Techno-economic comparison of hydrogen- and electricity-driven technologies for the decarbonisation of domestic heating

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ABSTRACT

Sustainable transition pathways currently being proposed for moving away from the use of natural gas and oil in domestic heating focus on two main energy vectors: electricity and hydrogen. The former transition would most likely be implemented using electric vapour-compression heat pumps, which are currently experiencing market growth in many industrialised countries. Electric heat pumps have proven to be an efficient alternative to gas boilers under certain conditions, but their techno-economic potential is highly dependent on the local climate conditions. Hydrogen-based heating systems, which could potentially utilise existing natural gas infrastructure, are being proposed as providing an attractive opportunity to maximise the use of existing assets to facilitate the energy-system transition. In this case, hydrogen can substitute natural gas in boilers or in thermally driven absorption heat pumps. Both heating system transition pathways may involve either installing new technologies at the household level or producing heat in centralised hubs and distributing it via district-heating systems. Although the potential of hydrogen in the context of heating decarbonisation has been explored in the past, a comprehensive comparison of electricity- and hydrogen-driven domestic heating options is lacking in literature. In this paper, a thermodynamic and economic methodology is developed to assess the competitiveness of a domestic-scale ammonia-water absorption heat pump driven by heat from a hydrogen boiler compared to a standalone hydrogen boiler, a classic vapour-compression heat pump and district heating, all from a homeowner’s perspective. Using a previously developed electric heat pump model, the different systems are compared for various climate conditions and fuel-price scenarios under a unified framework. The coefficient of performance of the absorption heat pump system under design conditions and the total system cost are found to be 1.4 and £5400, respectively. Comparing the annualised total costs of the options under consideration, it is shown that, assuming the future price of hydrogen for domestic end-users can be below 0.12 £/kWh, absorption heat pumps and hydrogen boilers can become competitive domestic heating technologies, and otherwise, electrification and the use of vapour-compression heat pump will be preferred.

KEYWORDS

absorption heat pump, ammonia-water, boiler, decarbonisation, district heating, domestic heating, heat pump, hydrogen, techno-economic comparison

INTRODUCTION

The UK has committed to net-zero carbon emissions by 2050 under the Climate Change Act [1]. Heating is a significant contributor to emissions in the UK, accounting for around one-third of the total emissions [2]. Therefore, achieving the emission target commitments requires the heating of all buildings and most industrial processes to undergo decarbonisation [3]. Of the 173 $MtCO_2e$ of carbon emissions from heating in the UK, 57% are attributed to space heating and hot water provision in buildings [4]. Cutting these emissions requires advancements in efficient and sustainable heat generation technologies.UK heating is currently dominated by natural gas boilers, which are installed in more than 85% of all households [5]. Retrofitting existing buildings on the gas grid with new technologies is challenging and the uncertainty in future heating demand is high [6]. Additionally, the UK housing stock exhibits a poor energy efficiency and there is generally a lack of public awareness of low-carbon heating [4], making the decarbonisation of heating a challenging task. The main technologies that are currently being proposed in the UK for heating decarbonisation in buildings are electric heat pumps [7, 8] and hydrogen boilers [9].

Electric heat pumps are a mature technology and have been recently experiencing significant market growth in many industrialised countries such as France and Germany, but the total uptake is still low (0.25 million in the UK) [10]. Heat pumps transfer heat from a cold region (e.g., air or ground) to a hot region (e.g., internal space of buildings), and are associated with considerably better thermodynamic performance than currently available gas-based or direct-electric heating technologies [11]. The Committee on Climate Change has indicated that gas boiler installations should cease by 2035 in order to achieve UK's decarbonisation targets and electric heat pumps are a promising technology to replace them [3]. In order to provide zero-carbon heat, the electricity driving the heat pump compressor must be generated from renewable sources.

Hydrogen is also being suggested as a possible option for the delivery of low-carbon heat to buildings, and benefits from the attractive opportunity of continuing to use the existing natural-gas grid infrastructure that in the UK is extensive and in an advanced state of development [12]. Transforming the natural gas system to supply boilers with hydrogen would involve additional costs (e.g., due to the requirement for additional compressors and replacement of certain pipelines [12]), but it incur no noticeable usage changes for customers, with the benefit of having no CO_2 emissions at the point of use. The recent "Hydrogen in a low carbon economy" report [13] suggested that hydrogen can make an important contribution to long-term decarbonisation. In that report, it is stated that heat pumps offer the potential to provide heat efficiently most of the time, and hydrogen boilers can be used on the coldest winter days to meet peak demands. The potential of hydrogen for decarbonised heating is currently experiencing extensive investigation.

Sunny et al. [9] conducted a systematic assessment of the regional transition from the natural gas supply chain to a hydrogen-based infrastructure with carbon capture and storage (CCS) to investigate the feasibility and costs of carbon-neutral heating with hydrogen boilers. Northern Gas Networks commissioned a feasibility study, the "H21 project" [14], examining the feasibility and cost of converting the gas grid in the north of England to 100% hydrogen. In that study, a conversion strategy was developed to achieve full switch from natural gas in a conversion period lasting seven years and the need for detailed engineering design of hydrogen technologies was outlined. Additionally, Hart et al. [15] demonstrated a "full-contribution" residential heat-provision scenario, which involves the long-term uptake of hydrogen. In that scenario, the natural gas boilers in most houses are replaced by hydrogen boilers and some high energy-efficiency houses have hybrid heat pumps integrated with hydrogen boilers to meet peak demands.

The current literature lacks studies assessing the potential of hydrogen-driven absorption heat pumps in a hydrogen-based economy. Absorption heat pumps, like electric heat pumps, extract renewable heat from a cold heat source, but instead of using an electric compressor, they are thermally driven. Absorption systems have been widely studied for refrigeration purposes and are now gaining attention for heating applications [16]. The technology has been shown to improve the efficiency and capacity of district heating (DH) networks [17].

An absorption heat pump system requires two separate fluids: an absorption medium and a refrigerant. Water (H_2O) – lithium bromide (LiBr) systems are one the most studied options due to high safety and efficiency, however their use in low-temperature-source applications is limited due to solution crystallisation and a high refrigerant freezing point, making it impossible to utilise heat-source temperatures lower than 5 °C at the evaporator [18, 19]. This is impractical in cold months in the UK. Another suitable fluid pair option is ammonia (NH_3) – water (H_2O). Garrabrant et al. [20] investigated a gas-fired residential NH_3-H_2O absorption heat pump for hot-water provision and measured a coefficient of performance (COP) in the range of 1.44 to 1.63 when supplying hot water at 45 °C at an ambient temperature of 20 °C. Wu et al. [19] investigated the applicability of NH_3-H_2O water-source absorption heat pumps and proved that a developed prototype can operate under evaporator inlet temperatures as low as -18 °C (when the heat source is calcium chloride). In that work, the authors predicted a COP between 1.43-1.55 when supplying hot water at 45 °C with a heat-source water inlet temperature of 15 °C. Literature investigating the integration of renewable power sources with absorption heat pumps tends to focus on solar energy. A combination of solar collectors with a hydrogen-driven heat pump shows promising energy and environmental performance and demonstrates the integration capabilities of intermittent solar resources [21].

Although NH_3-H_2O absorption systems have been extensively explored at the technology level, an in-depth wider techno-economic analysis of this technology, capturing how performance and cost depend on the operating conditions as well as the chosen configuration and components, has not been proposed in the literature. Thus, insights into the potential of this system in comparison to electric heat pumps have not been attained. The novelty of this work lies in the development of a thermodynamic and component-costing model of a hydrogen-powered, NH_3-H_2O air-source heat pump. Heat from a hydrogen boiler is used to power the heat pump. The annual performance of the system is analysed for an average UK household and the capital and operating costs are estimated. Using a validated electric heat pump model from previous work [22, 23], four electricity- and hydrogen-driven domestic heating options (electric heat pump, hydrogen-driven absorption heat pump, standalone hydrogen boiler and DH) are compared from the perspective of a household owner for various electricity, hydrogen and DH price scenarios. The following section describes the absorption heat pump and hydrogen boiler thermodynamic and economic models. Then, the different heating systems are compared and the environmental and energy-system implications of both hydrogen- and electric-driven heat pump options are discussed.

METHODS

Absorption heat pump configuration

Electric heat pumps in domestic applications consist of four main components: a condenser, an expansion valve, an evaporator and an electricity-driven compressor. In the absorption heat pump system, the compressor is replaced with an absorption cycle consisting of a generator, a solution heat exchanger (SHX), an absorber, an electricity-driven pump and another expansion valve. A schematic diagram of the NH_3-H_2O absorption heat pump is shown in Figure 1. The high-pressure components are the condenser, generator and SHX, and the low-pressure components are the evaporator and absorber. The principle of operation is that the vapourised refrigerant (in this case NH_3) coming out of the evaporator is absorbed by the absorber (in this case H_2O), forming a liquid solution, which is then pumped to the high-pressure components. This process requires negligible amount of electricity when compared to that required to compress vapour in electric heat pumps. Heat from the high-temperature source (in this case hydrogen boiler) is supplied to the system in the generator to retrieve the refrigerant from the liquid solution. The SHX is a useful component to improve the system's performance by preheating the solution.

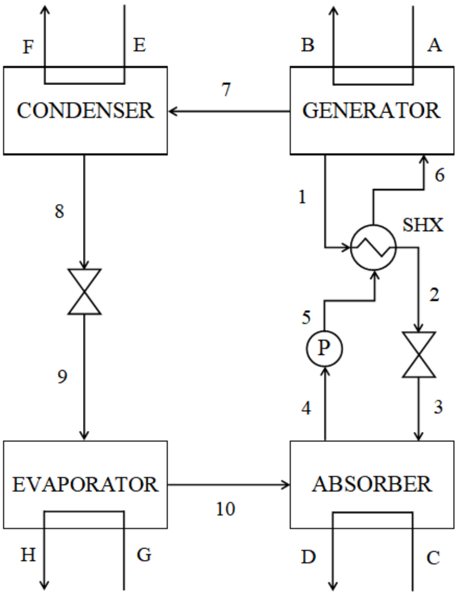


Figure 1. Schematic diagram of an absorption heat pump.

Referring to Figure 1, Stream 1 represents the 'weak' NH_3-H_2O solution, a high-pressure subcooled liquid following the heat input from the hydrogen boiler in the generator. Stream 1 enters the counter-flow SHX and following this, Stream 2 enters the expansion valve and exits as a low-pressure saturated liquid, Stream 3. Stream 4 is the 'strong' refrigerant solution, a saturated liquid, that is pumped to high pressure using the pump (P). Stream 5 is preheated in the SHX by recovering heat from the weak solution and exits as Stream 6 to enter the generator. High-pressure saturated refrigerant vapour exits the generator in Stream 7 and condenses into a liquid in Stream 8. The liquid enters another expansion valve to reduce the pressure, before Stream 9 enters the evaporator to become vapourised (Stream 10), which then enters the absorber. Streams A and B represent the hot water loop to the hydrogen boiler, while Streams C, D, E and F are the water-supply streams for household heating. Stream C is heated by heat being released by the absorption process and Stream E is heated by the condensation of the refrigerant in the condenser. Streams G and H represent the ambient air, from which low-grade heat is drawn.

For a given set of input conditions, the thermodynamic states of each point of the cycle are calculated to estimate the system's performance. The model is developed in MATLAB [24]. All thermodynamic properties are extracted from the NIST "Reference Fluid Thermodynamic and Transport Properties Database" (REFPROP) [25]. The main model assumptions are:

- all components operate at steady-state conditions;
- heat losses and pressure drops in components and piping are negligible;
- the NH_3-H_2O solution is saturated at the generator and absorber outlet [26];
- the refrigerant leaving the condenser is a saturated liquid [26];
- the pinch-point temperature differences (T_{pp}) in the heat exchangers are equal to 5 K;
- flow throttling processes through the valves are isenthalpic;
- the isentropic efficiency of the pump is equal to 0.8;
- the heat exchanger effectiveness factor is equal to 0.8;
- the degree of superheating in the evaporator is equal to 5 K;
- the hot water demand temperature is set to 55 °C (minimum required for hot water [27]).

Absorption heat pump thermodynamic model

The absorption heat pump system is represented by Equations (1)-(21). Hereby, the indices of temperatures (T), pressures (P) and enthalpies (h) refer to the fluid streams as shown in Figure 1. Detailed explanation of all symbols is provided in the nomenclature. The temperatures of the outlet stream of the condenser T_8 and absorber T_4 are calculated as shown in Equation (1). Assuming saturated liquid leaves the condenser, the pressure at its outlet is determined. This is equal to the pressure of all high-pressure components of the cycle:

$$T_8 = T_4 = T_\mathrm{d} + T_\mathrm{pp} \,, \tag{1}$$

$$P_\mathrm{high} = P_\mathrm{sat}(T_8) = P_8 = P_7 = P_6 = P_5 = P_2 = P_1 \,. \tag{2}$$

The temperature of the outlet stream of the evaporator is calculated using Equation (3), and assuming the latter is saturated vapour, the pressure of low-pressure components is determined:

$$T_{10} = T_\mathrm{air} - T_\mathrm{pp} - T_\mathrm{sh} \,, \tag{3}$$

$$P_\mathrm{low} = P_\mathrm{sat}(T_{10})\, P_{10} = P_9 = P_3 = P_4 \,. \tag{4}$$

The temperature of the weak solution is determined using Equation (5). The solution concentrations of the strong and weak solutions required to obtain these temperatures and pressures are obtained and the enthalpy of the fluid at the pump outlet is determined based on the isentropic efficiency:

$$T_1 = T_\mathrm{gen} - T_\mathrm{pp} \,, \tag{5}$$

$$h_5 = h_4 + \frac{(h_{5,\mathrm{ideal}} - h_4)}{\eta} \,. \tag{6}$$

The SHX effectiveness ε is used to calculate the temperature of stream 2:

$$T_2 = T_1 - \varepsilon(\, T_1 - T_5 \,) \,. \tag{7}$$

Assuming isenthalpic expansion across the expansion valve, the enthalpy of stream 3 is found:

$$h_2 = h_3 \,. \tag{8}$$

The mass conservation equation satisfied in each component is expressed as:

$$\sum_i \dot{m}_{i,\mathrm{in}} x_{i,\mathrm{in}} - \sum_i \dot{m}_{i,\mathrm{out}} x_{i,\mathrm{out}} = 0 \,. \tag{9}$$

The solution circulation ratio is defined as the ratio between the mass flowrate of the weak solution entering the generator and that of the refrigerant vapour leaving the generator [28]. From Equation (9), the solution circulation ratio can be written as:

$$f = \frac{\dot{m}_6}{\dot{m}_7} = \frac{x_1}{x_1 - x_4} \,. \tag{10}$$

The energy balances for each component of the cycle are the following:

$$\dot{Q}_\mathrm{gen} = \dot{m}_7 h_7 + \dot{m}_1 h_1 - \dot{m}_6 h_6 \,, \tag{11}$$

$$\dot{Q}_\mathrm{cond} = \dot{m}_7 (h_7 - h_8) \,, \tag{12}$$

$$\dot{Q}_\mathrm{evap} = \dot{m}_9 (h_{10} - h_9) \,, \tag{13}$$

$$\dot{Q}_\mathrm{abs} = \dot{m}_{10} h_{10} + \dot{m}_3 h_3 - \dot{m}_4 h_4 \,, \tag{14}$$

$$\dot{Q}_\mathrm{shx} = \dot{m}_5 (h_6 - h_5) \,, \tag{15}$$

$$\dot{W}_\mathrm{pump} = \dot{m}_4 (h_5 - h_4) \,. \tag{16}$$

Using the above equations, the mass flowrates of each stream of the cycle can be calculated:

$$\dot{m}_{10} = \dot{m}_9 = \dot{m}_8 = \dot{m}_7 = \frac{\dot{Q}_{\text{cond}} + \dot{Q}_{\text{gen}}}{h_7 - h_8 + h_{10} + (f-1)h_3 - fh_4}\,, \tag{17}$$

$$\dot{m}_4 = \dot{m}_5 = \dot{m}_6 = f\dot{m}_{10}\,, \tag{18}$$

$$\dot{m}_3 = \dot{m}_2 = \dot{m}_1 = \dot{m}_4 - \dot{m}_{10}\,. \tag{19}$$

The solution enthalpy at the generator inlet is thus obtained from the following mixing rule:

$$h_6 = h_5 + \frac{\dot{m}_1}{\dot{m}_4}(h_1 - h_2)\,. \tag{20}$$

The absorption heat pump cycle performance is evaluated using the COP, which is the ratio of useful heat output to the sum of heat and power input. In this idealised absorption heat pump model, it is assumed that the temperature of the water outlet stream from the absorber is the same as that of the condenser, and both are equal to the demand temperature. The heat output from both components is therefore the useful heat for the supply water:

$$COP_{\text{ahp}} = \frac{\dot{Q}_{\text{abs}} + \dot{Q}_{\text{cond}}}{\dot{W}_{\text{pump}} + \dot{Q}_{\text{gen}}}\,. \tag{21}$$

Absorption heat pump component sizing and costing

The heat transfer area of each heat exchanger (denoted with subscript k) is obtained using:

$$A_k = \frac{\dot{Q}_k}{U_k \Delta T_{\text{lm},k}}\,, \tag{22}$$

where A is the heat transfer area, $\dot{Q}$ the heat flow, U the heat transfer coefficient and $\Delta T_{\text{lm},k}$ is the logarithmic mean temperature difference, which is calculated by Equation (23):

$$\Delta T_{\text{lm},k} = \frac{\left(T_{\text{h,i}} - T_{\text{c,i}}\right) - \left(T_{\text{h,o}} - T_{\text{c,o}}\right)}{\ln\dfrac{T_{\text{h,i}} - T_{\text{c,i}}}{T_{\text{h,o}} - T_{\text{c,o}}}}\,, \tag{23}$$

where subscripts h and c represent the hot and cold streams, and i and o the inlet and outlet streams. The heat transfer coefficient U is assumed to be 1.6, 1.1, 0.6, 0.9 and 1 kW/m^{2}K for the generator, SHX, absorber, evaporator and condenser, taken from the literature for ammonia-water systems [29, 30]. Component and equipment cost correlations are summarised in Table 1. The generator and absorber are assumed to have the same cost function as the other heat exchangers (condenser, SHX). The correlations are based on a previously validated electric heat pump model [22].

Table 1. Cost correlations for different components and related variables.

Component	Dependent variable	Cost function
Generator	Heat exchange area A_{gen} (m^2)	337 + 214 A_{gen}
Solution heat exchanger	Heat exchange area A_{shx} (m^2)	337 + 214 A_{shx}
Condenser	Heat exchange area A_{cond} (m^2)	337 + 214 A_{cond}
Absorber	Heat exchange area A_{abs} (m^2)	337 + 214 A_{abs}
Evaporator	Heat exchange area A_{evap} (m^2)	270 A_{evap}
Pump	Work required W (kW)	512 $W^{0.460}$
Miscellaneous hardware	Total cost of components TC	0.2 TC
Profit margin	Total cost of components TC	0.2 TC
Tax	Total cost of components TC	0.2 TC

Hydrogen boiler

A catalytic hydrogen boiler is used to provide heat to the heat pump generator. Catalytic boilers are flameless heaters that convert the fuel and oxygen into the reaction products through catalysed chemical reactions. This results in negligible nitrogen-oxide emissions [31]. The hydrogen boiler is modelled as a reaction chamber and a separate heat exchanger which heats water to flow to the generator. The model is based upon a modified natural gas boiler [32]. The following assumptions are made:

- the reaction of hydrogen in the boiler is complete with dry air; and
- all components operate at steady-state conditions.

The reaction taking place in the reaction chamber is as follows:

$$\mathrm{H_2} + \frac{\lambda}{2}(\mathrm{O_2} + 3.76\mathrm{N_2}) \overset{\mathrm{Pt}}{\rightarrow} \mathrm{H_2O} + \frac{(\lambda - 1)}{2}\mathrm{O_2} + \frac{3.76\lambda}{2}\mathrm{N_2}\,, \tag{24}$$

where λ is the excess air ratio (equal to 1.13, in line with observed values in boilers [32]) and 3.76 represents the ratio of nitrogen to oxygen in air. Consequently, the total molar flowrate of the flue gases out of the reaction chamber is the sum of the coefficients of the products, multiplied by the molar flowrate of hydrogen. This is given by:

$$\dot{n}_{\mathrm{fg}} = \dot{n}_{\mathrm{H_2}}\left(1 + \frac{\lambda - 1}{2} + \frac{3.76\lambda}{2}\right). \tag{25}$$

The mole fraction of each product in the flue gases is equal to the product's molar flowrate divided by the molar flowrate of the flue gases. Hydrogen reacts in the catalytic boiler at approximately 300 °C [33]. A weighted flue gas molar heat capacity $\overline{C_{\mathrm{pfg}}}$ is estimated by summing the multiples of the mole fractions of each product with their respective molar heat capacity. The energy lost from the combustion process in the flue gas in two forms: as sensible heat energy (Equation (26)) and as latent heat in water vapour (Equation (27)):

$$\dot{E}_{\mathrm{fg,s}} = \dot{n}_{\mathrm{fg}}\overline{C_{\mathrm{pfg}}}(T_{\mathrm{fg}} - T_0)\,, \tag{26}$$

$$\dot{E}_{\mathrm{fg,l}} = \dot{n}_{\mathrm{fg}} x_{\mathrm{H_2O}} Ma_{\mathrm{H_2O}} L_{\mathrm{H_2O}}\,, \tag{27}$$

where $x_{\mathrm{H_2O}}$ is the mole fraction of water in the flue gas stream, $Ma_{\mathrm{H_2O}}$ the molar mass of water, $L_{\mathrm{H_2O}}$ the latent heat of vaporisation of water, T_{fg} the temperature of the flue gases and T_0 the temperature of the environment. Summing these two effects gives:

$$\dot{E}_{\mathrm{fg}} = \dot{E}_{\mathrm{fg,s}} + \dot{E}_{\mathrm{fg,l}}\,. \tag{28}$$

The amount of fuel energy required to run the boiler - heat pump system is calculated using:

$$\dot{E}_{\mathrm{fuel}} = \dot{Q}_{\mathrm{gen}} + \dot{E}_{\mathrm{fg}} + \dot{E}_{\mathrm{loss}}\,, \tag{29}$$

where $\dot{Q}_{\mathrm{gen}}$ is the heat supplied to the heat pump generator and $\dot{E}_{\mathrm{loss}}$ accounts for heat losses from the boiler structure (approximated to be 1% of the sum of $\dot{Q}_{\mathrm{gen}}$ and $\dot{E}_{\mathrm{fg}}$). In condensing boilers, the water vapour in the products is condensed and therefore the losses are reduced. Finally, $\dot{E}_{\mathrm{fuel}}$ can be divided by the lower heating value of hydrogen, HV, to provide the required mass flowrate of hydrogen into the boiler:

$$\dot{m}_{\mathrm{fuel}} = \frac{\dot{E}_{\mathrm{fuel}}}{HV}\,. \tag{30}$$

Electric heat pump thermodynamic and component-costing model

A spatially-lumped model of an electric heat pump based on a single-stage-compressor was developed in previous work of the authors [22, 23]. The model, like the absorption heat pump model, assumes steady-state operation of components, isenthalpic expansion and negligible pressure and heat losses in heat-exchange components and pipes. Validated comprehensive component-sizing and costing models are used to estimate the technoeconomic performance of the system. The electric heat pump's COP is the ratio of the heat provided by the condenser to the electricity required to drive the compressor:

$$COP_{\mathrm{ehp}} = \frac{\dot{Q}_{\mathrm{cond}}}{\dot{W}_{\mathrm{comp}}} \tag{31}$$

RESULTS

In this section, the results of the techno-economic analysis of the hydrogen-driven absorption heat pump are presented. The thermodynamic performance of hydrogen and electric heat pumps is compared at various heat source and sink temperatures and the competitiveness of the two systems as well as a standalone hydrogen-boiler and a DH system is assessed for various electricity, hydrogen and DH price scenarios. The heat pumps have a nominal size of 7 $\mathrm{kW_{th}}$, which is equal to the peak annual heating demand of a typical UK household according to the heating demand profile extracted from Watson et al. [34].

Techno-economic performance at design point

The Sankey diagram in Figure 2 shows the energy flows when the absorption heat pump is operated at its nominal heating capacity (7 $\mathrm{kW_{th}}$), with hot-water temperature of 55 °C and air temperature of 7 °C, which are standard conditions for heat pump efficiency [35]. The COP of the absorption heat pump at these conditions is found to be 1.42, which is in line with values of literature for similar-size and fluid systems [16, 19, 20]. For example, at the same source and sink conditions, the model of Scoccia et al. [16], based on experimental measurements performed on an ammonia-water heat pump prototype, predicts a COP of about 1.38 (just 3% lower).

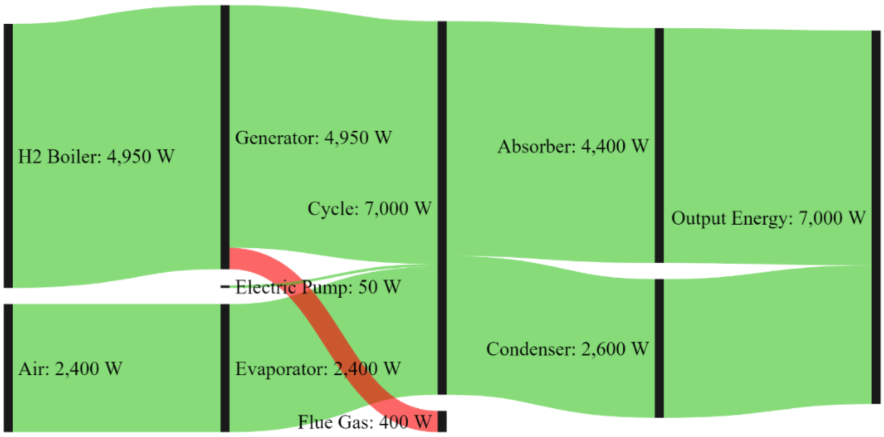


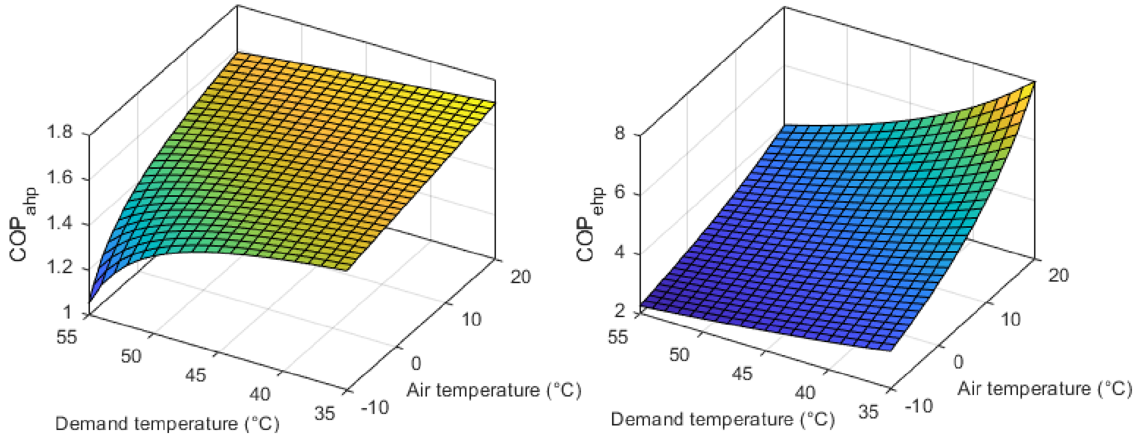
Figure 2. Sankey diagram depicting energy flows when the hydrogen boiler and absorption heat pump operate at nominal heating capacity (7 $\mathrm{kW_{th}}$), with hot-water temperature of 55 °C and air temperature of 7 °C.

Using the heat-exchanger-area sizing method and cost correlations shown in the previous section, the investment cost of the absorption heat pump system is estimated to be £4530. The cost of the hydrogen boiler is £850, taken from the work of Sadler et al. [14], bringing the total system cost to £5380 (specific cost: 770 £/$\mathrm{kW_{th}}$). The validated electric heat pump costing model predicts a slightly lower investment cost of £4080 (specific cost: 580 £/kW$_{th}$), which is in line with prices on the UK market [36]. Furthermore, the installation costs for heat pumps and boilers are assumed to be £3700 and £1700, respectively [37], and the annual maintenance cost is assumed to be equal to £240 [38] for all technologies.

COP at different heat-source and heat-sink conditions

The COP of the absorption and electric heat pumps are determined for a range of demand and air temperatures, as shown in Figure 3. The analysis assumes a fixed 5-K pinch-point temperature difference in all heat exchangers. The air temperature is varied between -10 °C and 20 °C, capturing the variations in system performance during different UK seasons. The demand temperature is varied between 35 °C and 55 °C, covering the range of applications from low-temperature underfloor space heating to domestic hot water provision.

For a demand temperature of 55 °C, the COP of the electric heat pump varies between 2.3 and 4, while it varies between 3 and 8 for a demand temperature of 35 °C. The electric heat pump performs especially well under low-demand-temperature conditions. The absorption heat pump provides more consistent COP values over the considered temperature range, with the COP varying between 1.3 and 1.8 over most of the tested range. A significant deterioration in performance is observed when the air temperature is very low (close to -10 °C) and the demand temperature is 55 °C, suggesting that that under extreme conditions it may be more economical to use the hydrogen boiler directly for heating.



(a) (b)

Figure 3. COP as a function of air and demand temperature for: (a) the hydrogen-driven absorption heat pump; and (b) the electric heat pump. Note: the definition of the COP of the two systems is different (refer to the Methods section). A fixed 5-K pinch-point temperature difference is assumed in all heat exchangers.

As shown in the Methods section, the definition of the COP is different for the two heat pump systems. The electric heat pump is driven by electricity and the absorption heat pump is driven by hydrogen, which means that the economic competitiveness of the two systems largely depends on the relative prices of electricity and hydrogen, which is investigated in the next section.

Techno-economic comparison for different electricity and hydrogen price scenarios

The hourly heating demand for an average UK household in 2019 is considered [34] to provide a techno-economical comparison of electric and hydrogen-driven absorption heat pumps as well as standalone hydrogen boilers. The performance of each heat pump is determined for each hour of the year based on the respective air temperature extracted from the MERRA meteorological reanalyses [39]. All results presented in this section are valid for a hot-water demand temperature of 55 °C. Based on the electricity and hydrogen price, the annual cost of operation for the three heating systems (electric heat pump, hydrogen-driven absorption heat pump, hydrogen boiler) is estimated and the effect of different electricity- and hydrogen-price scenarios is investigated. As an example, Figure 4 shows the daily average operational costs of the hydrogen-driven absorption heat pump for a hydrogen price of 0.08 £/kWh. As expected, the UK's seasonal climate causes a higher demand and thus higher operating costs during the winter compared to the summer months.

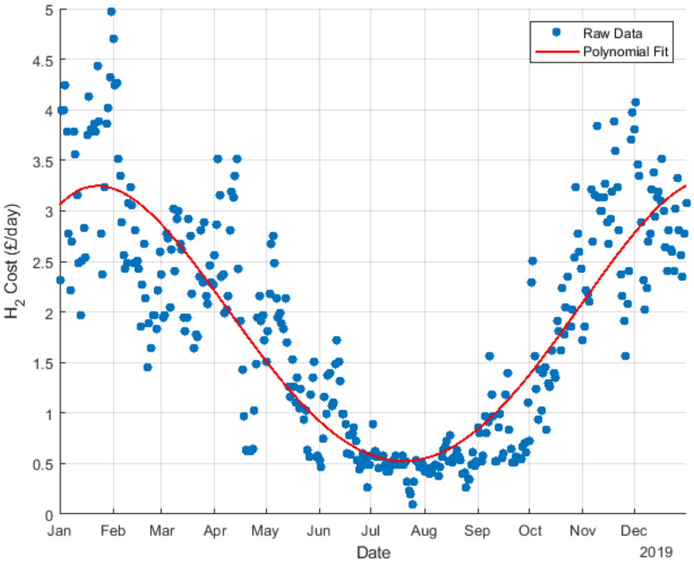


Figure 4. Hydrogen cost per day required for domestic absorption heat pump based on average heating demand data in the UK [34] and a hydrogen price of 0.08 £/kWh.

The investment costs of the three systems are annualised based on a discount rate of 3% and a lifetime of 20 years. The levelised cost of heat (LCOH), which is the ratio of the annualised total cost over the annual heat production, is reported in Figure 5, and the annualised operational and total (investment, operational and maintenance) costs are compared in Figure 6. The blue, yellow and green areas show the price ranges for which the electric heat pump, the absorption heat pump and the hydrogen boiler are more competitive, respectively.

The predicted prices of hydrogen delivered to homes show large variations across the literature. Sunny et al. [9] estimate that, including distribution charges, carbon-neutral hydrogen could be supplied at a retail price of about 0.085 £/kWh. This price includes: (i) generation via autothermal reforming (ATR) and biomass gasification; (ii) CCS; (iii) underground H2 storage; and (iv) gas-network reinforcement. Northern Gas Networks predict in the "H21 project" report [14] that the retail price of hydrogen supplied to consumers in Leeds in the UK could be 0.093 £/kWh, including all costs associated with steam-methane reforming (SMR), CCS, H_2 storage and gas-network reinforcement. Furthermore, in a study conducted by the Trinomics and LBST consultancies [40] to analyse the role of hydrogen in the National Energy and Climate Plans (NECP), the authors predict that, if hydrogen is produced using renewable electricity sources and electrolysis, the expected delivery cost could be between 0.130 and 0.163 £/kWh, while if it is produced by SMR and CCS, it might be close to 0.080 £/kWh. The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has set a goal to reach a retail price of renewably produced hydrogen of 0.11-0.15 £/kWh by 2025 [41, 42]. In the strategic research and innovation agenda of the Clean Hydrogen for Europe partnership, it is stated that, for renewably produced hydrogen to become competitive, it should be produced at a cost below 0.065 £/kWh by 2030 [43]. The estimated retail price of carbon-neutral hydrogen from different sources and current UK electricity price [44] are shown in Figure 6.

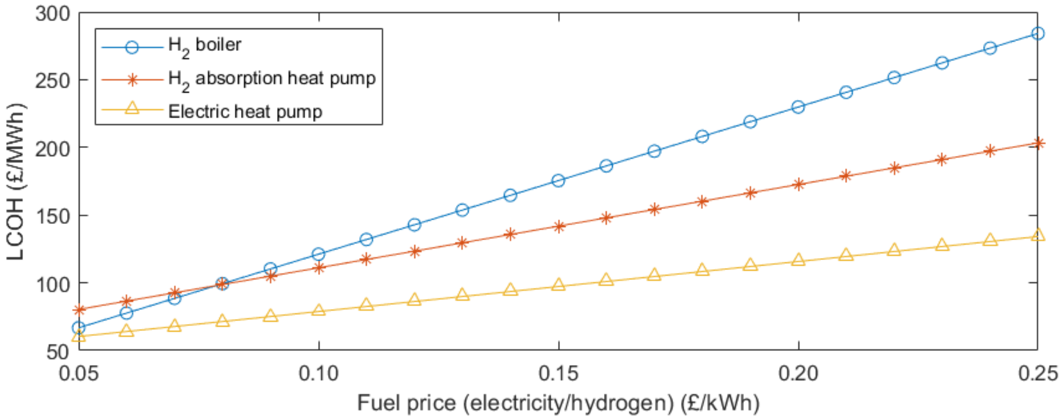
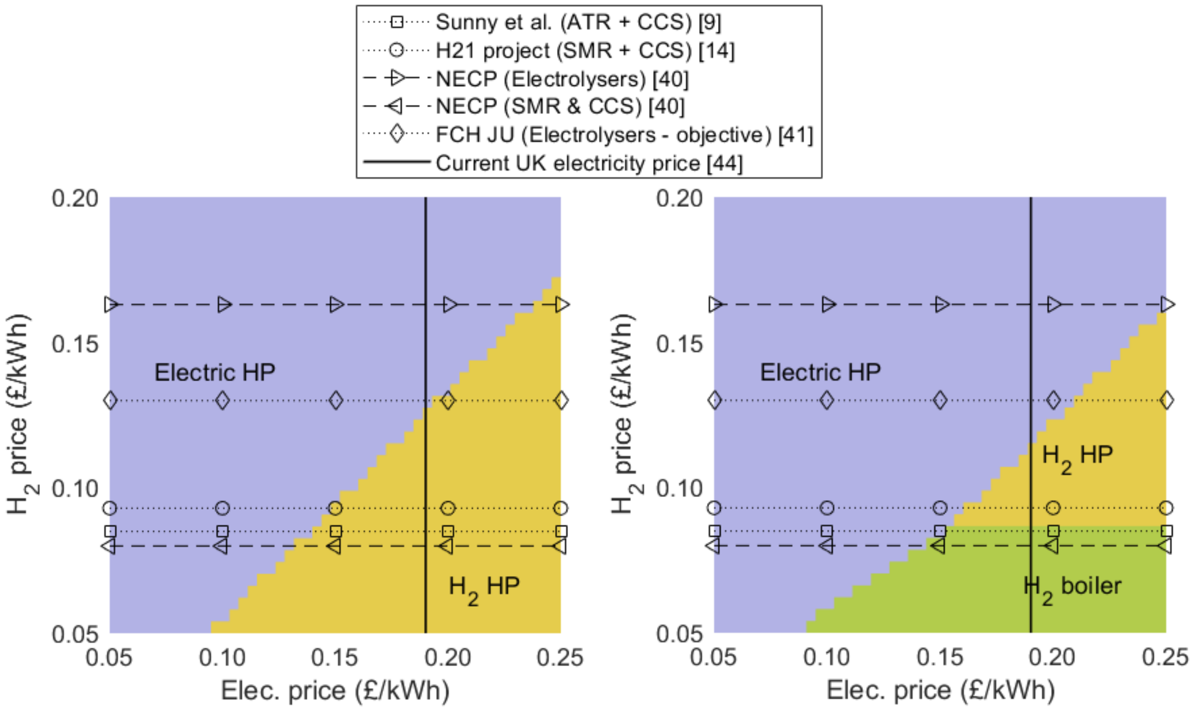


Figure 5. Levelised cost of heat (LCOH) for the electric heat pump, hydrogen-driven absorption heat pump and standalone hydrogen boiler for different electricity and hydrogen prices.



(a) (b)

Figure 6. Comparison of electric heat pump, hydrogen-driven absorption heat pump and standalone hydrogen boiler for different hydrogen and electricity prices: (a) annualised operational cost; and (b) annualised total cost. The blue, yellow and green areas show the price ranges for which the electric heat pump, the absorption heat pump and the hydrogen boiler are more competitive, respectively. Horizontal and vertical lines represent the estimated retail prices of carbon-neutral hydrogen from different sources and the current electricity price in the UK, respectively.

The absorption heat pump shows to be competitive under various electricity and hydrogen price scenarios. Given that the current electricity price in the UK is 0.19 £/kWh [44], the annualised operational cost (Figure 6(a)) associated with a hydrogen-driven absorption heat pump is lower than that of the electric heat pump for hydrogen prices below 0.12 £/kWh. If hydrogen is produced by SMR or ATR in conjunction with CCS, and thus the hydrogen price is close to what predicted by Refs. [9, 14, 40], the absorption heat pump becomes favourable in terms of operating costs. Since the investment cost of the absorption heat pump system is higher than that of the electric heat pump, the competitiveness of the latter improves when looking at the annualised total cost (Figure 6(b)). Hydrogen boilers will also be competitive if the price of hydrogen falls below 0.09 £/kWh. If hydrogen is produced by renewable electricity through electrolysis, the associated predicted retail price is much higher (0.13-0.16 £/kWh), making electric heat pumps the most cost-effective option. Therefore, assuming electricity prices do not drastically drop in future, the competitiveness of absorption heat pumps will be determined by the ability to produce hydrogen in a cost-effective way.

Comparison to district heating

District heating is another sustainable transition pathway that involves producing heat through large-scale, centralised technologies rather than domestic-scale heat pumps and boilers. This pathway can be either electricity- or hydrogen-based. A comparison to the previously discussed pathways is performed from an end-user's perspective assuming a DH network is in place. According to the data collected from the Department of Energy and Climate Change for 7 different heat-network schemes in the UK [45], the cost required to connect a house to the DH network is often embedded within the retail price of heat, and the average value of the latter for existing schemes for which the operator is responsible for the delivery of heat is 0.08 £/kWh. The investment cost to install a heat-interface unit is about £1080 [45] and the annual standing charge for system maintenance is estimated to be £210 [46]. It should be stated that the price of heat highly depends on the heat source, and most existing schemes are based on gas-fired combined heat and power systems, meaning that heating prices could be higher if renewable sources are used. Figure 7 shows the comparison of DH against the electricity- and hydrogen-driven options for a fixed electricity price at the current UK value of 0.19 £/kWh and for various hydrogen and DH prices.

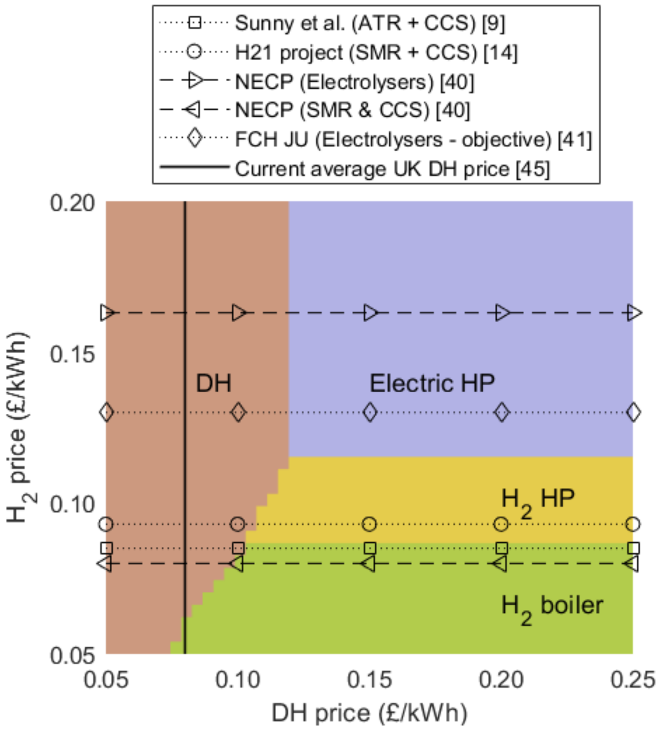


Figure 7. Comparison of electric heat pump, hydrogen-driven absorption heat pump, standalone hydrogen boiler and DH for different hydrogen and DH prices in terms of annualised total cost. The blue, yellow, green and brown areas show the price ranges for which the electric heat pump, the absorption heat pump, the hydrogen boiler and the DH system are more competitive, respectively. Horizontal and vertical lines represent the estimated retail prices of carbon-neutral hydrogen from different sources and the current average DH price in the UK, respectively.

As shown in Figure 7, DH systems can be the dominant heating option for domestic consumers (in locations where this option is available) if heat can be supplied at a price lower than 0.12 £/kWh. At the average price of heat of existing UK DH schemes (0.08 £/kWh) and given the current electricity price (0.19 £/kWh), electric and hydrogen technologies cannot compete. However, higher investments may be required for the heat delivered from DH systems to become zero-carbon or for the installation of DH networks in less suitable (e.g., rural) regions, causing an increase in the price of heat. If the latter is higher than 0.12 £/kWh, all other heating options (electric heat pumps, hydrogen-driven heat pumps and hydrogen boilers) come into discussion, and the decision as to which one of them is the most cost-effective option is highly dependent on the price of hydrogen.

Environmental issues

The proposed absorption heat pump system uses NH_3 as a refrigerant, which is common in industrial applications but presents a number of technical issues for domestic applications. In particular, NH_3 is highly toxic [47]. There is arguably more risk when toxic chemicals are used domestically and as such, any parts of the system in contact with NH_3 must be sufficiently proofed to limit breakage risk. These additional costs have not been considered in this paper. In addition, ammonia is corrosive, especially when impurities are present. Care must be taken to ensure rigid safety procedures in case of leaks and appropriate training must be undertaken by contractors to mitigate risks during installation and charging. In locations where air temperatures are higher, alternative refrigerant systems based on H_2O-LiBr or other fluids can be considered.

Energy-system effects and market viability

Decarbonisation of heat through electrification or hydrogen is associated with crucial upstream effects and huge changes to the energy system. Electrifying heat ties its carbon footprint to that of the power sector, where the path involves decarbonisation mainly through renewable energy. However, adding the burden of domestic heating onto the electric grid will require infrastructure reinforcement, improved energy efficiency measures and large-scale electricity storage. In the case of a hydrogen-based decarbonisation pathway, the possibility to inject hydrogen in the existing gas network at different percentages could be an effective option; however, this would be costly. Further research in hydrogen-production technologies is required, as CCS systems are still at an early stage of development and there are high uncertainties around the associated costs.

Investment cost and economic competitiveness of absorption heat pumps in comparison to vapour-compression ones are important aspects to be considered to explore their market uptake in the domestic sector. The total cost of the 7 kW_{th} absorption heat pump coupled to the hydrogen boiler proposed in this paper was found to be £5380, and the owner of an average-size household is unlikely to be willing to pay such upfront cost. Government incentives will be required to encourage purchasing. Zero- or low-interest payment plans can be devised or carbon taxes on fossil fuels can be imposed. Governments could even ban the use of traditional heating systems in new buildings (the UK government decided to ban the sale of natural gas boilers in all new homes by 2025 [48]). These measures could be implemented in tandem with subsidies.

CONCLUSIONS

A number of current pathways based on electricity and/or hydrogen are currently under examination in the context of domestic heating decarbonisation. Electric heat pumps are experiencing market growth in many industrialised countries, while at the same time a hydrogen-based heating framework utilising the existing natural gas infrastructure is being proposed as an attractive alternative, particularly in the UK, which has relied on this infrastructure for decades.

In this paper, a comprehensive thermodynamic and component-costing model of a domestic-scale ammonia-water absorption heat pump driven by heat from a hydrogen boiler developed for thermodynamic and economic (capital cost) performance perditions has been presented, and performance predictions of this technology have been validated against values reported in the literature. Technology performance has been analysed for different heat-source and -sink temperatures, specifically in the context of the UK. Using an average UK household as a focal case study, a suitable absorption heat pump was sized, costed and the annual operational costs associated with meeting the domestic demand for space heating and hot water were estimated. For comparison purposes, a validated electric heat pump model was also used to perform a similar analysis under a unified framework (consistent modelling methodology and assumptions) and the techno-economic potentials of the two systems as well as those of a standalone hydrogen boiler and a DH system were analysed from a homeowner's perspective for various fuel-price scenarios.

The COP of the absorption heat pump system at design conditions was found to be 1.4, which is as expected from the relevant literature, and the total system cost was estimated at around £5400. The annualised operational and total costs associated with the three heating options were compared, and the results demonstrated that, if the future price of hydrogen for domestic end-users is below about 0.12 £/kWh, hydrogen-driven absorption heat pumps and hydrogen boilers may be in a position to compete with electric heat pumps and DH, and otherwise, electrification and the use of vapour-compression heat pump will be preferred by homeowners.

This paper provides insights into the potential of currently proposed domestic heating options and into the key techno-economic factors that influence their competitiveness. Future work will include detailed modelling of the absorption heat pump components, comparison to further alternative technologies (e.g., solar-thermal) and a similar assessment in other regions with demands for both heating and cooling, while extending to whole-energy-system (infrastructure) comparisons.

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NOMENCLATURE

Sets

i	stream	k	component

Subscripts/superscripts

abs	absorber	in	inlet
ahp	absorption heat pump	l	latent heat
comp	compressor	loss	losses from boiler
cond	condenser	out	outlet
ehp	electric heat pump	pp	pinch-point
evap	evaporator	s	sensible heat
fg	flue gas	sh	superheating
gen	generator	shx	solution heat exchanger

Symbols

A	area (m^2)	$\dot{m}$	mass flowrate [kg/s]
COP	coefficient of performance [-]	$\dot{n}$	molar flowrate [mol/s]
c_p	heat capacity [J/kg/K]	P	pressure [Pa]
ε	heat exchanger effectiveness [-]	$\dot{Q}$	heat transfer rate [W]
f	solution circulation ratio [-]	T	temperature [K]
h	enthalpy [J/kg]	ΔT_lm	log-mean temperature difference [K]
HV	hydrogen lower heating value [J/kg]	U	heat transfer coefficient [$W/m^2/K$]
η	isentropic efficiency [-]	$\dot{W}$	work output [W]
λ	excess air ratio [-]	x	mass fraction [-]

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