INTERNATIONAL BUILDING PERFORMANCE SIMULATION ASSOCIATION ENGLAND

Proceedings of BSO-V 2020
5th Building Simulation and Optimization Virtual Conference
21-22 September 2020
Loughborough, UK

Techno-economic Feasibility of Replacing Oil Boilers with Air-To-Water-Heat-Pumps Coupled with Thermal Energy Storage

Paraskevi Vatougiou[1], David P. Jenkins[1], Peter McCallum[1]
[1] Urban Energy Research Group, School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, EH14 4AS, UK

Abstract

The increasing share of renewables in electricity generation establishes heat pumps as a high potential alternative to fossil-fuel based heating systems. However, a large-scale roll-out of heat pumps might be challenging for the stability of the current electricity grid. In this context, Thermal Energy Storage (TES) supporting heat pumps is identified as a means to balance the mismatch of energy supply and demand through the increase of demand-side flexibility. Using dynamic simulations, this paper studies the heating performance of this coupling technology under a tariff-based load-shifting strategy. The objective of this work is to investigate the extent to which the dwelling's thermal storage capacity and occupancy pattern can balance the required TES volume in order for domestic heating loads to be shifted to low-tariff periods of the day. The results show that the required TES volume to minimise AWHP's operation during peak hours varies from 0.4 m^3 to 1.5 m^3 depending on the storage capacity of the building itself and household profile. Compared to oil-fired boilers, heat pumps could obtain a reduction of running costs in the range of 13%-55% depending on the boiler efficiency as well as the operation regime of the heat pump and electricity tariff used.

Introduction

The UK Government has set a target of bringing all greenhouse gas emissions to net zero by 2050 with the transformation of the domestic building sector being a major infrastructure priority. Given the fact that the existing UK housing stock constitutes one of the oldest and least energy efficient stocks across Europe (Guertler *et al.* 2015), a deep decarbonisation of the built environment requires a concerted effort by national policies, economic instruments and local markets. The need for new buildings to comply with tight energy efficiency requirements suggests that houses are currently designed to fit to the future climate change projections more effectively than before. However, in parallel with that, the Committee on Climate Change (CCC) states that the UK should also focus on "*making the existing housing stock low-carbon, low-energy and resilient to a changing climate*" (CCC, 2019). With the penetration rate of new-built houses being significantly lower compared to other European countries (Nicol *et al.*, 2014), retrofitting the existing stock (consisting of 29 million houses) needs to be seriously planned and prioritised.

To date, UK houses mainly rely on the utilisation of gas to meet their heating needs at a percentage of 85% and 78% in England and Scotland, respectively (Morrison and Moyes 2018). Following the suggestions of the CCC, the UK Government should ban the connection of new-built houses to the gas grid by 2025; this will signify a first but significant step towards the end of a fossil-fuel era. A large-scale electrification of the domestic heating (alongside with upgrading building fabric) should be effectively promoted by the UK Government through the adoption of new legislative incentives that are beneficial and appealing in the eyes of consumers. Embracing an electric future is further encouraged due to the increasing share of renewables in the electricity generation. During the third quarter of 2019, 20% of the total UK electricity generation was from wind, while another 18% was from biomass and solar (Evans, 2019).

The potential ban on fossil-fuel based heating systems combined with the decarbonisation effort of electricity generation is expected to stimulate an increase in the roll-out of heat pumps and their establishment as the main heating system of the future UK residential sector. The currently low penetration of heat pumps in the UK market is expected to change within the next few years with the total number of installations doubling by 2025. Nowak (2018) discusses the reasons for the low uptake of heat pumps in the UK compared with other European countries. The high electricity to gas price ratio in the UK is identified amongst the most important reasons for the delay of a wide switch from gas boilers to heat pumps. Nevertheless, when it comes to replacing oil boilers, heat pumps become a more cost competitive technology (Le *et al.* 2020). Although the price of electricity is still higher than oil, their difference is more limited (than in the case of gas). In addition to that, running cost differences between heat pumps and oil boilers do further decrease considering the frequent cleaning and maintenance of chimneys required for houses being heated by the latter technology (Nowak, 2018).

The adoption of Demand-Side Management (DSM) strategies can significantly improve the applicability of heat pumps (Arteconi *et al.* 2013). Gellings and Smith define DSM as follows: "*the planning and implementation of utility activities designed to influence* *the time pattern and/or the amount of electricity demand in ways that will increase customer satisfaction and coincidentally produce desired changes in the utility's load shape* (Gellings and Smith, 1989). Based on that, it can be argued that DSM has a twofold purpose; maintain grid stability and ensure reliability and cost benefits for consumers. In this context, the coupling of heat pumps with TES systems is considered to be an effective DSM strategy to increase demand flexibility through the shifting of heating loads from high-demand to low-demand periods (Arteconi *et al.* 2012). In addition to that, the utilisation of TES might be a means to address the intermittent nature of renewable energy sources (Hussain *et al.,* 2015). Achieving an effective load-shifting does significantly depend on the TES volume and thermal storage capacity of the building itself (Romero Rodríguez *et al.,* 2018). Eames *et al.* (2014) investigate the required TES volume to shift morning and evening peak heating loads (7-9 am and 4-7 pm, respectively) for a large detached house located in Derby, UK. Their work shows that 560 L of TES is needed when the house complies with the 2010 Building Regulations, while this might exceed 2500 L if the house's age of construction is before 1980.

Load-shifting strategies can additionally benefit from the adoption of suitable pricing programs by ensuring a reduction of electricity bills without compromising occupants' comfort. Time of Use (ToU) tariffs are increasingly penetrating electricity markets and attracting consumers' attention. As opposed to the conventional flat tariffs offering a standard electricity rate throughout the year, the price signal of a ToU tariff can be static (pre-defined periods of high and low rates during the day) or dynamic. Dynamic ToU tariffs are usually updated on a daily basis and provide hourly or even sub-hourly electricity prices reflecting on the real-time cost of energy on the grid. A dynamic ToU tariff might charge up to 2x higher than conventional tariffs during typical peak consumption periods (usually between 4-7 pm in the UK), while for the rest of the day, rates are significantly lower or they might even be negative implying that consumers are paid for using electricity (see *Figure 2*).

Several previous works evaluate the effectiveness of heat pumps combined with TES to achieve load-shifting using static ToU electricity tariffs that are available in the UK. Kelly *et al.* (2014) use the ESP-r dynamic simulation tool to estimate the TES volume required for an Air-to-Water-Heat-Pump (AWHP) to operate only during off-peak periods (defined by the Economy 10 electricity tariff). The heating performance of the system is studied for a typical detached house with filled cavity walls (U-value=0.37 W/m^{2}K) located in Northern Ireland and the results show that a hot water storage tank of at least 1000 L is needed in order for occupants' comfort to be maintained. The simulations also show that load-shifting using E10 tariff results in increasing annual running cost at around 30% compared to a baseline scenario where AWHP operates following active occupancy. Arteconi *et al.* (2013) use TRNSYS to investigate the applicability of heat pumps with TES for a detached house insulated according to the 1990 Building Regulations (U-value=0.45 W/m^{2}K). Considering that the distribution heating system consists of low-temperature modern radiators, they found that a water storage tank of 800L is required in order to achieve 1-hour load-shifting (between 6-7 pm). Le *et al.,* (2020) study the load-shifting potential using a high-temperature heat pump integrated in a house consisting of unfilled cavity walls (U-value=1.65 W/m^{2}K). In this case, the required TES volume is estimated at 1200 L in order for heating demand to be wholly shifted to off-tariff periods of the day as defined by the Powershift tariff, this presents a similar pattern with the English E10. The heat pump is found to reduce annual energy cost at 16% when compared with a 90% efficient oil boiler.

The case of Orkney Islands, Scotland

Increasing demand flexibility is crucial for regions with excess electricity generation from Renewable Energy Sources (RES); this being the situation in Orkney Islands, which accommodate the highest concentration of wind turbines (both domestic and community-owned) in the UK supplemented by solar, wave and tidal energy. Orkney produce between 110%-140% of its own electricity needs. However, lacking connectivity with the main GB transmission system, electricity generators cannot export their surplus to the mainland. In addition to that, local grid constraints result in RES curtailment, which can be as high as 50% for some generators. Rather than entirely relying on the Government's response to provide financial support and enable grid connectivity with the mainland (new transmission line), Orkney seeks ways to increase electricity usage on the islands and eliminate dependence on fossil fuels. In this context, a flexible energy supply is of high importance in order for Orkney to achieve a 100% renewable future. The islands are not connected to the gas grid; 51% of existing houses use electricity as their main heating fuel, while another 40% still rely on the utilisation of oil (EST, 2019).

In an attempt to inform decision-making and drive relative policy for off-grid regions, this work assesses the applicability of AWHPs as a heating alternative to oil-fired boilers. Using dynamic building performance simulations, this paper aims to evaluate the effectiveness of AWHPs to shift space-heating demand to off-peak periods and the extent to which this depends on the storage thermal capacity of the building itself. As a result of the study, the balance between TES volume and fabric insulation will be determined for houses belonging to various age bands and presenting different occupancy patterns. Lastly, assuming flat and ToU tariffs (with these resulting in different operation regimes for the AWHP), the cost saving potential of AWHPs is compared with oil-fired boilers.

Methodology

The methodological approach followed in this work is based on the simulated performance of several variants of a typical UK house, which is used as a virtual testbed to assess the coupling of AWHPs with TES and the role that such a system can have on demand response. The modelled house variants are selected to cover a wide range in age of construction with this resulting in different wall and loft insulation levels. In addition to that, different occupancy profiles are assumed, which in turn, leads to variations in the operation regime of the system. A set of dynamic simulation models are developed and studied throughout the winter heating months using the EnergyPlus (E^+) simulation engine. A detailed E^+ Weather (EPW) file for Aberdeen, Scotland is selected to represent similar climatic conditions with Orkney islands (EnergyPlus, 2020). The models created for the purpose of this work consist of a detailed representation of the house itself (incorporating geometry, materials, internal heat gains etc.) and a component-based definition of the integrated heating system.

Dwelling

The building used represents a typical semi-detached house with cavity walls and a total conditioned floor area of 88.4 m^2 spread over two storeys. The ground-floor includes those rooms of the house that accommodate active occupancy such as living-room, kitchen, etc., while the upper floor includes only bedrooms and bathrooms. Each room of the house is modelled as a separate thermal zone with the internal heat gains (from artificial lighting and electric appliances) being assigned to each zone following a deterministic approach as recommended by the UK's National Calculation Method (NCM).

Seven house variants are considered with each presenting a different combination of external wall and loft construction based on the dwelling's age of construction. More specifically, the recommendations of the UK's Standard Assessment Procedure (SAP) are used to assign the U-value of exposed walls and thickness of loft insulation (if present) in respect with the age band of the house; these are derived from Table S7 and Table S9 included in the *Appendix S of SAP2016* (Reduced Data SAP for existing dwellings) (SAP, 2016). The selected house variants reflect on the evolution of Building Regulations; they range from dwellings built before 1975 (where Building Regulations did not impose minimum U-values) to those built from 2012 onwards (see *Table 1*).

Table 1: Combinations of wall U-value and loft insulation thickness for various age bands. Data are derived from SAP (2016)

Age of construction (SAP Age band)	Cavity wall $U_{\text{-value}}$	Loft insulation thickness (mm)
Before 1975 (A-E)	1.50	0
1976-1983 (F)	1.00	50
1984-1991 (G)	0.60	100
1992-2002 (H, I)	0.45	150
2003-2007 (J)	0.30	270
2008-2011 (K)	0.25	270
Post 2012 (L)	0.22	270

The recommended U-values are then used as an indicator to assign the material layers for the exposed-wall of the houses. Loft insulation is modelled to be at joist level.

Each of the above dwelling variants is modelled for two different household compositions, these being a typical four-member working family and an elderly couple. The family is considered to be away from home between 9 am and 4 pm during the weekdays, while the house is fully occupied for the rest of the week. The elderly couple is considered to stay at home all day (including weekends). To enable a fair comparison regarding the effect of occupancy on the performance of the heating system (and load-shifting potential), temperature setpoint is regulated at 21°C for both the working family and elderly couple (all occupied thermal zones). Based on BS EN 16798-1:2019 [1], this operative temperature complies with buildings of a high thermal expectation (Category I).

Heating system

An electrically driven AWHP coupled with a TES tank is considered to be retrofitted in each house to replace the "existing" oil boiler. The AWHP unit is linked to a storage water tank through which the heat is transferred to the distribution heating system of the house consisting of radiators (with each radiator serving one thermal zone). The retrofitted heating system is modelled to meet only the space-heating demand of the house (domestic hot water is not considered in this work).

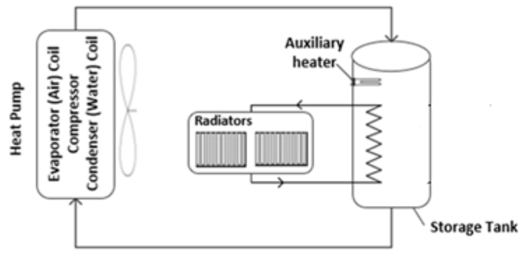

Figure 1: Configuration of the AWHP heating system

The radiators are modelled as hot water convective baseboard heaters (the amount of heat given off to the space via radiation is ignored). In order to make the heat-pump an economically viable retrofit solution and avoid occupants' disruption, the common practice in actual retrofit applications is to maintain the existing distribution heating system (usually) consisting of high-temperature radiators, these being (originally) designed to serve conventional boilers (with flow and return temperature of 75°C and 65°C, respectively). However, this results in reducing the heat output of the installed heat pumps and is considered to be an important reason for their poor performance in practice (Shah and Hewitt 2015). In this work, the distribution heating system is autosized by the E^+ to match the heat output of the AWHP with this implying that modern radiators are employed; these are suitable for low-inertia heating systems (such as heat pumps) as they are designed to supply heat at lower

[1] BS EN 16798-1:2019 will be issued to replace the previous BS EN 15251:2007. A draft version of the Standard is currently available.

temperatures than in the case of conventional boilers. Assessing the impact of replacing the current distribution heating system on the cost-effectiveness of the technology is outside the scope of the present study; this, however, should be evaluated in future studies as it is considered to be a determinant factor for the wide adoption of heat pumps.

An auxiliary, capacity-limited (3 kW), electric heater is linked to the storage water tank to operate as a secondary heat source providing supplementary heating when needed; the control of the system is described in detail later in the paper.

The size of the retrofitted AWHP is selected separately for each of the fourteen house variants to reflect on the variation of the houses' heating energy demand. The Microgeneration Installation Standard (MIS) developed to support the UK Government's Microgeneration Certification Scheme (MCS) for renewable energy technologies (including heat pumps) suggests sizing the heat pump to meet 100% of the house's space heating power demand. However, as heating loads close to peak value occur for a limited number of hours throughout the heating season, this practice might lead AWHP to operate significantly far from its full load conditions for most of the time with this reducing its Coefficient of Performance (COP). Bagarella *et al.* (2016) used an AWHP coupled with supplementary electric heating to study the impact of AWHP's size selection on the seasonal performance factor (SPF) of the whole system. Their work showed that the highest SPF is achieved when the AWHP's heating capacity is selected to be in the range 59%-72% of the house's peak heating load, while a further reduction of peak load coverage leads to excess use of supplementary electric heating. In the present study, the heating capacity is selected so that the AWHP itself (without the contribution of the supplementary electric heater) is capable of meeting at least 70% of the house's peak heating load. The latter is calculated using E^+ and assuming that space heating is provided through an "*ideal air load*" heating system with infinite capacity and 100% efficiency. Based on the above, for the working family, the heating capacity of the modelled AWHP is 14.0 kW for the house built before 1975 and 11.2 kW for the rest houses. For the elderly couple, the heating capacity of the AWHP is 14.0 kW for the house built before 1975, 11.2 kW for houses built between 1976-2002 and 9.0 kW for houses built after 2003. AWHP sizes are selected based on actual products that are available in the UK market (Mitsubishi Electric, 2015). It should be also noted that nominal values correspond to ambient temperature of 7°C and water temperature of 35°C (A7/W35). Under these conditions, the nominal COP of the modelled units is 4.2, 4.5 and 4.2 for the 9.0, 11.2 and 14.0 kW AWHP, respectively.

Table 2: AWHP's performance curves, where: x=DBT, y= condenser water temperature

AWHP	Performance curves
9.0 kW	$COP = (6.9+2.0*10^{-1}*x+9.9*10^{-4}*x^2-1.2*10^{-1}*y+6.0*10^{-4}*y^2-2.8*10^{-3}*x*y)$
11.2 kW	$COP = (5.2+2.0*10^{-1}*x+1.6*10^{-3}*x^2-2.5*10^{-2}*y-5.8*10^{-4}*y^2-2.2*10^{-3}*x*y)$
14.0 kW	$COP = (4.7+1.7*10^{-1}*x-5.7*10^{-5}*x^2-2.8*10^{-2}*y-2.6*10^{-4}*y^2-2.0*10^{-3}*x*y$
Part-load	$PLF = 0.85+0.15*PLR, PLR=Q_{Time-step}/Q_{nominal}$

The nominal heating capacity and COP of actual heat pump installations varies based on the variations of the temperature of the air entering the evaporator (outdoor dry-bulb temperature, DBT) and the temperature of the water entering the condenser in such a way that as the difference between DBT and condenser water temperature increases both heating capacity and COP of the heat pump decrease. To account for this, data are derived from the manufacturers' datasheet in order to construct suitable performance curves (Mitsubishi Electric 2015). Based on these curves, E^+ calculates the heating capacity and COP of the heat pump for each simulation timestep. A part-load performance curve is also employed to account for efficiency losses due to compressor's cycling.

Control

As mentioned before, the AWHP is modelled to be the primary heat source, while the auxiliary electric heater operates to top-up the energy provided by the heat pump. These two devices are controlled using an ON-OFF strategy, with their operation being separated by their control setpoints and control differentials. The set-point temperature of the AWHP unit and auxiliary heater is 45°C and 40°C, respectively (with both having a control differential of 2°C). To avoid the accumulation of frost on the evaporator side, the heat pump is forced to switch OFF when DBT drops below -5°C and in this case, the house's heating demand is entirely met using the auxiliary heater. During periods that DBT is no lower than -5°C, the coupling heating system operates as follows. If tank temperature is in the range 38°C-43°C, the AWHP operates alone to raise temperature to 45°C. If tank temperature is below 38°C, both the AWHP and auxiliary heater operate with the auxiliary heater remaining ON until tank temperature reaches 40°C.

The operation hours and duration of heating periods for the modelled AWHP system are determined based on two factors, these being the household profile (working family/elderly couple) and employed electricity tariff (ToU/Flat) (see *Table 3*).

Load-shifting (Agile tariff):

A ToU electricity tariff (*Agile*) providing sub-hourly price signals is used in order to explore the load-shifting potential for the different house variants. The variation of electricity rate for the employed ToU tariff is illustrated in *Figure 2* over the course of a year (2019) with the horizontal black line corresponding to an average electricity rate provided by conventional fixed-price tariffs available in the UK. As seen, prices for the ToU tariff are higher than that of the flat tariff between 4-7 pm (from November to March) or between 3-6 pm (for the rest of the year). Based on that, the modelled AWHP system is controlled to perform a 3-hour pre-heating of the TES tank between 1-4 pm (or 12-3 pm). During the pre-heating, the setpoint temperature of the AWHP is raised from 45ºC at 60ºC and during the high-tariff period, it is regulated again at 45ºC. In other words, the tank temperature is raised during the pre-heating period as a strategy to eliminate the system's operation during peak hours of the grid.

No Load-shifting (Flat tariff):

In this case, the ON/OFF periods of the modelled system follow active occupancy (no load-shifting strategy is applied) and the setpoint temperature of the AWHP is 45ºC.

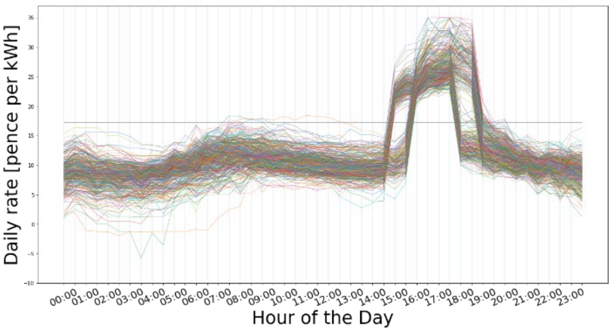

Figure 2: Agile tariff, daily electricity rates for 2019

Simulations

To meet the objectives of this work, the 14 different house variants (*7 fabric alternatives x 2 household profiles*) are simulated under the following scenarios:

Scenario 1

An oil boiler is used for each house variant to meet its space-heating demand. The efficiency of the oil boiler varies from 60% (old heavy boilers) to 90% (new condensing boilers) to reflect on the variation of boilers found in existing UK houses. The annual running cost is compared with the following scenarios.

Scenario 2:

An AWHP is considered to be retrofitted in each house variant and its operation regime follows active occupancy (no load-shifting is considered). The annual running cost for each different house variant is calculated considering a fixed-price tariff.

Scenario 3:

In this case, the AWHP operates following a tariff-based load-shifting. In successive simulations, the TES volume varies from 100 L-1500 L (in 100 L increments). This will permit to investigate the required TES volume for each house variant in order for the house's heating demand to be shifting to low-tariff periods. The annual running cost for each different house variant is calculated considering a ToU tariff (see *Table 3*).

Table 3: AWHP's operation regime and electricity rates based on flat and dynamic ToU tariffs

Tariff	ON periods			AWHP's setpoint
No Load-shifting Flat tariff 17.38 p/kWh	Family	Mon -Fri	07:00-09:00	45ºC
			16:00-23:00	
		Sat-Sun	07:00-23:00	
	Elderly couple	All days	07:00-23:00	
Load-shifting ToU, sub-hourly price signal shown in Figure 2 (Agile)	Family	Mon -Fri	07:00-09:00	45ºC
			13:00–16:00	60ºC
			16:00-23:00	45ºC
		Sat-Sun	07:00:13:00	45ºC
			13:00-16:00	60ºC
			16:00-23:00	45ºC
	Elderly couple	All days	07:00:13:00	45ºC
			13:00-16:00	60ºC
			16:00-23:00	45ºC

The input data files (IDFs) required for this work are automatically generated and run using a Python script. The house models are simulated throughout the entire heating season (October-May included) with 10-minute intervals.

Results and Discussion

Analysis for Scenario 3

The simulations carried out result in a large volume of outputs containing numerous temperature and energy time-series for the modelled buildings and integrated heating systems. *Figure 3* is plotted as an example to demonstrate the variation of AWHP's electric input in response to different TES volumes for two houses occupied by the working family. The graphs refer to a typical working day (09 January) with mean outdoor air temperature fluctuating between 4.0ºC and 6.5ºC. For the location considered in this study, outdoor temperature is in that range for 28% of the total heating hours during winter heating months. As seen, the duration of TES tank pre-heating varies from 40 min for a 300L tank to 120 min for a 1500L tank. For the uninsulated house *(Figure 3a)*, a 1500L tank is required for this particular day in order for the system to be entirely switched-off during the high-tariff period (4-7 pm). However, in the case of the highly insulated house *(Figure 3b)*, a 1000L storage tank is suitable for entirely shifting AWHP' s operation to low-tariff periods. It should be noted at this point that the results presented in this paper are restricted to the control of the modelled heating systems and employed electricity tariff.

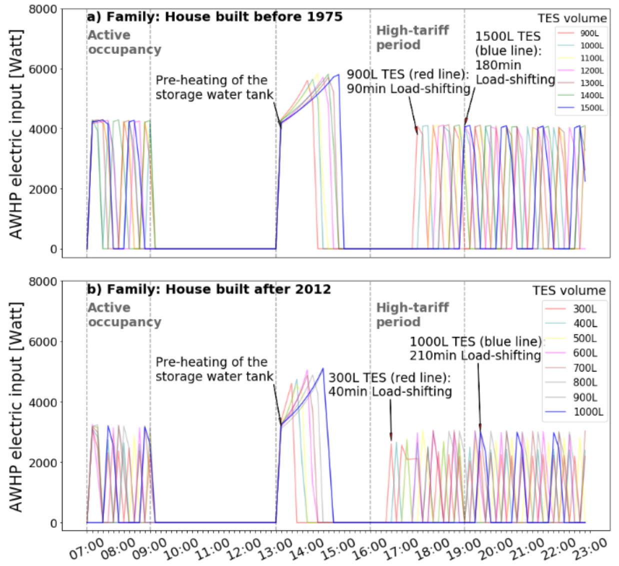

Figure 3: Variation of AWHP's electric input during a typical working day for (a) a poor insulated house and (b) a well-insulated house.

Figure 4 illustrates the annual electricity used during peak hours in response to the different simulated storage volumes for houses belonging to various age bands and being occupied by the working family (*Figure 4a*) and elderly couple (*Figure 4b*). The results suggest that as storage volume and house's insulation level increase, the annual load coverage during high-tariff periods decreases. However, the required storage volume to eliminate AWHP's operation during peak periods is found to be significantly lower for the elderly couple compared to the working family. This is due to the heating regime followed by the two different households. With the houses occupied by the elderly couple being continuously heated between 7 am and 4 pm (or 3 pm based on the low-rate periods offered by Agile tariff), the thermal energy stored in the building's mass increases the potential of achieving a 3-hour load-shifting compared to houses following an intermittent heating regime. The selection of the required storage volume based on the restriction of electricity usage during peak periods of the day results in storage volumes, which might be impractical for domestic applications. This becomes more critical for UK houses (especially flats), which do often present space constraints. A more sophisticated approach should also consider the capital cost and payback period of the system, but this is outside the scope of the present work, which focuses on selecting the TES volume for each case by setting as a constraint the elimination of the system's operation during high-demand hours of the grid. The selection of the TES volume is carried out considering that the percentage of AWHP's energy use during high-tariff periods must not be higher than 2% of the total annual energy use. Based on that, the TES volume required for the case of the working family is in the range of 1.0 m^3–1.5 m^3 depending on the house's fabric insulation level. On the other hand, the required TES volume for the houses occupied by the elderly couple varies from 0.3 m^3 (very well insulated houses) to 0.6 m^3 (uninsulated house).

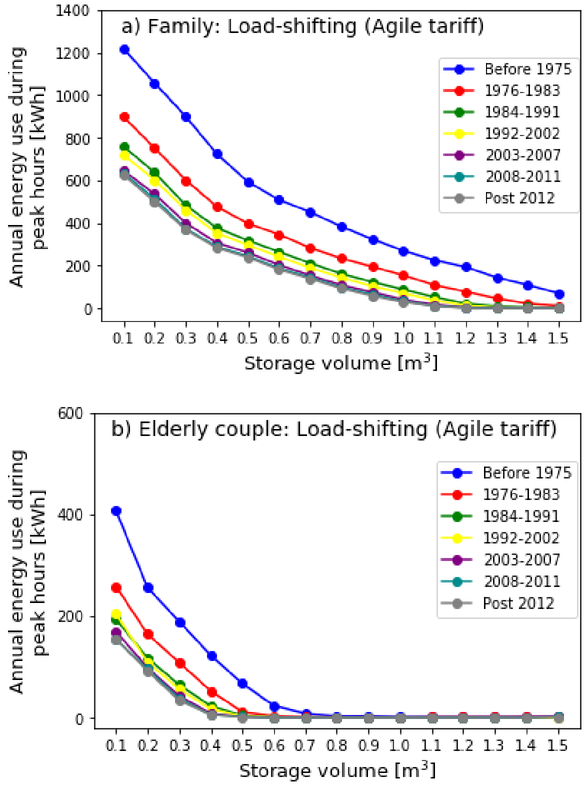

Figure 4: Annual energy use during peak hours (4-7 pm or 3-6 pm) for (a) the working family and (b) the elderly couple

Comparison with Scenario 1 and Scenario 2

Having selected the suitable TES volume for each house variant, the analysis then focuses on comparing the total energy use and running cost of the AWHP operating under the tariff-based load-shifting against a typical scenario, where the AWHP's operation follows active occupancy and no load-shifting is considered (*Scenario 2*).

Table 4: "Optimal" TES volume for each house variant when a tariff-based load-shifting strategy is applied and when the system operates following active occupancy

	Load-shifting		No Load-shifting	
	Working family	Elderly couple	Working family	Elderly couple
Before 1975	1.5	0.6	0.5	0.5
1976-1983	1.4	0.5	0.4	0.4
1984-1991	1.2	0.4	0.4	0.4
1992-2002	1.1	0.4	0.4	0.4
2003-2007	1.0	0.4	0.4	0.3
2008-2011	1.0	0.4	0.4	0.3
Post 2012	1.0	0.4	0.4	0.3

Table 4 summarizes the employed tank size for the various house variants. For the typical operation of the system, the tank size is selected so that running costs are minimised. In this case, tank volume varies from 0.3 m^3 - 0.5 m^3 depending on the household profile and thermal storage capacity of the building (reflecting on the age of construction). Lower tank volumes are found to increase cost as a result of the shorter compressor's cycling, which decreases COP.

Figure 5 illustrates the annual energy use (*AWHP plus auxiliary electric heater*) for the different operation regimes (load-shifting and typical operation) and house variants. It should be noted that the auxiliary energy use corresponds to less than 4% of the total energy use for all house variants and control scenarios. As seen in the figure, the annual energy use is estimated around 23% greater when the system operates under the tariff-based load-shifting strategy (for all house variants). This occurs due to the increased setpoint temperature of the AWHP during the pre-heating period with this resulting in operating the AWHP with lower COP (as the difference between DBT and water temperature increases, see equations in *Table 2*). In addition to that, the employment of significantly larger tanks required for shifting loads to off-peak hours (*especially for the case of the working family*) does also contribute to the increased energy used compared to the typical AWHP's operation.

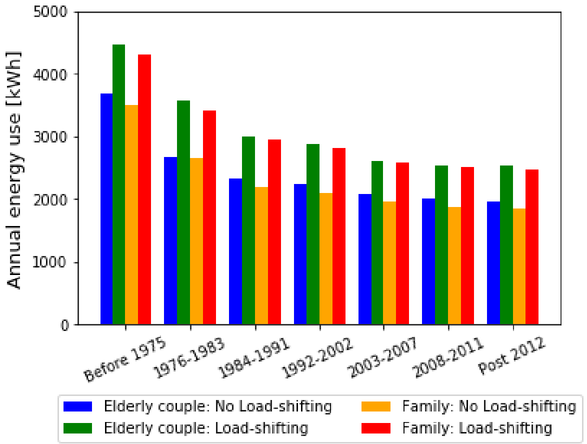

Figure 5: Comparison of the annual energy use for different house variants and AWHP's operation regimes

Figure 6 depicts the total running cost for the different AWHP's operation regimes and house variants. The ToU tariff is employed to estimate operational cost for the load-shifting scenario, whereas the flat (fixed-price) tariff is used for the case that AWHP's operation follows active occupancy. As seen, (although energy use is found to increase for the load-shifting scenario), the employment of the ToU electricity tariff decreases total running cost in the range of 18% - 25% with the higher percentage reductions corresponding to the less insulated houses. The annual running cost for the elderly couple is found to be slightly higher compared to the working family for either the ToU or flat tariff. However, due to the variation of employed TES volumes, this difference does not directly reflect on the different system's on/off schedule applied for the two households (continuous vs intermittent AWHP's operation). This graph can also be used to show the impact of upgrading building fabric on the total operational cost. As seen, energy cost can reduce up to 43% between the uninsulated and very well insulated houses.

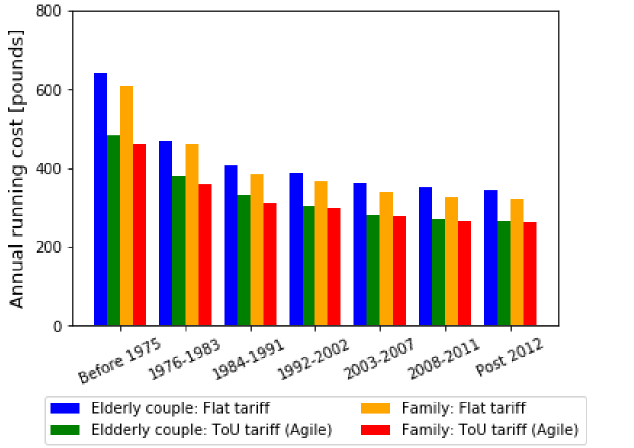

Figure 6: Comparison of AWHP's annual running cost between flat and ToU electricity tariff

Figure 7 illustrates the annual cost savings between the AWHP and an oil boiler of varying efficiency for a medium-insulated house (very similar results are observed for the rest age bands). The oil price is assumed to be £0.0524 per kWh (EST, 2019). As seen, switching from oil boiler to AWHP -and when the latter is coupled with a ToU tariff- can reduce annual cost at a percentage of 30%-55% (depending on boiler efficiency). Even for the case that the AWHP is coupled with a fixed-price electricity tariff, cost savings are still significant between the two technologies (13%-45% depending on oil boiler efficiency).

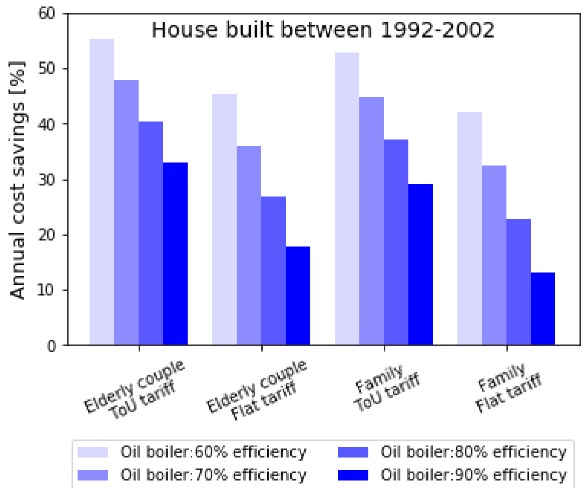

Figure 7: Annual cost savings of the AWHP compared to oil boiler for a medium-insulated house (positive percentages indicate that the AWHP is cost effective)

Conclusions

The paper assesses the applicability of AWHPs coupled with TES for a range of houses built at different standards and occupied by both a typical working family and an elderly couple with these resulting in different operation regimes of the system. Focusing on a tariff-based load-shifting strategy, the required TES volume is investigated for each house variant so that AWHP's operation is eliminated during high-tariff periods. The results show that as the level of fabric insulation increases, the required TES volume decreases for either the working family or elderly couple. However, the intermittent heating pattern considered in the case of the working family results in selecting significantly larger tanks compared to the elderly couple in order for a 3-hour load-shifting to be achieved. In respect with the "optimised" tank size selected for each case, the energy use and running costs are only slightly lower for the working family compared to the elderly couple. This raises the need for further exploring the extent to which the selection of TES volume based on the restriction of AWHP's operation during peak hours does also result in cost-effective solutions for occupants. Future work should account for capital costs and estimation of payback period for each solution. With the paper focusing on the simulated performance of a small set of virtual semi-detached houses, the results suggest that the coupling of AWHPs with TES is a high potential retrofit solution for houses being heated by oil-fired boilers. Annual running costs are found to reduce between 30%-55% depending on boiler efficiency. The methodology developed in this paper will be used to evaluate AWHP's viability at the stock level, this being part of a large-scale consortium effort to convert Orkney Islands into a carbon-free region.

Acknowledgements

This work is part of the ReFLEX Project (a PFER demonstrator, main funder: Innovate UK, grant: 104780)

References

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

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

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

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

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

EnergyPlus, 2020. Weather data by region [online]. Available from: https://energyplus.net/weather [Accessed 5 Mar 2020].

EST, 2019. Home Analytics [online].

Evans, S., 2019. Analysis: UK renewables generate more electricity than fossil fuels for first time. *Carbon Brief*.

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

Guertler, P., Carrington, J., and Jansz, A., 2015. *The Cold Man of Europe – 2015*. Association for the Conservation of Energy. London.

Hussain, I., Mohsin, S., Basit, A., Khan, Z.A., Qasim, U., and Javaid, N., 2015. A review on demand response: Pricing, optimization, and appliance scheduling. *Procedia Computer Science*, 52 (1), 843–850.

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

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

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

Morrison, K. and Moyes, D., 2018. *Off-gas consumers: Updated information on households without mains gas*. Edinburgh.

Nicol, S., Beer, C., and Scott, C., 2014. The Age and Construction of English Housing, 88.

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

Romero Rodríguez, L., Sánchez Ramos, J., Álvarez Domínguez, S., and Eicker, U., 2018. Contributions of heat pumps to demand response: A case study of a plus-energy dwelling. *Applied Energy*, 214 (January), 191–204.

SAP, 2016. *Appendix S: Reduced Data SAP for existing dwellings v9.93 (Draft version for public consultation)*. London.

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