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Heat Pumps and Thermal Storage for Domestic Dwellings

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Abstract

IEA HPT Annex 55 Comfort and Climate Box aligned with the UKRI funded Comfort and Climate Box to review the challenges and research necessary to deliver at scale heat pump and thermal storage solutions for single family homes across the partnering nations. Building on the deliverables to IEA HTP Annex 55, an updated review of the state of the art is presented here and how that was implemented in a small sample trial in social housing in Northern Ireland. Early results of this field trial indicate strong participant satisfaction with the air source heat pump and thermal store with reduced heating costs when allied to a modest upgrade to building thermal fabric i.e., improved glazing, insulation etc. and larger hydronic radiators to facilitate lower temperature heat delivery.

Keywords: Heat Pump, Thermal Storage, Integration, Single-Family Homes

1. Introduction

IEA HTP Annex 55 Comfort and Climate Box and the subsequent UKRI//BEIS funded Comfort and Climate Box (EP/V011340/1, CCB, facilitating UK participation) targeted the implementation of typically air source vapour compression heat pumps and accompanying thermal storage in single family homes. It could be argued that such a focus was restrictive to global participation, but it was recognised that a focus had to be applied to deliver an in-depth analysis of the CCB concept to address concerns, that often are ultimately related to capital cost.

The Annex therefore identified several criteria that required inputs to deliver significant heat decarbonisation and integration with non-dispatchable and variable renewable electricity resources, such as:

- Affordability
- Suitability
- Compactness
- Efficiency
- Plug & Play, maintenance
- Integral design
- Smart Grid ready
- Controls & monitoring
- Appreciation

These factors were considered as the backbone of the research and implementation required to provide the necessary confidence for governments and other agencies to successfully promote the decarbonisation of space heating with electrically driven vapour compression heat pumps and thermal storage. Initially, observations were obtained from the participating countries of Austria, Belgium, Canada, China, Germany, Italy, the Netherlands, Sweden, Turkey, the UK, and the USA, but relevant results from other countries were also

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incorporated. The purpose of this paper is then to update the reports that addressed aspects of these issues and to report on the implementation of this research that led to a demonstration of air-source heat pumps and thermal stores in social housing (alongside a modest retrofit) as a cost-effective decarbonisation approach to space and water heating in homes.

2. Vapour Compression Heat Pump – Examples of Technical and Financial Supports

At the core of this approach to the decarbonisation of space and water heating in single family homes is the vapour compression heat pump. New (and existing) working fluids that decrease/eliminate global warming potential, and indeed reduce capital costs, are noted. In terms of single-family home systems, the role of hybrid heat pumps may seem attractive. Natural gas is seen as a contributor to decarbonisation in the short-term and its replacement (by biomethane and/or hydrogen) in the longer term is being considered. The price of natural gas is a current challenge and the scale of switching to more decarbonised sources much be at such a scale that the decarbonised gas sources are not costed at international gas prices. An example of this is the US Henry Hub price for natural gas. The US (and Canada) was largely insulated from European price increases resulting from war in Europe due to availability of low-cost "fracking" (hydraulic fracturing) gas. Natural Gas prices are also of course two-sided. Lower natural gas prices may hinder heating decarbonisation with heat pumps but now, electrification of heating (aligning with large scale renewable energy resources such as wind and solar) has gained a significant driver beyond decarbonisation, and it is incumbent upon us to deliver this opportunity. Regarding hybrid heat pumps therefore, Beccali et al [1] noted existing gas boilers can be utilised in "parallel" or in "series" alongside various ground source and air source heat pumps, both with and without thermal storage. Series or parallel approaches lend themselves to demand side management in terms of reducing electrical load at peak electricity demand times, with obviously the parallel approach facilitating a significant electricity load reduction like that of thermal storage, but perhaps with a less time limiting factor i.e., the gas boiler can operate at peak electricity demand times and/or low (renewable) electricity supply times. Sun et al [2] noted that such "smart" hybrid heat pumps could avoid heat pump oversizing (reducing capital cost), avoid/minimise electricity distribution network capacity challenges (facilitating technology introduction), and overcoming social barriers to new technology adoption.

Vapour compression heat pumps need to be cost effective. Examples of how to achieve this is in the technology itself, selling heat as a service and demand response electricity market services. Regarding the technology, optimal sizing and impact on the electricity network is critical, as noted with gas boiler hybrid heat pumps. Unfortunately, not all countries with electrically driven vapour compression heat pump aspirations have sufficient capacity at local low voltage electrical distribution network level. Therefore, advanced high coefficient of performance (COP) heat pumps can be aided with the wider deployment of (5th Generation) heat networks (waste heat, renewable heat from excess renewable energy, geothermal heat etc.). So called "booster" heat pumps have upgraded heat for domestic applications with Thorsen et al [3] demonstrating an average seasonal COP of 5.25 and improved heat pump economics. Østergaard et al [4] noted that if district heating networks are operated in conjunction with lower heat distribution temperatures in the buildings, the overall efficiency of building/heat pump/heat network is significantly improved, with, again, cost savings as in some cases, little must be done to the building heating distribution system as the older hydronic radiators work sufficiently well at lower temperatures.

Regarding utilisation of the heat pump and thermal store as heat as a service and/or demand side response (electricity grid balancing), selling heat as a service to lower the barriers for heat pumps is noted by Kircher and Zhang [5]. A host purchases heat from a heat pump owned by an aggregator. The aggregator purchases power (at scale) and with the aid of thermal storage can address demand side response requirements of the local electricity market, whether renewable energy driven, electricity network constraint driven etc. It is claimed that the value of the heat pump investment is nearly doubled, i.e., a strong return on investment is possible. However, there is a concern over "data". While "the internet of things" facilitates significant data flows, the question must be "what is the minimum amount of data that can be securely interrogated to deliver demand side response?". The question arises as we become "smart", we also may become vulnerable to cyber-attack. The fear is not when something is turned off (which is very inconvenient and possibly personally challenging), but when a significant number of devices are turned on at the same time, thus potentially initiating long-term damage to an electricity network. The electrification of heating (and transport) will require an amount of control and an expectation that by a given time, heat (and power) will be provided. Thermal storage (and/or hybrid heat pumps) are an example of peak electricity demand avoidance. Other approaches (e.g., for electric vehicle charging) are more time manageable where we expect our car to be charged overnight for example. Smart domestic electricity load controllers will therefore "manage" electrical demands through an understanding (whether a fixed concept of a maximum electrical demand or through a "floating" concept associated with available local electricity network capacity) or our needs and, for example, reduce/turn off demands for short periods when we (the end user) do not notice. Thus, our fear of a cyber-attack to turn everything on could destroy infrastructure.

However, on the positive side, the role of integrated renewable energy i.e., photovoltaics, solar thermal or indeed their combination in PVT, can be aligned to heat pumps and thermal storage. Typically (but not always the case), winter solar energy is limited (when we want it the most) and summer solar energy can be excessive. Affordable seasonal thermal storage that is also sufficiently dynamic for diurnal/demand side response operations would be an advantage. Returning to "solar-assisted" heat pumps, Gaonwe et al [6] describes the likely types, while Yang et al [7] addresses the traditional solar thermal approach, heating a storage vessel and the heat pump utilising this storage as a heat source utilising TRNSYS modelling. This model accounted for the UK geographical extremes in temperature encountered in the UK (represented by an additional 21 days in space heating requirements but still represented a 30% increase in COP when using solar assisted united compared to an air-source heat pump. Regarding financial supports, at an electricity market level, we see several markets addressing aggregated technologies to coordinate demand side response/management for the greater integration of variable, non-dispatchable renewable electricity. These include CAISO, ERCOT, Hawaii, Australia's NEM, GB's Smart Systems and Flexibility Plan, EU MCs, including Denmark's community renewables ownership model, etc). An example is the TenneT-Veissmann Viflex project where domestic heat pumps, thermal storage, and photovoltaics (PV) manage the electricity network in areas of high PV penetration. OpenADR is also being considered as a mechanism for standardised Demand Response control. In the UK, Gupta and Morey [8] assessed a domestic heat pump, PV and battery arrangement for single family homes noting 2-hour intervention times and their impact on electricity demand and export. Automation was deemed too be very important, as was transparency of financial transactions. Agile electricity tariffs were deemed advantageous.

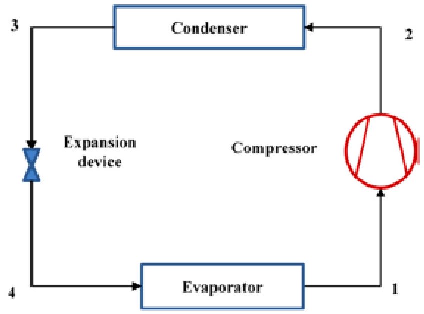
3. Heat Pumps and Thermal Storage – What is emerging as best practice?

The Kigali Amendment to the Montreal Protocol requires developed countries to reduce their use of HFCs by 85% by 2036. This would challenge the use of the most popular air-source heat pump working fluid, namely R410A. Several alternatives are being explored namely R452B, R454B, R454C etc. e.g., Shen et al [9]. However, the question arises as to what is a low global warming potential (GWP) refrigerant? Very low GWP refrigerants refer to the natural fluids such as CO_2, Ammonia, Propane etc. with GWP's of less than 3. Low GWP refrigerants is accepted as those below 150 (on a 100-year basis), although there appears to be no absolute definition. Unfortunately, when taking the more extreme requirement of low GWP, there appears to be currently one no HFC, HFO replacement for the current incumbent R410a. Therefore, propane (R290) is of interest and Schnabel et al [10] demonstrated that for a charge of 200g of R290, a 10kW heat pump could achieve a COP of 3.5 across a 35ºC temperature lift. With R290 having a Lower Explosion Limit of 2.1% volume per volume, 200g of propane would be "safe" in a space as low as 0.11m^3. Regarding alternative refrigerants to R410a for air-source heat pumps, the following refrigerants have been modelled (Table 1) for different heat pump configurations (Figure 1). These are not always drop-in replacements but are being considered for domestic heat pumps, given the challenges of finding a suitable (<150 GWP) direct replacement for R410a.

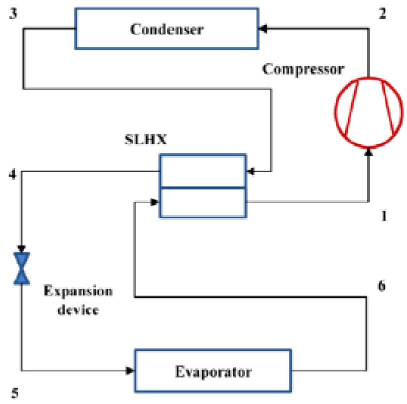
Table 1. Modelled Refrigerants

Refrigerant	Class	GWP	Flammability	Critical Temperature ºC	Critical Pressure Bar
R32	HFC	677	A2L	78.11	57.82
R410A	HFC	1924	A1	71.34	49.01
R1234ze(E)	HFO	<1	A2L	109.24	36.35
R1234yf	HFO	<1	A2L	94.7	33.82
R454B	HFC/HFO	466	A2L	78.1	52.67
R452B	HFC/HFO	676	A2L	77.1	52.2
R513A	HFC/HFO	631	A1	94.9	36.49
R515A	HFC/HFO	387	A1	108.71	35.65
R454C	HFC/HFO	148	A2L	85.7	43.2

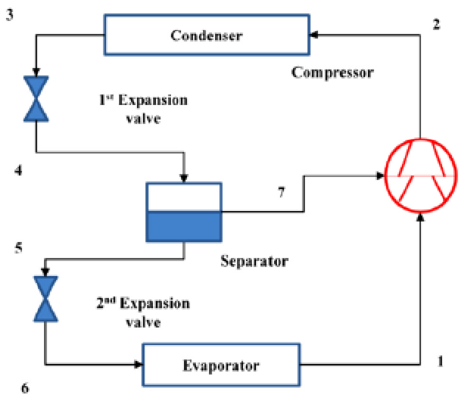
The choice of system is interesting. Capital cost of domestic heat pumps has come under pressure and development of lower cost units is very worthy of effort. Energy Poverty and Fuel Poverty are themes at the time of writing that imply heat pumps and thermal storage for single family homes i.e., the pathway to space heating decarbonisation, may become the preserve of the wealthy. For mass adoption, capital costs must reduce and/or schemes for ownership spread that cost over the lifetime of the system. However, improving COP is also welcome.



(a) Basic



(b) LL-SL IHX



(c) Flash Tank

Fig. 1. Vapour Compression cycles considered in this analysis.

The performance of the alternative refrigerants is evaluated in three different heat pump cycles i.e., basic, liquid line-suction line internal heat exchanger (LL-SL IHX) and flash tank heat pump cycles. For all cycles, the condenser temperature is set at 60ºC, and the evaporator temperature changes ranging from 0ºC to 10ºC to calculate the COP, Volumetric Heat Capacity (VHC), discharge temperature, and pressure for systems working with different refrigerants. In the current analysis, the subcooling and superheating values are set at 0ºC and isentropic efficiency has been considered for the compressor operation based on the pressure lift.

Figure 2 shows the variation of COP with evaporator temperature in different heat pump cycles working with alternative refrigerants. As expected, the COP increases by increasing the evaporator temperature. For the basic cycle at an evaporator temperature of 0ºC, the R32 provides the best COP followed by R32, R454C, R452B, R1234ze(e), R515A, R454B, R513A, R1234yf, and R410A. The difference between the maximum (R32) and minimum (R410A) COPs is about 7%. The COP ranking differs with changing the evaporator temperature or cycle configuration. For example, at an evaporator temperature of 10ºC, R1234ze(e) performs marginally (1%) better than R32. Also, it is observed that the COPs may improve slightly by adding a LL-SL IHX to the cycle at the expense of higher discharge temperature. However, employing a flash tank can considerably enhance the COP compared to the basic cycle. Volumetric heat capacity reveals that R32 has the highest VHC followed by R452B, R454B, and R410A. Pure HFO refrigerants (R1234ze(e) and R1234yf) has considerably lower VHC values compared to R32 due to low vapor density.

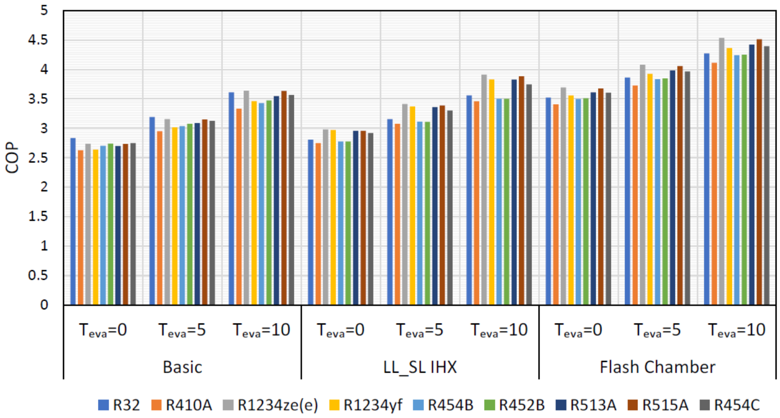


Fig. 2. Variation of COP.

By adding R32 to HFO refrigerants the VHC improves as is seen for R454B (69% R32 and 32% of R1234yf) with 153% improvement in VHC compared to that of R1234yf (Figure 3). Figure 4 illustrates the variation of discharge temperature of the compressor versus evaporator temperature in different heat pump cycles working

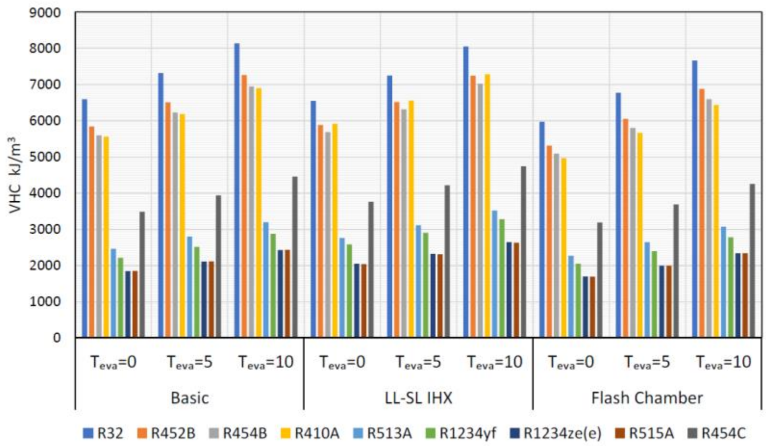


Fig. 3. Variation of volumetric heating capacity with evaporator temperature for different heat pump cycles

with alternative refrigerants. The maximum discharge temperature corresponds to the pure R32 and reduces by decreasing the share of R32 in the mixed refrigerant. The minimum discharge temperature belongs to R1234yf. It is seen that the discharge temperature increases with raising the evaporator temperature. The value of temperature rises in the case of LL-SL heat exchanger running with R32, R452B, and R454B are not realizable in practice, and they are shown just for comparison. The figure shows that depending on the refrigerant type, employing the flash tank decreases the discharge temperature by 9 to 17% compared to the basic cycle. Figure 4 also depicts the discharge temperature for different alternative refrigerants employed in basic, LLSL IHX, and flash tank heat pump cycles at evaporator temperatures of 0, 5, and 10ºC. As expected, the pressure lift decreases by increasing the evaporator temperature. At 0ºC, the maximum pressure lift is about 5.9 which is related to R1234ze(e) and R515A, and the minimum pressure lift is 4.8 obtained by R410A. Thus,

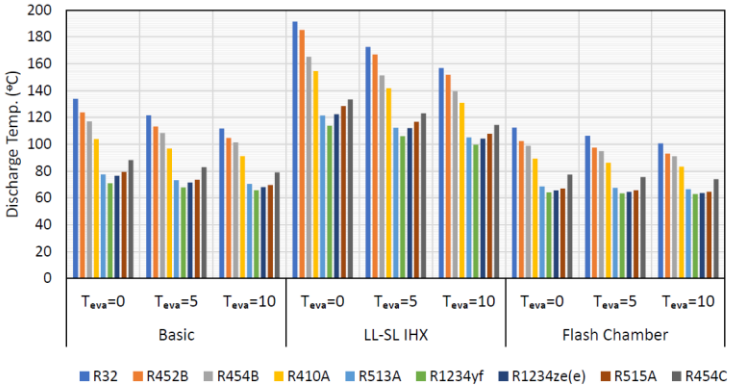


Fig. 4. Variation of discharge temperature with evaporator temperature for different heat pump cycles

we can conclude that from these choices, it is challenging to address a direct replacement for R410a that possesses a GWP <150. Therefore, new systems will emerge, or existing systems will re-emerge that can address low GWP (and safety) while, in the best traditions of the automotive mass manufacturing industry were saving in weight equate to manufacturing savings, retain of exceed the size of R410a units. About the control of alternative cycles, such as a flash tank, this requires additional expansion valves to manage superheat at the intermediate compression stage. There are the challenges of expansion valve sizing in that there is typically reduced pressure drops than those encountered with a traditional heat pump cycle. However, managing flow rate to maintain the usual minimum superheat is normal with a digital valve e.g., a stepper motor and pre-programmed refrigerant saturation temperature curves.

Finally, R290 and moving beyond F-Gas regulations to the future phase out of working fluids proposed by the European Chemicals Agency, we see proposal to cut perfluoroalkyls, leaving the domestic air-source heat pump sector with for example, R32 and R290 as their main choices. The US EPA has also banned certain working fluids. Utilising the data provided by OST (Switzerland), Air-Source Heat Pumps (ASHPs) are tested under conditions of both EN14511 (COP at certain temperatures, humidities etc.) and EN14825 (seasonal COP). The available data is summarised in Figure 5 for conventional air-source heat pump cycles.

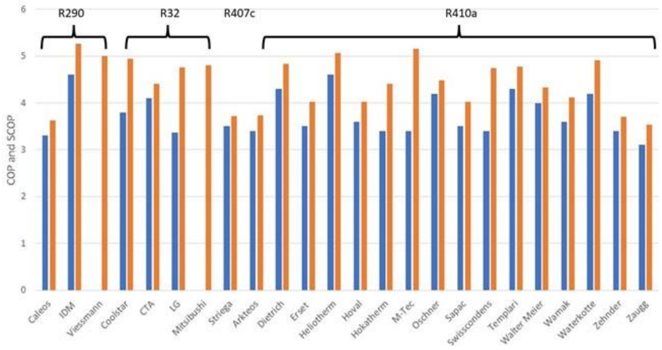


Fig. 5. COP Comparison of Existing Tested Air Source Heat Pumps

In terms of thermal storage, our understanding of electricity network constraints to be combined with our understanding of our heating and hot water needs to provide an optimal system. As previously reported, a 2-hour period was noted for demand response and the greater integration of non-dispatchable, variable renewable energy. For our domestic space heating and domestic hot water needs, water as a medium has flexibility in temperature (for weather compensated heating control), low cost and well understood systems and properties. However, the size of water-based systems (in both retrofit and expensive inner-city terms) along with heat losses, may deem water to have rival storage media. Nair et al [11] reviewed phase change materials (PCMs) for space heating and domestic hot water applications and noted that many organic PCMs are flammable (potentially limiting their application), salt hydrate types are highly corrosive and suffer from supercooling and phase separation, and long-term cycle stability is questioned by some. However, encouraging trials and examples are noted with for example, the then Department of Energy and Climate Change funded trial in 7 homes in the UK starting in 2013. Using an Air Source Heat Pump and a phase change material storage, an average heating bill saving of 50% compared to fossil fuels was achieved [12]. There remain numerous studies on laboratory-based systems and thus the need to verify PCM based systems in the field.

4. Field Trials in Northern Ireland

Ulster University has been developing heat pumps for 50 years. Initial interest was in heat pump performance in a controlled environment during an energy crisis of the 1970's. This evolved into the challenge of compressor lubrication and oil transport, its effects on heat transfer and of course, compressor longevity based on refrigerant/lubricant solubility and miscibility. This work continued as we moved from CFC's to HCFC's and HFC's, with HFC's typically utilising Polyol Ester lubricants (POEs) and combined system performance comparisons, material compatibility and lubrication aspects. New heat exchangers such as all-welded compact plate types saw improvements in performance. Natural fluids also were noted and indeed their challenges as drop-in replacements for, for example, R407c heat pumps, where R290's lack of compatibility with POEs lead to compressor failures. Compressors for domestic heat pumps moved to scroll types (again with new lubrication concepts needed) and future developments such as the vapour injection for higher temperature lift applications where developed. R410a heat pumps where introduced and new working fluids such as R1233zd(E) are being evaluated for different applications, including industrial heat pumps. Therefore, it was correct to not only assess the heat pump system, but how it would be used in homes and how it would need thermal storage to address the electricity network, renewable energy integration and perhaps of increasing importance, the role of the end-user in the success of heating decarbonisation.

In understanding heat pumps and thermal storage in single family homes, Shah et al [13] utilised an air course heat pump and 600 litres of water to heat a "hard-to-treat" home, purposely built on a campus of Ulster University. This house, as part of "Terrace Street" was home to a family and was monitored for temperature, electricity consumption, gas consumption (when the boiler was required) with a heavily monitored heat pump and thermal store. The occupier and their family were free to heat the home as appropriate and the gas boiler was available for comparisons as well as a back-up during system modifications. In general, the occupants were happy with the level of heat provided but no formal test was carried out as the then objective was to observe what performance was required to maintain thermal comfort.

Overall COP of the high temperature heat pump could have been better and spurred our interest in an overall system methodology i.e., building improvements (a "Fabric First" approach) followed by a heat pump of appropriate size. About the size of thermal store, we had anticipated a time frame that approached 4 hours rather than a shorter time. The 3-to-4-hour time frame addressed the peak time for electricity usage (typically 4pm to 7pm) in the UK but was later proved to be not as important as the shorter term changes in for example, wind derived electricity from the network (as demonstrated by the 48 time periods incorporated into the current All-Ireland electricity market structures). A secondary (but important factor) was the heat losses associated with such a large (but still well insulated) water storage tank. Thus, smaller storage systems with less heat loss were required and therefore air source heat pumps and compact thermal stores applied to homes with improved building fabric (typically glazing and insulation).

Interreg VA Spire 2 and UKRI EPSRC CCB and Lot-NET projects provided the means to work with the Northern Ireland Housing Executive (one of the largest social housing providers in the UK) to deliver the solutions and the analysis of the installation of air source heat pumps and thermal storage into retrofitted homes in the west of Northern Ireland. This significance of the area chosen is to reassure those out of our major cities that cost-effective decarbonisation approaches can be delivered in rural communities, and secondly, the west of Northern Ireland is where our dominant wind energy resource is found, and therefore local demand response solution may have to be found soon. UKRI EPSRC CCB and IEA HPC Annex 55 gave confidence in delivering a viable solution to decarbonisation of our homes. RULET – Rural-Led Energy Transition – is an initiative within the SPIRE 2 project (Figure 6) aimed at reducing or eliminating the risk of low-income households being left behind in the transition to clean, smart, integrated energy systems. Not only where air source heat pumps and thermal storage systems investigated, but also hybrid systems (with oil or gas boilers) to address

Fig. 6. Rulet Heat Pump and Thermal Storage Installations

the householder concerns regarding the "radical, new technology" of heat pumps.

Figure 7 shows typical operational data per home and Figure 8 illustrates the CO_2 seen from the different options across a three-month operating period. As expected, with Northern Ireland producing nearly half of its electricity from wind power, the heat pump has the lowest emissions. Furthermore, as part of the trial, a local electricity supplier agreed to provide an Economy 7 tariff i.e., a reduced cost from 12:00 to 07:00 daily as a prelude to flexible tariffs. Householders were generally pleased with their running costs.

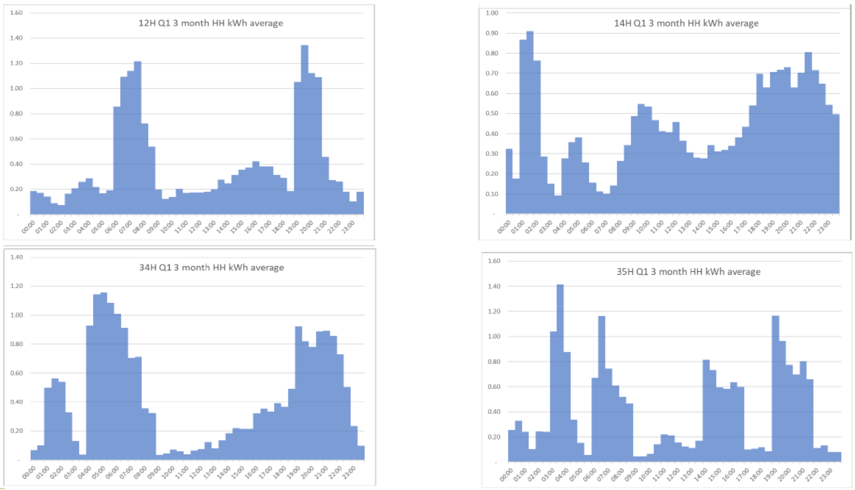


Fig. 7. Household electricity consumption profiles.

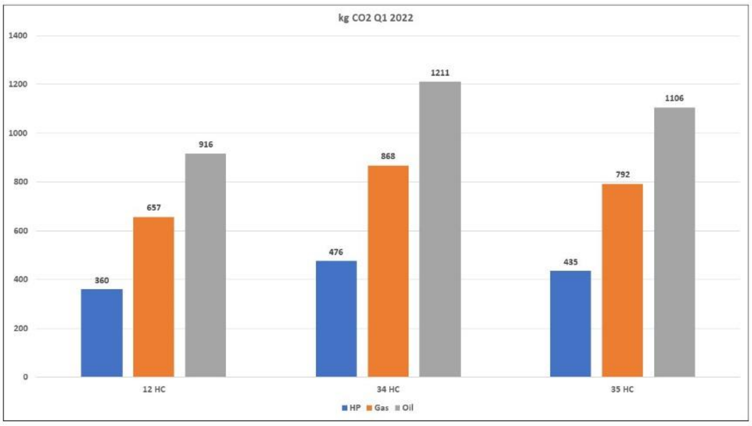


Fig. 8. CO2 Emissions for the Selected Options

However, the most important aspect during this energy crisis is that of running costs. Figures 9 and 10 illustrate the current running costs and the projected running costs for the Winter period 2022/2023.

The small-scale trial has illustrated that an air source heat pump with thermal storage can mee the demands of householders, at least at a similar cost basis and, with the help of flexible tariffs, could reduce the running costs further. However, what of capital cost? For this field trial, approximately £18,000 was spend per home, with a building fabric upgrade of glazing and insulation being approximately £9,000 per home, the PCM thermal store of 6kW was £6000 and the 5kW (thermal) air source heat pump was £3,700. With 880,000 homes in Northern Ireland (not all requiring this level of retrofit prior to heat pump installation), Ogunrin et al [14] estimated approximately £2bn would be required for the building fabric upgrade alone. However, the kWh not used is the best kWh. Aggregation systems that use the heat pump and thermal storage as a renewable electricity integrator must become part of the value-added aspects of heat pump deployment.

Regarding reducing heat pump capital costs, in addition to mass production, smaller machines due to reduced heating demands and moving away from air to waste heat/geothermal heat networks, the use of lower cost components and natural working fluids that have lower pressures and no doubt other innovations not requiring copper and steel may make systems cheaper, while maintain reliability. Water for thermal storage with vacuum insulation tanks may be more cost effective.

Finally, the move towards R290 in the field of domestic air-source heat pumps is typically beneficial. A 5% increase in seasonal COP has been noted in Figure 5 and this would translate in an equivalent reduction in electricity demands.

5. Conclusions

Air source heat pumps and thermal storage are a solution to decarbonisation of space and domestic water heating. We have seen (albeit informally) that residents are happy with their decarbonisation solution, especially as in many cases is saves on running costs. The heat pumps and accompanying thermal stores need to be smart. The use of an Economy 7 tariff was successful, but a 10-hour tariff would be more beneficial. A flexible tariff following excess wind generation, thus reducing wind derived renewable electricity curtailment and constraint and operated by aggregators, should benefit electricity distribution companies (better utilisation of existing network capacity and lower rates of new builds), the aggregators themselves, and the end-users (the residents and as such, prosumers with lower tariffs). This help with affordability. Retrofit, even at a basic level improved building suitability. Compactness may be challenged by refrigerant changes. Efficiency will be improved with new components, a move to R290, and a move away from air-source. Finally, integral design of heat pumps, thermal store and building will see improved results.

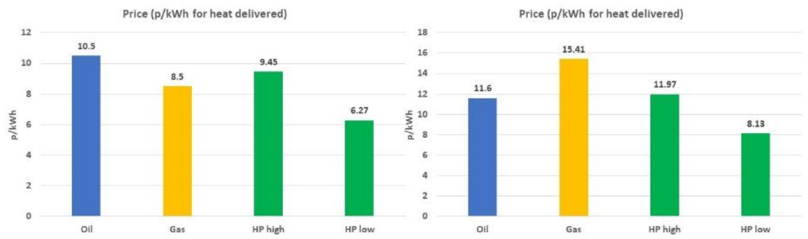


Fig. 9. Energy Price (left) and Fig. 10. Projected Running Costs with Likely Energy Cost Increases (right).

6. Copyright

Acknowledgements

The authors would like to acknowledge numerous projects, whose individual elements began to come together into heat pumps and thermal storage for single family homes including Interreg VA Spire 2, UKRI EPSRC CCB and Lot-NET.

References

[1] Beccali, M., Bonomolo M., Martorana, F., Catrini P., Buscemi, A. *Electrical hybrid heat pumps assisted by natural gas boilers: a review'* Applied Energy, 6 July 2022
[2] Sun M., Djapic, P., Aunedi, M., Pudjianto, D., Strbac, G., *Benefits of smart control of hybrid heat pumps: An analysis of field trial data*, Applied Energy 247 2019 525–536
[3] Thorsen, JE., Svendsen, S., Smith, K., Ommen T., Skov, M., *Feasibility of a booster for DHW circulation in apartment buildings*, Energy Reports 7, 2021, 311–318
[4] Østergaard PA, Werner P., Dyrelund A,, Lund H., Arabkoohsar A., Sorknæs P., Gudmundsson O., Thorsen JE., Mathiesen BV., *The four generations of district cooling - A categorization of the development in district cooling from origin to future prospect*, Energy, 253, 2022.
[5] Kircher KJ., Zhang KM., *Heat purchase agreements could lower barriers to heat pump adoption*, Applied Energy 286 (2021)
[6] Gaonwe TP., Kusakana K., Hohne PA., *A review of solar and air-source renewable water heating systems, under the energy management scheme*, Energy Reports 8 (2022) 1–10
[7] Yang LY., Li Y., Yang Y., Wang HS., *Low temperature heating operation performance of a domestic heating system based on indirect expansion solar assisted air source heat pump*, Solar Energy 244 (2022) 134–154
[8] Gupta R., Morey J., *Empirical evaluation of demand side response trials in UK dwellings with smart low carbon technologies*, Renewable Energy 199 (2022) 993–1004
[9] Shen B., Li Z., Gluesenkamp K., *Experimental study of R452B and R454B as drop-in replacement for R410A in split heat pumps having tube-fin and microchannel heat exchangers*, Applied Thermal Engineering 204 (2022)
[10] Schnabel l., Dankwerth C., Methler T., Schossig P. *Low Charge Heat Pump Module – development and evaluation of charge reduced designs using 150g of R-290*, Chillventa, 13-15 October 2020.
[11] Nair AM., Wilson C., Huang MJ., Griffiths P., Hewitt N., *Phase change materials in building integrated space heating and domestic hot water applications: A review*, Journal of Energy Storage, Volume 54, October 2022
[12] https://www.gov.uk/government/publications/advanced-heat-storage-competition
[13] Shah NN., Wilson C., Huang MJ., Hewitt NJ., *Analysis on field trial of high temperature heat pump integrated with thermal energy storage in domestic retrofit installation*, Applied Thermal Engineering Volume 143, October 2018
[14] Ogunrin OS., Vorushylo I., Okpako O., Hewitt N., *Domestic Energy Efficiency Scenarios for Northern Ireland*, Energies, April 2022.