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

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Abstract

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

Introduction

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

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

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

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

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

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

Methodology

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

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

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

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

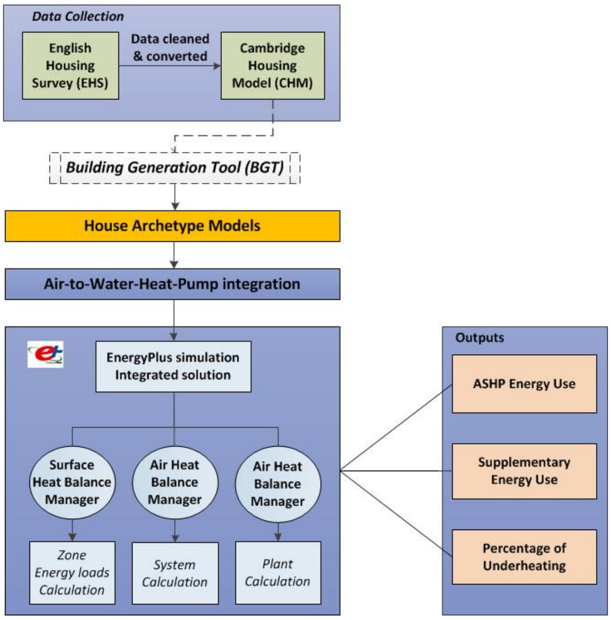

Figure 1: Methodological approach.

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

Housing stock

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

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

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

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

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

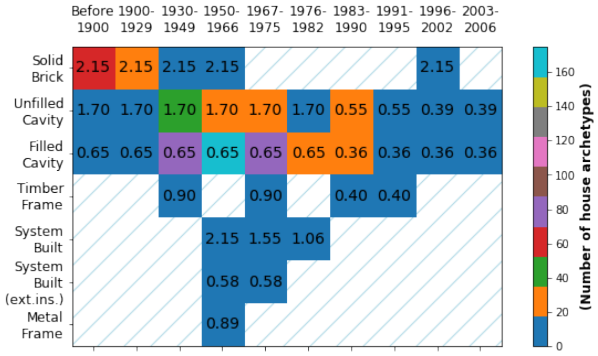

Figure 2: Exposed-wall U-value (W/m^2 k) and total number of house archetypes per age band and construction type.

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

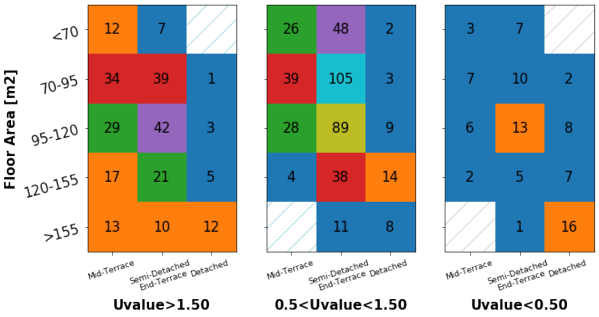

Figure 3: Total number of house archetypes per dwelling type, range of floor area and exposed-wall U-value. House archetypes with U-value>1.50 W/m^2 k have no wall insulation.

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

Integration of an AWHP heating system in the housing stock

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

AWHP characteristics

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

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

Water heater tank

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

Control of the AWHP system

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

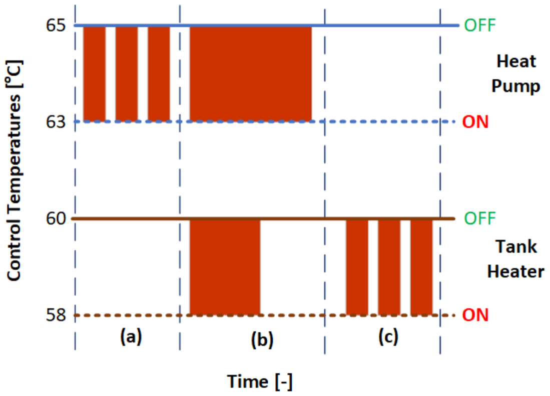

Figure 4: Representation of system's controls and operational modes.

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

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

Table 1: Characteristics of the AWHP system

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

Heating pattern

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

Simulations

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

Results and discussion

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

Level of underheating

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

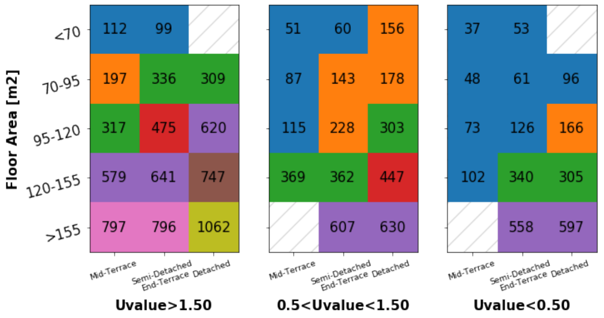

Figure 5: Average annual number of underheating hours per various house categories.

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

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

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

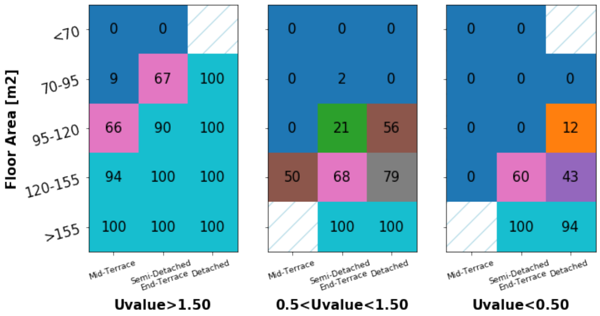


Figure 6: Percentage of house archetypes with more than 300 hours of underheating per various house categories.

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

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

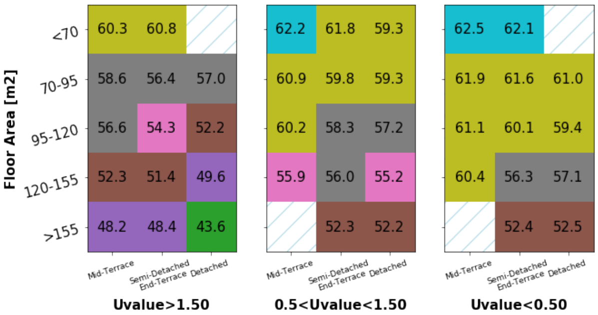


Figure 7: Average annual water tank temperature per various house categories.

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

Performance of the AWHP system

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

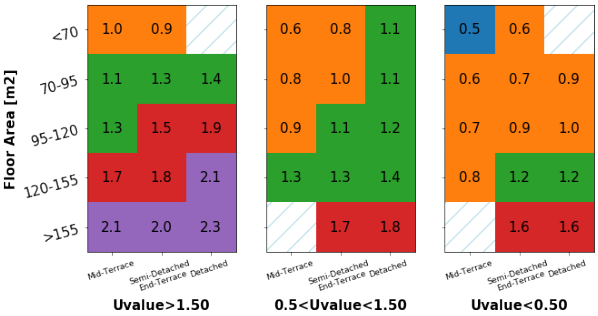
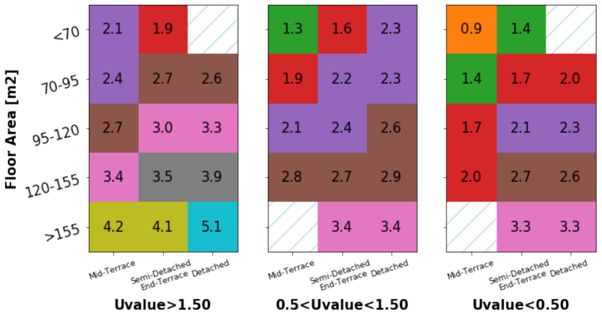


Figure 8: Average annual AWHP energy use (MW) per various house categories.



Uvalue>1.50

Floor Area [m2]	Mid-Terrace	Semi-Detached End-Terrace	Detached
<70	2.1	1.9	
70-95	2.4	2.7	2.6
95-120	2.7	3.0	3.3
120-155	3.4	3.5	3.9
>155	4.2	4.1	5.1

0.5<Uvalue<1.50

Floor Area [m2]	Mid-Terrace	Semi-Detached End-Terrace	Detached
<70	1.3	1.6	2.3
70-95	1.9	2.2	2.3
95-120	2.1	2.4	2.6
120-155	2.8	2.7	2.9
>155		3.4	3.4

Uvalue<0.50

Floor Area [m2]	Mid-Terrace	Semi-Detached End-Terrace	Detached
<70	0.9	1.4	
70-95	1.4	1.7	2.0
95-120	1.7	2.1	2.3
120-155	2.0	2.7	2.6
>155		3.3	3.3

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

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

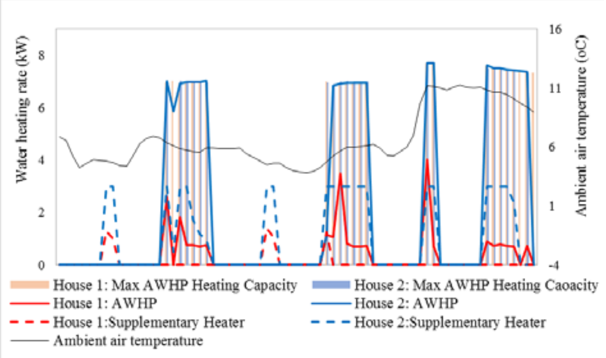
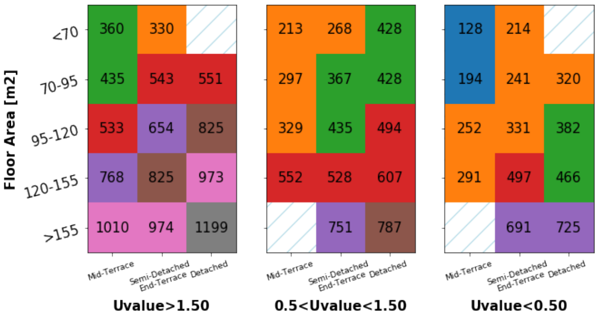


Figure 10: Example of AWHP's system operation in house archetypes with different characteristics during three working heating days.

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

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



Uvalue>1.50

Floor Area [m2]	Mid-Terrace	Semi-Detached End-Terrace	Detached
<70	360	330	
70-95	435	543	551
95-120	533	654	825
120-155	768	825	973
>155	1010	974	1199

0.5<Uvalue<1.50

Floor Area [m2]	Mid-Terrace	Semi-Detached End-Terrace	Detached
<70	213	268	428
70-95	297	367	428
95-120	329	435	494
120-155	552	528	607
>155		751	787

Uvalue<0.50

Floor Area [m2]	Mid-Terrace	Semi-Detached End-Terrace	Detached
<70	128	214	
70-95	194	241	320
95-120	252	331	382
120-155	291	497	466
>155		691	725

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

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

Conclusions

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

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