for every property is then read. The data is grouped by time, and the electricity consumption and temperature values at the specific half-an-hour resolution time of the day are averaged over all the households. Then a plot showing the daily profile of heat pump consumption averaged over the year and averaged over all properties is produced. The same plot is also produced for each season. Plots are displayed in the results section.

The primary objective of the thesis is to understand how house characteristics influence heat pump consumption. To investigate this, three key indicators are chosen: the EPC (Efficiency Performance Certificate), the MCS heat loss (the product of heat loss in $\mathrm{W/m^2}$ units and property area) and the MCS space heat load (in kW). The EPC is an indicator used in the UK to inform on the energy efficiency of a building, including the expected energy consumption of the building and carbon emissions. EPCs have a rating scale going from 'A' to 'G', in decreasing energy efficiency. The MCS heat loss is an average of the building area's heat loss, and the MCS space heat load indicates the average heating power required to heat the house sufficiently.

To maintain the same sample size for the comparative analysis that identifies the best indicator, properties that either don't have an EPC or that don't have MCS values are excluded from the house sample. Table 3 shows the distribution of shortlisted heat pump types for further analysis, which add up to 221 properties.

Table 3. Key statistics on shortlisted households for the data analysis (own analysis).

Group	Installations number	Installation percentage
Low temperature ASHP	99	45%
High temperature ASHP	82	37%
Hybrid heat pump system	36	16%
GSHP	4	2%

For the purpose of analysing the impact of different building characteristics on heat pump consumption, the dataframes are divided by EPC into two groups: the ones that have efficiency A, B or C (98 properties) and the ones with a D, E, or F rating (123 properties). To sort houses into two groups based on MCS space heat load and MCS heat loss characteristics, the median value is identified, and houses are split by the median. This, for example, results in a group with the lowest half MCS SHL houses (111 properties) that have an average value of 5.23kW and another one with the rest of the houses with highest MCS SHL values (110 properties) with an average value of 9.53kW. The low MCS HL group has an average value of 5.46kW and the high one has an average MCS HL value of 10.4kW. Figure 9 and Figure 10 show how the properties were divided into two groups for each building characteristic indicator.

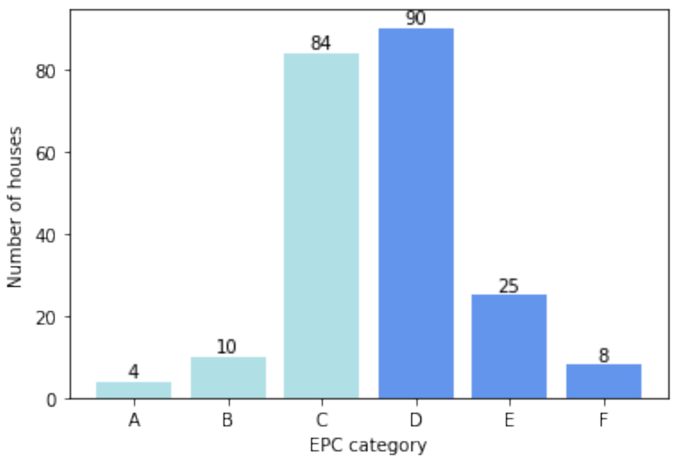

Figure 9. Distribution of houses in EPC groups – houses with ratings 'A, B, C' were considered as a single group, as well as the ones with ratings 'D, E, F' (original plot).

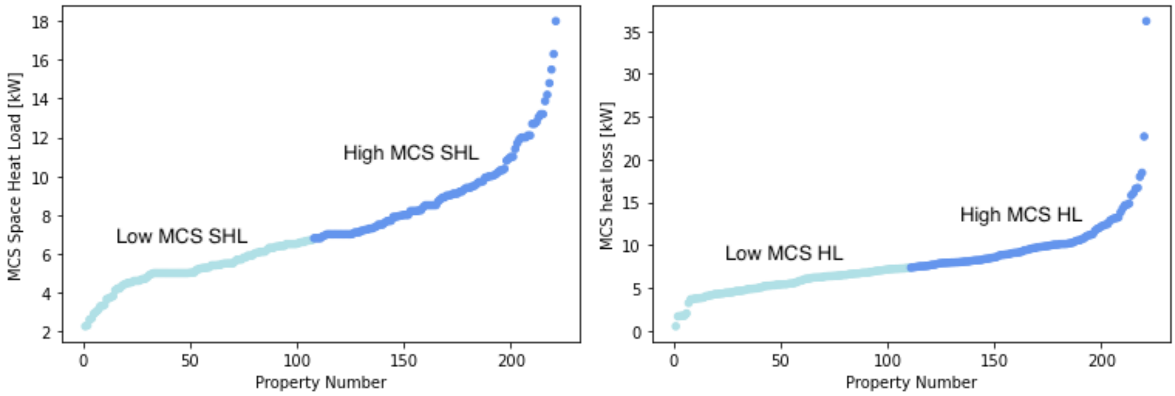

Figure 10. Distribution of houses based on MCS space heat load and MCS heat loss (original plots).

Then, the average yearly heat pump consumption and average indoor temperature profile can be plotted for the groups of houses with different building characteristics. The same procedure is repeated to obtain the seasonal and coldest day profiles in each house group.

To assess the statistical significance of findings, regressions are used for highlighting the correlations between heat pump consumption and MCS space heat load, MCS total heat loss, MCS heat loss (per unit area), and total floor area. Additionally, to perform a deep dive into relevant themes, data is arranged in bar graphs showing how average daily heat pump energy consumption changes in different house groups, and how SPF changes. Furthermore, a comparison of the average SPF over the year and on the coldest day is also provided, as well as how daily energy consumption of different heat pump components (heat pump, immersion heater, back-up, circulation pump) on the coldest day compares to average winter and yearly consumption.

RESULTS

The results section is structured in three blocks. Firstly, we answer 'How *do building characteristics affect heat pump consumption and performance?*'. Secondly, general patterns on the coldest day are displayed. Lastly, we investigate what the coldest day looks like in properties with different building characteristics.

THE EFFECT OF BUILDING CHARACTERISTICS ON HEAT PUMP CONSUMPTION AND PERFORMANCE

The daily profile of the heat pump consumption averaged over the year and seasons for all heat pumps in the clean dataset (353 properties) is displayed in Figure 11. Two main patterns emerge: heat pump electrical consumption presents a high morning peak and slightly lower evening peak, with a lower night-time consumption. As expected, winter is the season with highest heat pump consumption, followed by transition seasons and lastly summer, where the heat pump is mainly operated for DHW use.

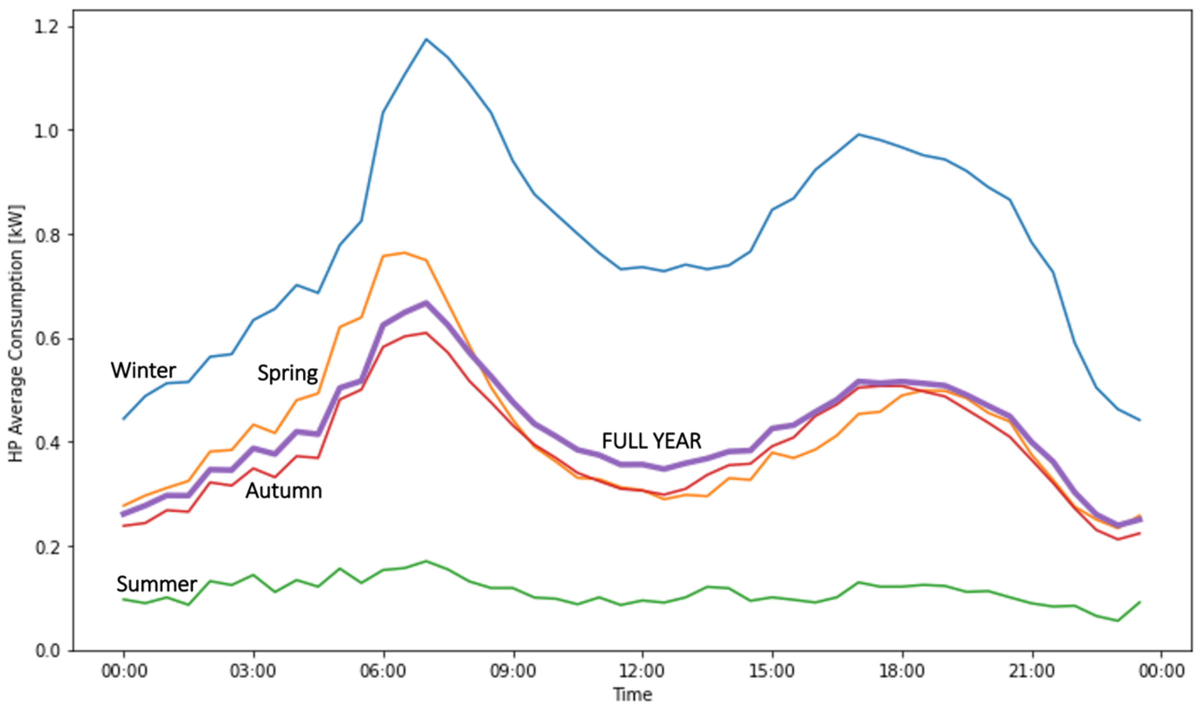

Figure 11. Average heat pump consumption over the year and seasons (original plot).

Properties are divided into EPC, MCS heat loss (HL) and MCS space heat load (SHL) groups, as described in the methods section. The profile of a typical day averaged over the year is shown in Figures 12–14 for each of these groups: the mean heat pump (HP) consumption and the mean indoor temperature profile of properties is shown for different building characteristic groups.

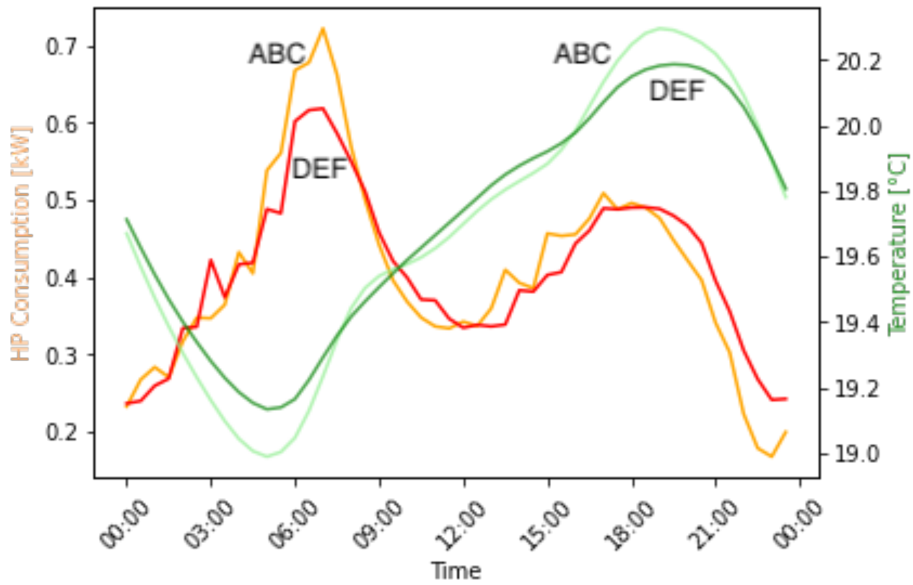

Figure 12. Daily HP consumption and indoor temperature profiles for houses in A, B, C and D, E, and F EPC rating groups averaged over the year (original plot).

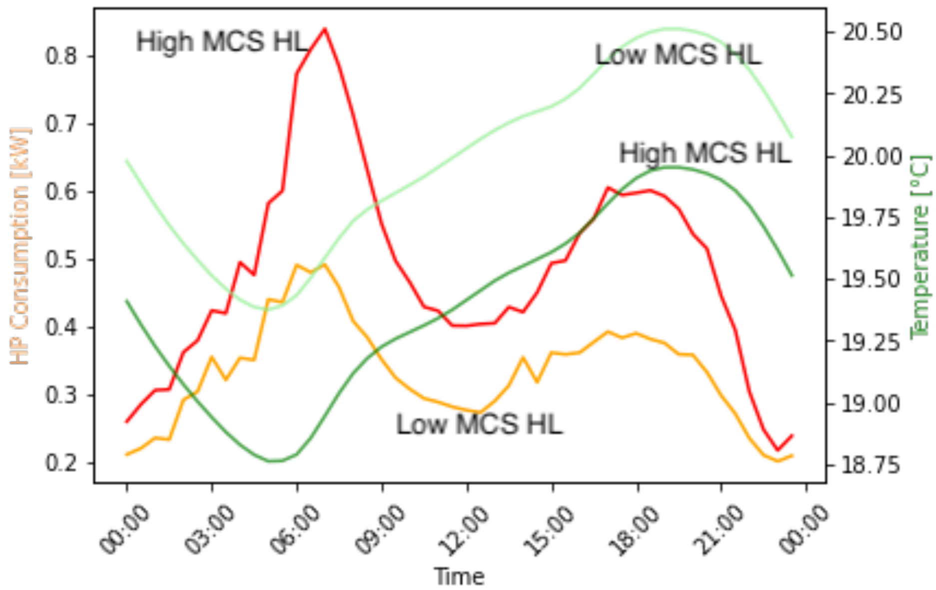

Figure 13. Daily HP consumption and indoor temperature profiles for low and high MCS heat loss houses averaged over the year (original plot).

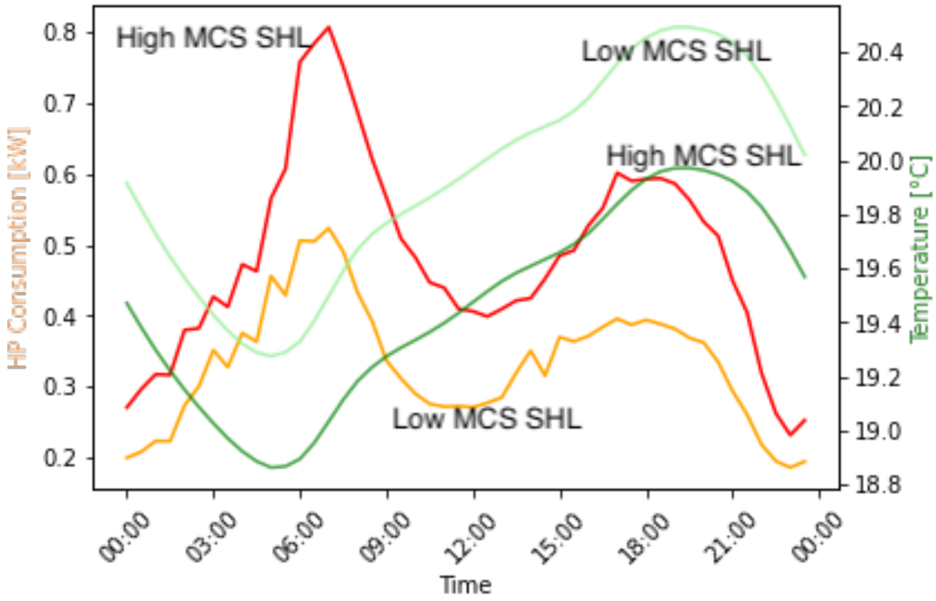

Figure 14. Daily HP consumption and indoor temperature profiles for low and high MCS space heat load houses averaged over the year (original plot).

The distinction between consumption and indoor temperatures is more evident in both MCS HL and MCS SHL cases compared to the EPC case. Houses with lower MCS values not only use less electricity for heating, but they also achieve consistently higher indoor temperatures. More plots are presented in the Appendix.

To understand which of the two MCS calculation methods is more strongly correlated to heat pump consumption, linear regression results are summarised in Table 4. Between the two, the MCS SHL calculation is slightly more relevant for predicting heat pump consumption, due to a higher coefficient than the MCS HL one (0.0294 vs 0.0204).

Table 4. Linear regression results between MCS calculation methods (own analysis).

X_n	Y	Coefficient	Confidence interval
MCS Space Heat Load [kW]	HP consumption	0.0295	0.028 – 0.031
MCS total Heat Loss [kW]	HP consumption	0.0204	0.019 – 0.022
MCS heat loss value [kW/m^2], total floor area [m^2]	HP consumption	0.0106, 0.0935	0.006 – 0.015, 0.089 – 0.098

The third row of the table provides more detailed insight into what makes a house consume more energy for heating. MCS (total) HL is calculated by multiplying the specific MCS heat loss value of the property (W/m^2), by the total floor area of the property. When the two factors of the heat loss multiplication are considered as separate variables x_1 and x_2 in the regression, results show that heat pump consumption is more correlated to building area than building fabric (such as insulation, glazing, and house type, determining an overall W/m^2 value).

To visualise the effect of grouping houses by EPC as opposed to MCS calculations, the daily heat pump energy consumption averaged over the year in different house categories is displayed in Figure 15. For clarity and to avoid redundancy, only the MCS SHL compared to EPC groups is displayed, since MCS HL shows almost identical results, and since MCS SHL is the most correlated to heat pump consumption between the two. Results show that when EPC is used as a metric for comparison between house groups, little difference in consumption can be expected. Instead, houses within the low MCS SHL group save around 3.59kWh per day compared to houses in the high MCS SHL group, resulting in a 0.15kW lower average heat pump power over the year.

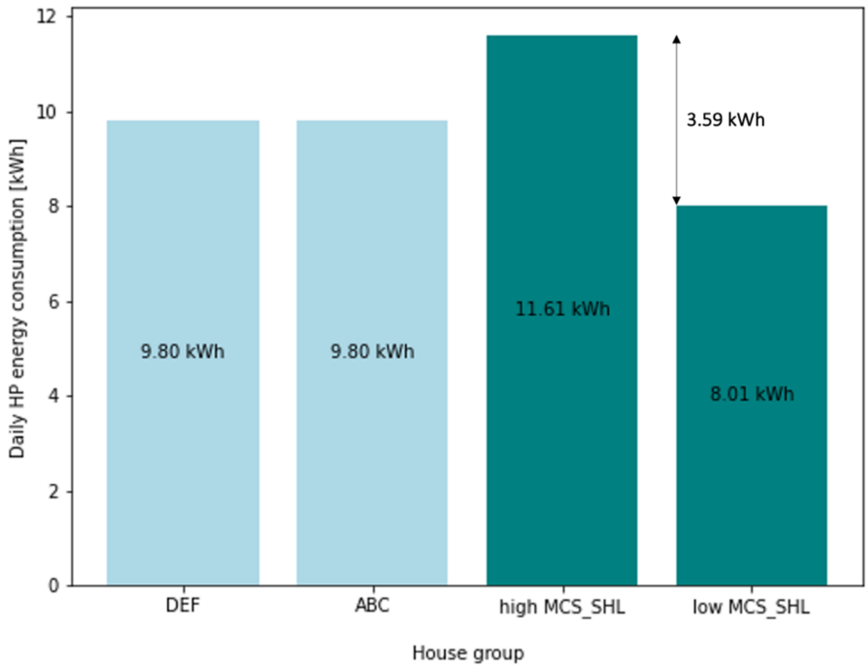

Figure 15. Daily heat pump energy consumption averaged over the year, by EPC and MCS SHL house group (original plot).

Figure 16 shows that the average UK property requires 9.81kWh a day for the operation of a heat pump (averaged over the year). Compared to the average UK property in the sample, low MCS SHL properties consume 1.8kWh less electricity a day for heating.

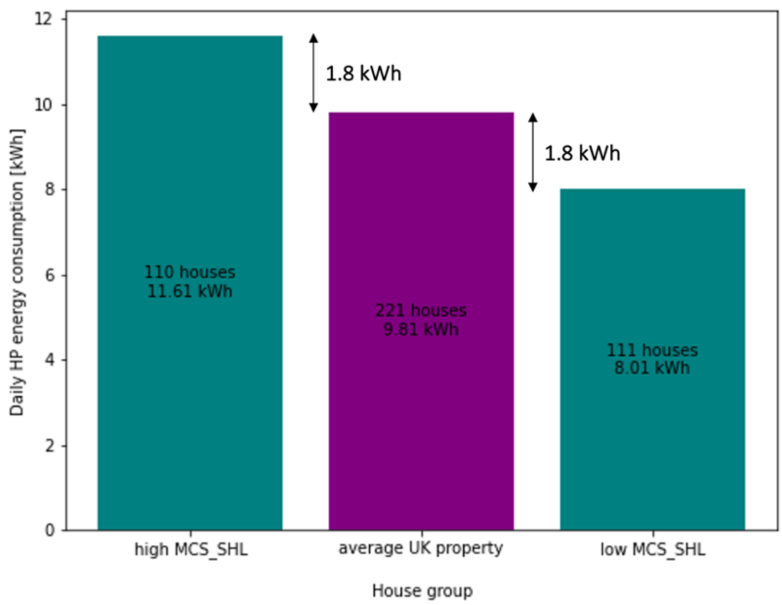

Figure 16. High and low MCS SHL properties daily heat pump consumption compared to the average UK property heat pump consumption (original plot).

To further investigate the reasons for lower consumption for houses with lower MCS SHL values, the yearly heat pump average SPFH4 in each house group is plotted. Figure 17 shows that the SPFH4 of a heat pump is not significantly impacted by heat pump operation in buildings with different characteristics.

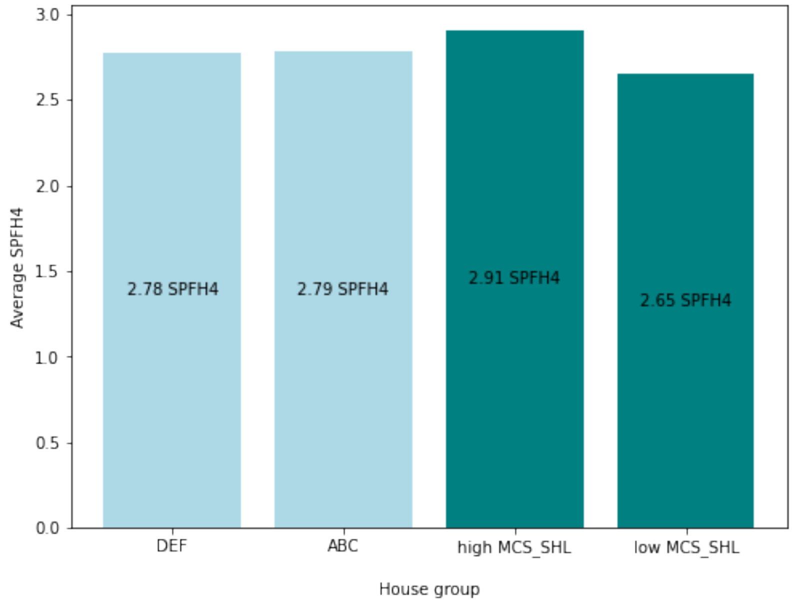

Figure 17. Average SPFH4 in different house categories (original plot).

THE COLDEST DAY

One major concern of heat pump adoption is whether the new extra electricity load is too high to be supported by the existing electricity network. Infrastructure is often planned based on the most critical time, hence this section presents the key findings on electricity consumption, heat pump efficiency and indoor temperatures when looking at the coldest day of the year.

The difference between winter and coldest-day heat pump consumption is presented in Figure 18. On the coldest day, heat pump run at a higher power, but it is worth noting that the achieved indoor temperatures are less than 0.5°C lower than other the average winter day.

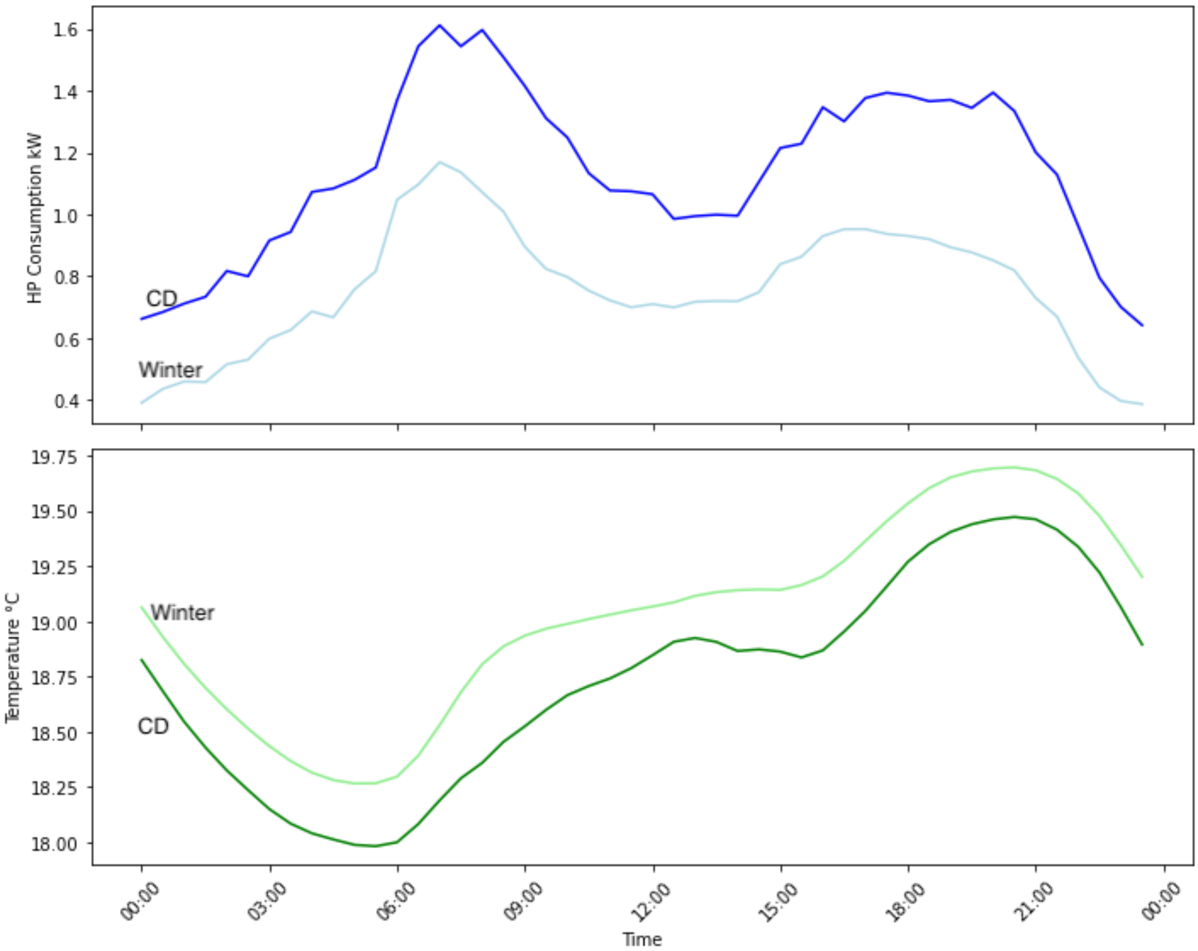

Figure 18. Average winter and coldest day (CD) heat pump consumption and indoor temperature (original plot).

Figure 19 displays how energy is consumed by different heat pump components, including the heat pump itself, the immersion heater, the back-up heating system, and the circulation pump, over different periods. The sample considered here excludes hybrid heat pumps, hence instead of 353 properties, the sample size decreases to 294. On the coldest day, electricity used for heating is around x1.5 times the typical winter day, and both the backup and immersion heater energy use increase substantially.

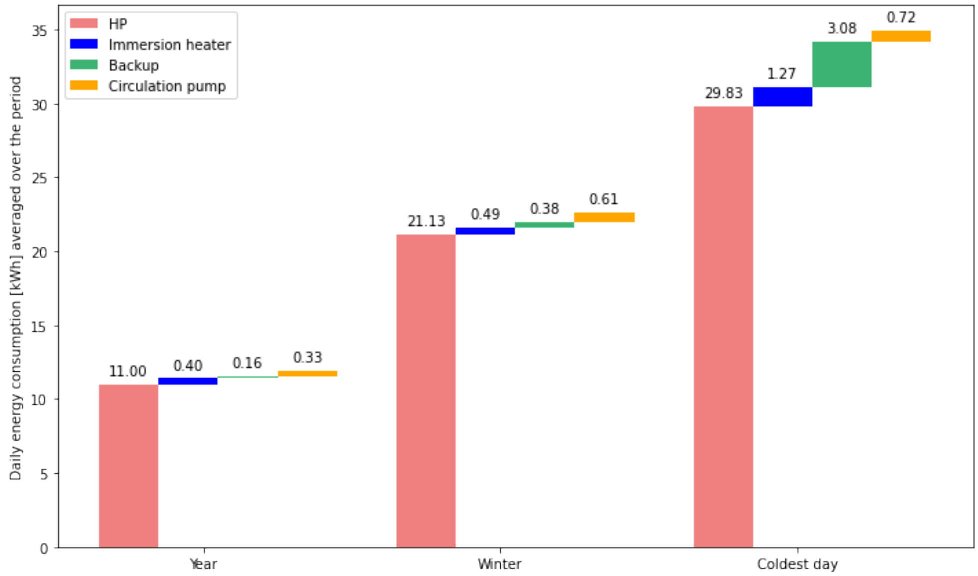

Figure 19. Average daily energy consumption by component for different cases (original plot).

In addition to more power being required to heat houses appropriately when the temperature outside is coldest, due to basic thermodynamics laws, heat pumps work less efficiently when the difference between the source and sink is larger. Figure 20 shows that compared to the average yearly SPF, the heat pump COP is reduced on the coldest day to some extent, but not in a substantial way (13% approximate reduction). In this analysis only non-hybrid systems were part of the sample, to avoid boiler energy consumption interfering with the pure heat pump use. These results are closely coherent with the ones published in the EoH interim report *(Energy Systems Catapult 2023 a).*

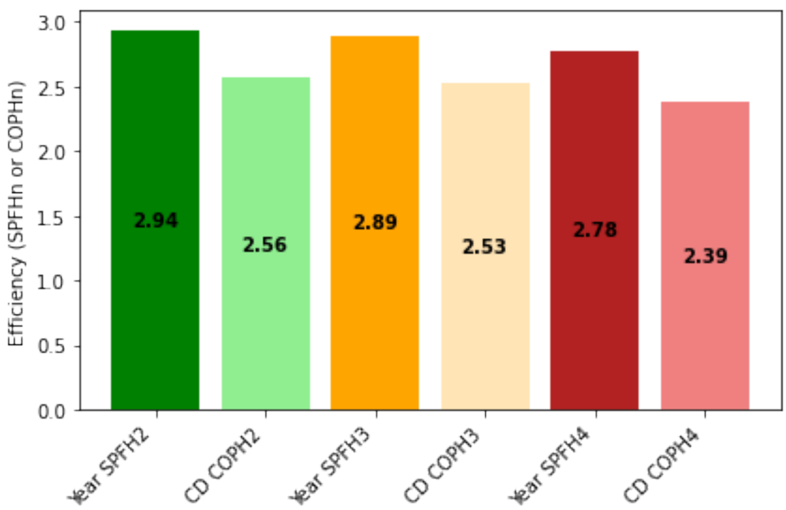

Figure 20. Comparison of average SPFH and COPH over the year and on the coldest day (original plot).

ANALYSIS OF THE COLDEST DAY FOR DIFFERENT HOUSE GROUPS

This section builds on the previous results to assesses how building characteristics impact heat pump consumption patterns specifically on the coldest day of the year.

Figure 21 shows two trends: on the coldest day, houses with higher MCS SHL tend to consume more electricity for heating, but they reach lower temperatures. Temperature at 6pm is displayed since most people are expected to be in the property at that time.

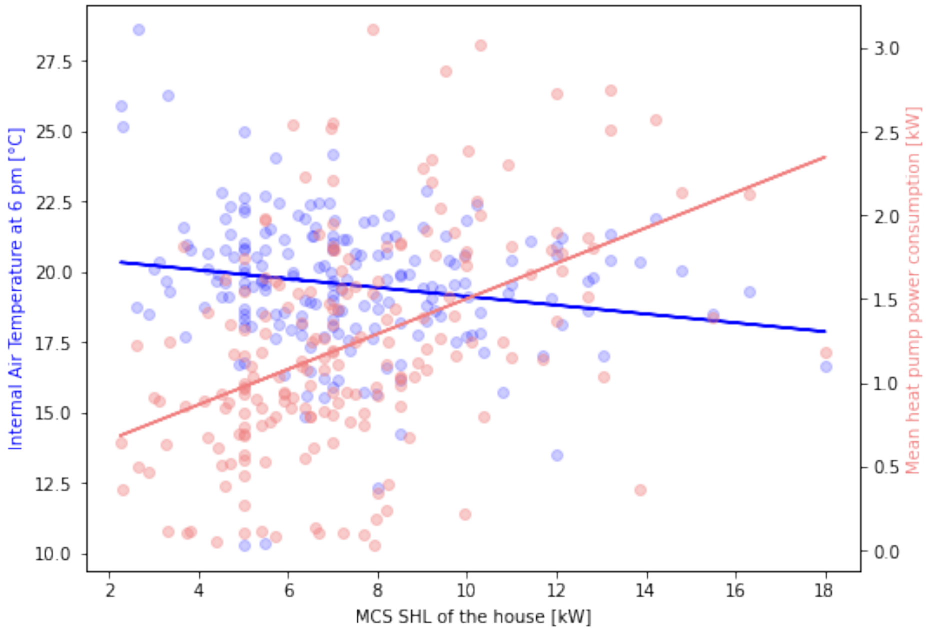

Figure 21. Coldest day internal air temperature (at 6pm) and mean heat pump power consumption for houses with different MCS SHL values (original plot).

Figure 22 and Figure 23 show the heat pump consumption profile on the coldest day averaged over all houses. Once again, dividing houses by MCS SHL seems to be a substantial indicator of heat pump consumption. On the coldest day of the year, houses that have lower space heat loads consistently run at lower average powers, and both the morning and evening peaks are largely reduced. The same can’t be said regarding houses split into EPC groups, where the distinction in power consumption between ABC and DEF-rated houses is unclear.

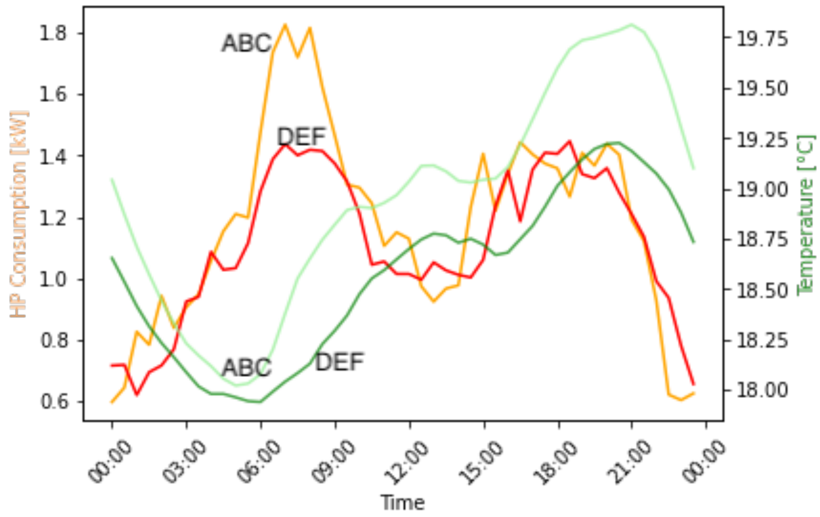

Figure 22. Daily HP consumption and indoor temperature profiles for ABC, DEF houses averaged on the coldest day (original plot).

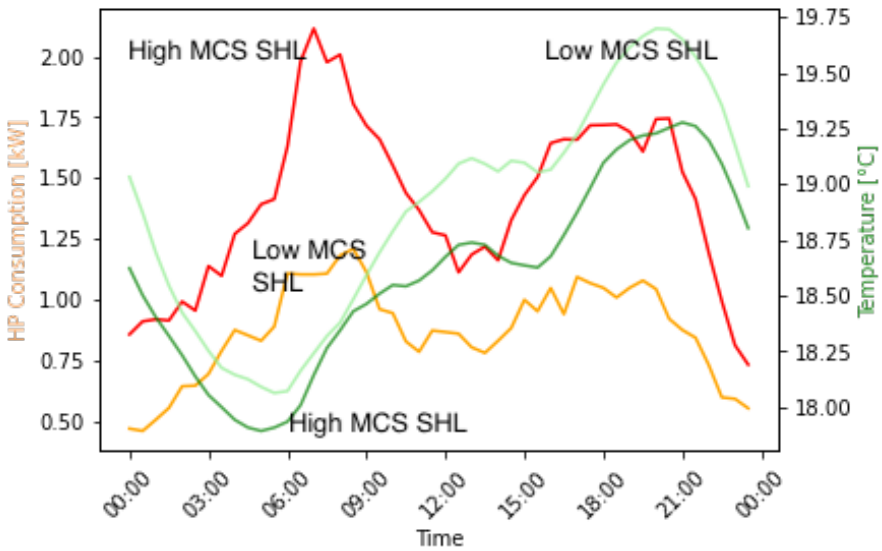

Figure 23. Daily HP consumption and indoor temperature profiles for low and high MCS Space Heat Load houses averaged on the coldest day (original plot).

Compared to the previous result section (containing the profiles averaged over the year for different house groups), on the coldest day the scale of the difference between heat pump consumption and indoor temperature deviates even more between house groups. This is because, on the coldest day, extremes are inflated. Additionally, when looking at the EPC groups, a new phenomenon is noticed: houses that have a higher EPC rating (which also have a higher morning consumption peak) tend to have higher indoor temperatures on the coldest day. Apart from these two remarks, other patterns between house groups stay roughly unchanged.

The comparison of heat pump consumption profiles between EPC groups and both MCS SHL on the coldest day are illustrated all together in Figure 24. Low MCS SHL houses have a 0.7kW lower heat pump consumption than high MCS SHL houses at peak time.

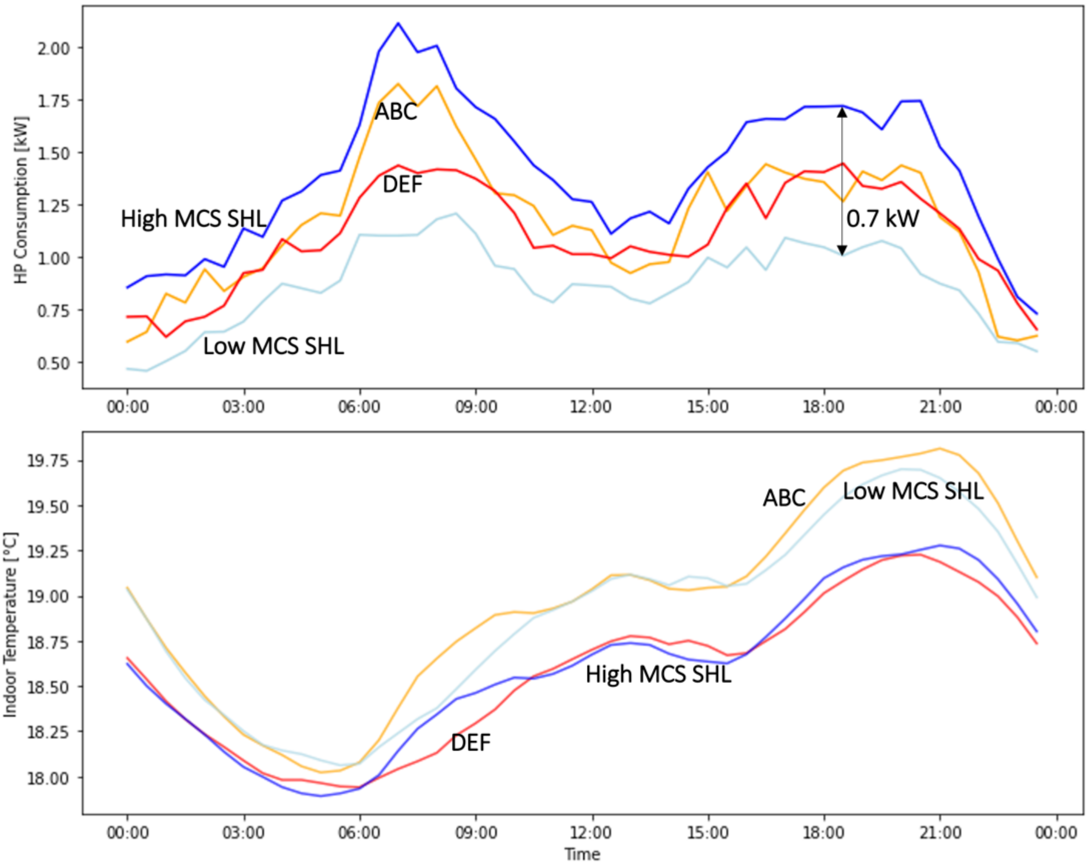

Figure 24. HP consumption and indoor temperature profiles on the coldest day for houses in EPC groups and MCS space heat load (original plot).

Figure 25 displays the difference in consumption between the average UK property in the sample and the low and high MCS SHL on the coldest day. It shows that if the average UK property was to be transformed in a low MCS SHL one, a demand reduction of 0.35kW would be achieved at peak time.

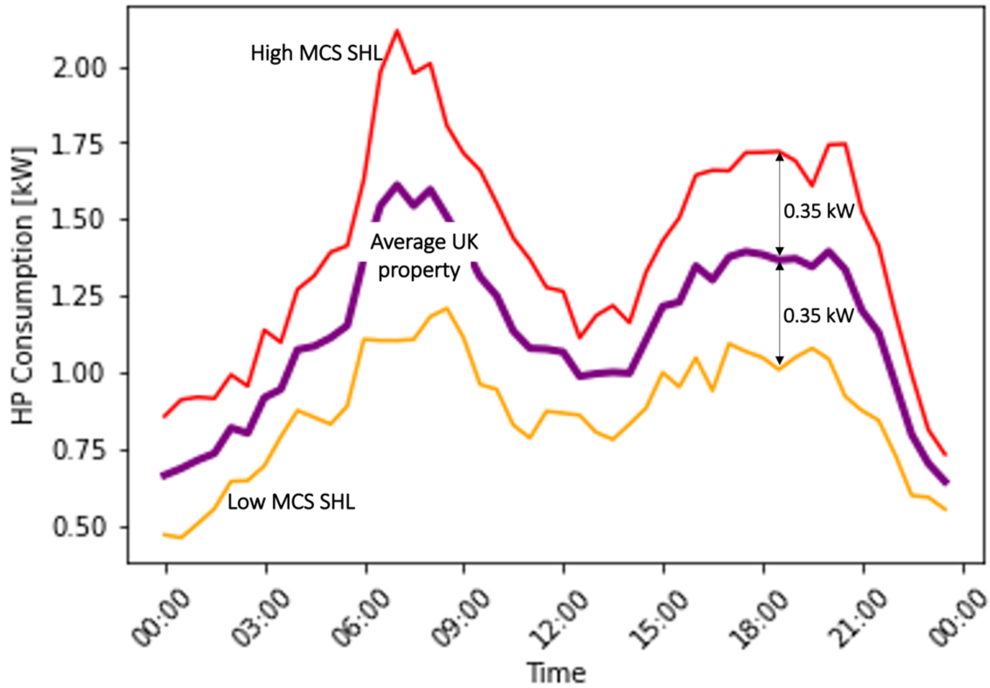

Figure 25. Comparison of heat pump consumption on the coldest day between the average UK property and the high and low MCS SHL property (original plot).

To explore the potential difference in heat pump performance between different property groups, Figure 26 shows the comparison of the COPH4 on the coldest day. There seems to be no substantial difference in heat pump performance between house groups. Additional resources are displayed in the Appendix.

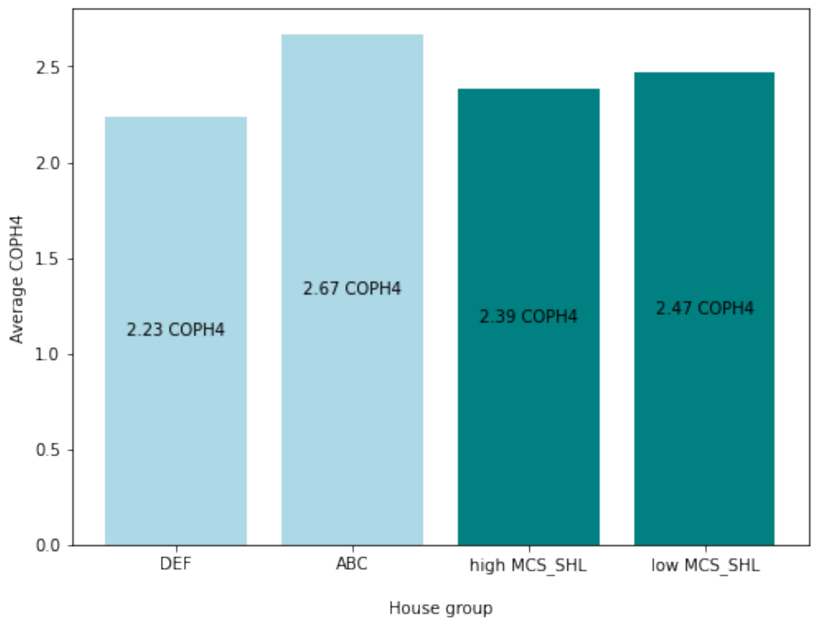

Figure 26. Average COPH4 on the coldest day, by EPC and MCS SHL house group (original plot).

DISCUSSION

CRITICAL ANALYSIS OF THE STUDY'S FINDINGS

The results of this study are possible thanks to novel data with unprecedented detail. To the best of our knowledge, the relation between building characteristics and heat pump consumption had never been investigated and quantified with trial data in this way before. In addition, previous heat pump demand response trials to reduce peak demand in the UK were to a much smaller scale than the EoH trial. The reasons this area is unexplored is because data was not available until the EoH trial one was published. This data is very precious due to the large number of heat pumps, long monitoring periods, large amount of information in relation to heat pump setups and extensive information on properties where heat pumps were installed and its occupants.

1) MCS INDICATORS ARE STRONG PREDICTORS OF HEAT PUMP CONSUMPTION

The clean EoH sample shows that, regardless of EPC ratings, houses have very similar heat pump consumption and indoor temperatures, both when averaging over the year and on the coldest day. This might be influenced by the fact that the 'ABC' sample contains mostly 'C' rated houses, and the 'DEF' sample contains mostly 'D' rated houses. Hence there might not be significant diversification in terms of properties' characteristics in the different groups. Furthermore, the EPC ratings average over many indicators, not only factors that are related to insulation and heating requirements. For example, having a solar PV or a battery both improve the rating of the property, although these don't necessarily reduce heat pump consumption. Overall, the hypothesis that EPCs are a good indicator for heat pump energy consumption is not supported by the available trial data.

Instead, using the MCS space heat load and heat loss calculations appears to be more effective for predicting heat pump consumption. This makes sense since MCS calculations are designed specifically for heat pump sizing. The contribution of this dissertation is the newly observed finding that MCS calculations of both MCS SHL and HL are strongly correlated to heat pump consumption. These are effective indicators for predicting the energy consumption of heat pumps before installation.

2) IMPROVED BUILDING PERFORMANCE COULD SAVE UP TO £3.6BN ON HOUSEHOLD BILLS

The significance of the finding can be understood by estimating the potential system wide impact. A 2050 scenario in which 100% of UK houses install a heat pump and they improve their performance such that they achieve an average MCS SHL equal to the low MCS SHL classification (with a mean MCS SHL value of 5.23kW), would save 19.1TWh of annual electricity compared to if the UK house stock maintained the current MCS SHL average (7.27kW). Assumptions and calculations are displayed in Table 5 and Table 6. Furthermore, the cost sensitivity in Table 7 shows that, depending on the retail electricity price, achieving low MCS SHL classification in 100% of UK properties could allow consumers to save between £0.57bn and £3.62bn in annual bills. In addition, properties with a smaller heat load require a smaller heat pump system, which also leads to a reduced cost for the consumer. These calculations assume that the trial sample is representative of the average MCS SHL of UK properties. Although this might not be fully accurate as a baseline, these calculations serve to illustrate the scale of the implications of having properties with different MCS heat loads, and hence the importance of having a well performing building stock.

Table 5. Assumptions for estimating energy and bills savings through low MCS SHL.

ASSUMPTIONS	Unit	Amount	Source
Daily electricity consumption reduction (per average UK property) to achieve low MCS SHL classification	kWh/day	1.8	Dissertation results
Number of properties in the UK	unit	29,000,000	*(BEIS 2022 a)*

Table 6. Estimated annual electricity demand reduction and associated savings in a 2050 100% UK heat pump deployment scenario if properties achieve an average low MCS SHL classification.

CALCULATIONS	Unit	Amount
Yearly electricity consumption reduction (per average UK property) as a result of low MCS SHL classification	MWh/year	0.66
Total annual energy demand reduction if UK houses achieved an average MCS SHL corresponding to the low MCS SHL group	TWh/year	19.1

Table 7. Electricity bills savings sensitivity.

Cost savings sensitivity							
Electricity price £/MWh	30	60	90	110	130	160	190
UK customers annual bills savings £bn	0.57	1.14	1.71	2.10	2.48	3.05	3.62

3) PEAK DEMAND COULD BE REDUCED BY 10GW WITH BETTER HOUSING STOCK

The interim report by ESC did not utilise the breadth of EoH data to its full potential. Arguably, superficially focusing only on refrigerant type, dwelling type and heat pump SPF (both in the whole year and on the coldest day) can't answer one of the most pressing questions related to heat pumps adoption, which is: *how much do they impact infrastructure capacity at critical times, and how is their consumption spread over the day?.* Hence, this study has used the EoH data to provide more insight for answering this question.

As introduced previously, the key reason for focusing on the coldest day in different EPC and MCS house groups is to understand the possible implications of different building characteristics on the sizing of the electrical network. Low MCS SHL properties not only result in the previously estimated yearly bills savings, but, due to the reduced impact to peak demand, they also reduce the need for network upgrades. Again, the significance of findings can be understood by making an approximate calculation. As per the results from the dissertation analysis, at peak time (between 5pm and 9pm) on the coldest day, low MCS SHL properties save 0.35kW compared to the average UK property. In a 2050 UK scenario with 100% heat pump deployment, this translates into a 10.15GW peak demand saving. A figure published by BEIS estimates that 15GW of demand side response (DSR) can save up to £50bn in the UK network in 2050

(BEIS 2022 b). Having a house stock with an average MCS SHL corresponding to the low MCS SHL classification of this study rather than the current average MCS SHL can be considered as a type of DSR. Hence, by using the same scale factor, we estimate that £33.8bn could be saved thanks to avoided network upgrades. Assumptions and calculations are summarised in Table 8 and Table 9. Again, these calculations serve to illustrate the scale of the network implications of having properties with different MCS space heat loads.

Table 8. Assumptions for estimating network savings.

ASSUMPTIONS	Unit	Amount	Source
Peak power demand reduction by achieving low MCS SHL compared to the average UK MCS SHL (per heat pump)	kW	0.35	Dissertation results
Number of houses in UK	unit	29,000,000	*(BEIS 2022 a)*
BEIS prediction of UK demand side response (DSR) by 2050	GW	15	*(BEIS 2022 b)*
BEIS prediction of UK network saving because of DSR by 2050	£bn	50	*(BEIS 2022 b)*

Table 9. Estimated network savings in a 2050 scenario with 100% HP deployment in the UK if properties' average MCS SHL achieves the low MCS SHL group value.

CALCULATIONS	Unit	Amount
BEIS predicted cost saving per GW of peak reduction through DSR by 2050	£bn/GW	3.33
Peak demand reduction if UK houses achieved a low MCS SHL average	GW	10.15
Overall maximum network saving by 2050 if all UK houses achieved a low MCS SHL average	£bn	33.8

To investigate what are the factors that influence the most MCS heat loss in houses, the area of the property and its heat loss resulting from the building fabric (MCS heat loss value in kW/m^2) have been assessed separately in a linear regression. It appears that the correlation of heat pump consumption is more strongly related to floor area rather than the heat loss per unit area resulting from building fabric. Since it is unlikely that major modifications to properties' areas are performed, this result highlights the crucial importance of implementing insulation and efficiency measures to reduce heat loads in houses. This finding is relevant for policymakers, who, for example, might consider investigating the idea of reducing taxes or introducing subsidy schemes for smaller properties, or who might want to boost the effort on homes energy efficiency schemes. Having quantified the relation between building characteristic and heat pump consumption also helps policymakers to form clearer and more realistic expectations of the effects of implementing efficiency measures in houses.

4) HEAT PUMPS MAINTAIN A SATISFACTORY PERFORMANCE ON COLD DAYS

Moving on to the assessment of seasonal performance factors, it appears that there is no substantial difference in heat pump performance (or SPFH4) in different EPC or MCS groups. Reasonably, this indicates that building characteristics don't strongly affect heat pump efficiency. In all house groups, when assessing SPF on the coldest day of the year, COPH4 only decreased by around 13% compared to the yearly average SPFH4. Moreover, the indoor temperature achieved was only reduced by less 0.5°C with respect to other winter days. This challenges the idea that heat pumps 'don't work well' on cold days – which is a typical critique by heat pump adverse advocates.

Furthermore, results show that on the coldest day, heat pump energy consumption increases by around 30-40% with respect to winter. Quantifying this is useful to aid planning the supply of appropriate electricity on the most critical days. The analysis also shows that on the coldest day, the contribution of backup power and immersion coils is minor compared to the heat pump system itself (around 10% of the day's heat pump consumption). To understand whether this indicates that heat pumps were probably suitably sized, additional information regarding other potential heat sources in the house should be collected. It is recommended to monitor this aspect in future trials.

LIMITATIONS

Some misrepresentations still exist in the data, as acknowledged by ESC *(Energy Systems Catapult 2023 a)*. Firstly, due to the timestamps alignment to every 2 minutes, instantaneous calculations may incur in a 9-11% variation. Additionally, some circulation pump meters did not record any consumption: in these cases, when the heat pump consumption is calculated by subtracting components' consumption from the whole system one, heat pump consumption seems higher than it is (as it includes the circulation pump energy too). Hence, ESC estimates that the results of the SPFH2 and SPFH3 analysis might be 0.021 and 0.011 lower than in reality. Furthermore, monobloc heat pumps containing the back-up heater within the external heat pump unit also affect the boundaries of SPFH2 and SPFH3. Thus, SPFH4 is the most accurate for the purposes of this study.

Another limitation of this thesis is that the dataset presents some biases which might affect heat pump consumption. The participant report *(Energy Systems Catapult 2023 c)* shows that the largest participant group was occupied by full-time workers earning above £50,000 per year per household, corresponding to a higher income than in the general UK population. Additionally, the dataset does not evenly represent the UK climate zones: installations were only located in England and Scotland. When the trial is complete and the sample is increased, it will be possible to perform additional statistical analysis to clean the data from the above biases and to reassess findings.

Moreover, it is important to point out that few houses with insufficient insulation were excluded from the trial candidate properties, which represents a bias towards the EPC and MCS building characteristics analysis.

When drawing conclusions on thermal comfort, it is important to note that temperature sensors were installed in 'central and shaded areas in the house', without specifying the room purpose. Since comfort in different house areas depends on their purpose (i.e., corridors can be colder, but it is more desirable to have warmer living spaces), we must be aware that inherent biases in the thermal data might be present, and that the temperature sensor doesn't allow us to paint the full picture.

Lastly, reducing the sample size for comparing EPC and MCS values altered the proportions on building type and age that were initially set to mimic as much as possible the state of the UK building stock. Hence, the sample used to assess MCS and EPC characteristics might not be representative. Additionally, the few hybrid heat pumps in the sample (which only provide space heating but no DHW, unlike the rest) are not distributed evenly between house groups.

OPPORTUNITIES FOR FURTHER RESEARCH

In this study, hybrid heat pumps were not excluded from the house groups: having a larger sample size was prioritised. After the end of the monitoring period (expected in September 2023), there should be enough data to remove hybrid heat pump systems from the analysis. It is desirable that future research removes hybrid heat pumps since, in a net zero scenario, burning gas will likely have to be minimized. Additionally, with a larger data sample, more statistical analysis can be performed to understand the impact of income and location on heat pump consumption.

As previously touched upon, to understand fully what happens on the coldest day, it would be useful that future research focuses on whole house data collection. Hence, it is advised to include additional information and metering on other potential heat sources in properties (such as fires, infrared heaters, other electric and resistive heaters). These were not recorded by the EoH trial meters.

Additionally, for a more thorough cost-benefit analysis, it is suggested that future studies focus on estimating the costs of implementing building efficiency measures to lower the MCS SHL. This would be complementary information, which, together with the present study, could be useful for policymakers involved in designing the UK heat decarbonisation strategy.

The present study has focused on how lower MCS SHL could reduce electricity consumption in houses where heat pumps were installed. Although the MCS SHL indicator was designed with the purpose of sizing heat pumps specifically, it provides information regarding building characteristics. In theory, a lower MCS SHL indicates a lower heat demand of a house, no matter the heat system. Thus, it would be useful to repeat this analysis for houses with gas boilers as well. This would allow to understand how a better building stock (with lower MCS SHL values) could reduce overall heating demand and hence reduce gas consumption as well.

In the academic community and heat pump sector, there have been many critical voices around MCS calculation. As noted in the Home Surveys and Install Report *(Energy Systems Catapult 2022),* there seems to be a compliance issue with the MCS, since manufacturers utilise their own tools for performing the recommended MCS calculations, but they are not required to prove that the calculations are compliant. Although it is important that all manufacturers use the same tool for performing MCS calculations and that this aspect is improved, the thesis shows that, within the EoH trial, calculations have been done consistently enough (even between three different DCs) that the usefulness of MCS indexes was confirmed. Another relevant note for the dissertation result is that, since MCS heat loss and space heat load calculations are locked *(MCS 2021)*, it was impossible to verify that MCS space heat load and MCS total heat loss (calculated by multiplying floor area to heat loss per unit area) are different things. Even after contacting the MCS for an enquiry, they did not provide satisfactory answers. We advise to investigate further into this aspect in future research.

CONCLUSION

Heat pumps are an important technology for decarbonising the residential heating sector, which accounts for around 21% of UK emissions. This thesis identifies and addresses a research gap in the quantification of the effect of building characteristics on heat pump consumption, and the possible contribution of building stock to reduce peak demand. This topic is particularly relevant in the UK, where building performance standards are lower than in other European countries and heat pumps have been found to perform less well.

Addressing this gap is now possible due to the recently published trial data from the UK Electrification of Heat project, which includes heat pump consumption data together with information regarding participants, properties and system design of 742 installations.

The thesis' findings help seeing the heat pump deployment challenge with different eyes, and they can potentially change our thinking on topics related to home efficiency and heat pump installations. The relevance of the present study is recapitulated below.

1) **MCS indicators are strong predictors of heat pump consumption.**

The results of this thesis show that Efficiency Performance Certificate is not a good indicator for heat pump consumption, and that MCS space heat load (and MCS total heat loss) is a useful tool to predict a house's heat pump consumption. To the best of our knowledge, this relationship has not been investigated before in the way presented here.

2) **Improved building performance could save up to £3.6bn on household bills.**

To analyse data, properties were split by the median MCS space heat load values into two groups. As per the data sample, compared to the average UK property that consumes around 9.81kWh/day for its heat pump operation, a property in the low MCS SHL group has on average 1.8kWh/day lower consumption. In a 2050 scenario with 100% deployment of heat pumps, if the average MCS SHL of UK properties were brought down to the mean value of the low MCS SHL group of 5.23kW (corresponding to a 28% decrease in MCS SHL compared to the average UK house), then electricity demand for heating homes would be reduced by over 19TWh/year. This could reduce consumer bills by £0.57-3.62bn annually, in addition to necessitating smaller and consequently cheaper heat pump systems and national infrastructure.

3) Peak demand could be reduced by 10GW with better housing stock.

Results show that on the coldest day of the year, properties in the low MCS SHL group consume 0.35kW less electricity at peak time compared to the average UK property. In a 2050 scenario with 100% deployment of heat pumps, if all UK properties achieved a low MCS SHL average, it would result in a peak demand reduction of over 10GW, corresponding to a saving in excess of £33bn due to the avoidance of network upgrades.

4) Heat pumps maintain a satisfactory performance on cold days.

The study has demonstrated that different building characteristics don't strongly impact the seasonal performance factors, and that the COP is only reduced by around 13% on the coldest day of the year compared to the yearly SPF. Furthermore, indoor temperatures are only reduced by less than 0.5°C on the coldest day with respect to an average winter day. These results confirm that heat pumps are suitable even in the most extreme cold days in the UK.

When considering installing heat pumps at a large scale in the UK, these results show the striking potential for reducing costs and stress on the energy systems by improving the building stock quality. Substantial benefits can be unlocked by lowering the average UK property MCS space heat load value. Properties with a lower space heat load use less electricity for heat pumps. This not only allows households to reduce their bills, but it also reduces the requirement of additional expensive and potentially carbon intensive electricity generation plants. A lower electricity demand is also helpful for reducing the risks of electricity infrastructure overloading events and the need for upgrading lines. These contributions are extremely relevant in the context of the overall UK decarbonisation strategy, which is reliant on electrification of heat and transport. Hence, any contribution that reduces stress on electricity infrastructure is precious.

Clear and data-grounded information on the relation between improved building stock and heat pump cost saving will be particularly useful for policymakers. The study's findings can aid the designing of well thought heat pump roll out schemes and home efficiency schemes.

In the discussion, we have touched on opportunities for further research in relation to this study. We advise future research to reassess this analysis by removing hybrid heat pump data, to include information on other potential heating sources in future trials, to estimate the costs of implementing building efficiency measures for lowering the MCS SHL, to assess the impact of MCS SHL on houses with other heating sources such as gas boilers, and to gain more understanding on how the MCS calculation is performed.

Overall, this study has contributed to better understanding what factors influence heat pump energy use and costs. These findings are relevant as they can help to guide the roll out of insulation measures in a targeted and effective manner, such that the roll out of heat pumps can be achieved faster, at lower cost and with less impact on the electricity system. Achieving large scale heat pump deployment is likely fundamental if the UK plans to achieve its ambitious Net Zero target by 2050, which it has committed to do.

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APPENDIX

Table 10 shows the detailed EoH results published by *Energy Systems Catapult (2023 a)*.

Table 10. EoH results *(Energy Systems Catapult 2023 a)*

Heat Pump Type	SPF Type	Sample Size	Median [IQR]	Mean [95% CI]
ASHP	SPFH2	291	2.94 [2.66, 3.20]	2.95 [2.90, 3.00]
ASHP	SPFH3	291	2.89 [2.62, 3.17]	2.90 [2.85, 2.95]
ASHP	SPFH4	291	2.80 [2.53, 3.09]	2.82 [2.77, 2.87]
Heat Pumps within Hybrid systems	SPFH2	58	2.54 [2.25, 2.93]	2.60 [2.47, 2.73]
Heat Pumps within Hybrid systems	SPFH4	58	2.37 [2.01, 2.81]	2.42 [2.28, 2.55]

Heat Pump Type	SPF Type	Sample Size	Median [IQR]	Mean [95% CI]
LT ASHP	SPFH2	187	2.94 [2.63, 3.26]	2.94 [2.88, 3.01]
LT ASHP	SPFH3	187	2.86 [2.56, 3.19]	2.87 [2.81, 2.94]
LT ASHP	SPFH4	187	2.74 [2.47, 3.09]	2.77 [2.71, 2.84]
HT ASHP	SPFH2	104	2.94 [2.71, 3.15]	2.96 [2.88, 3.04]
HT ASHP	SPFH3	104	2.94 [2.67, 3.15]	2.95 [2.87, 3.03]
HT ASHP	SPFH4	104	2.89 [2.66, 3.07]	2.89 [2.82, 2.97]

Further dissertation results are displayed below. Figure 27 shows that the difference in power consumption at peak time (5pm to 9pm) is on average 0.34kW lower in buildings classified as Low MCS SHL. The data is averaged over the whole year (rather than just on the coldest day).

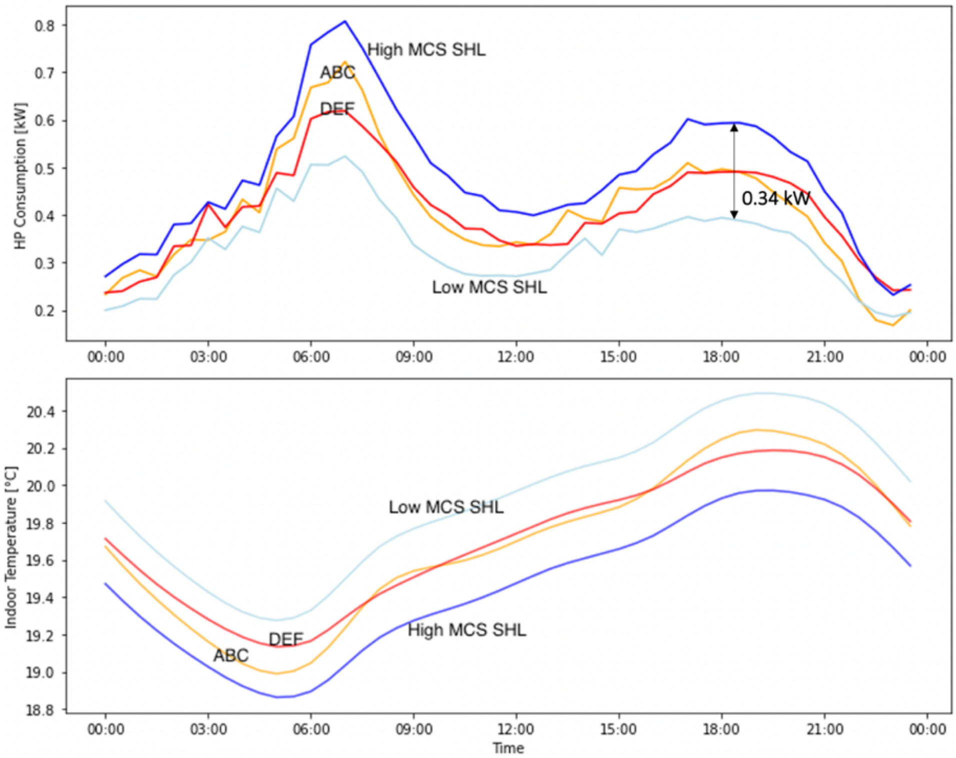

Figure 27. Comparison of HP consumption and indoor temperature in houses divided by EPC and by MCS space heat loss groups (original plot).

Figure 28 shows that on the coldest day, low MCS SHL houses consume around 13.33kWh less than the ones in the high MCS SHL group.

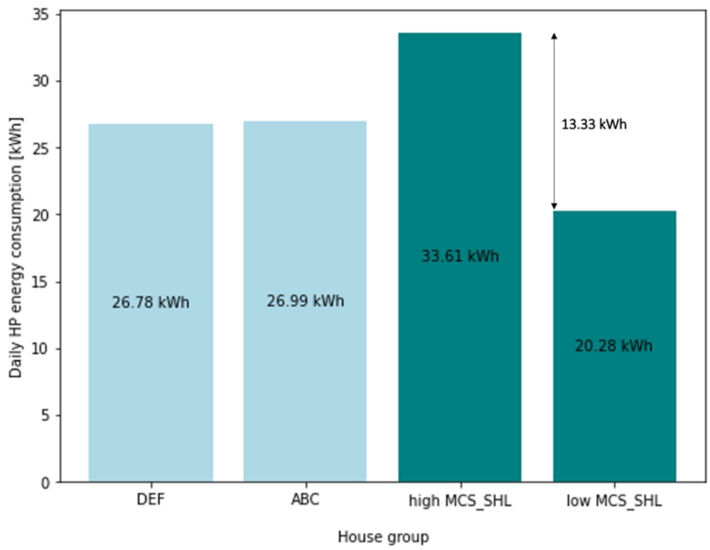

Figure 28. Daily heat pump energy consumption averaged over the coldest day, by EPC and MCS SHL house group (original plot).

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