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Heat Pumps: The future of heating

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Heat pumps: The future of heating

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Abstract

Despite the many benefits that humanity has obtained by burning fossil fuels, the impact of the concomitant emissions of carbon dioxide has created a grave climate crisis. Responding to the need to drastically reduce emissions of carbon dioxide presents a massive challenge to all sectors of society. But having failed to respond to our first warnings, we now need to respond rapidly. Fortunately, we have technologies available which will allow us to respond on the scale required.

In recent years, the energy landscape has been transformed, with renewable generation technologies now being the cheapest way to make electricity. Wind and solar generation, used alongside conventional nuclear generation, make it possible to produce electricity with zero proximate emissions of carbon dioxide. By electrifying as many processes as possible, we can 'de-carbonise' processes that previously used fossil fuels. Applying this 'electrify everything' principle to heating, heat pumps offer us the chance to electrify – and hence de-carbonise – our heating in both domestic and industrial settings. The energy savings available are so large that the widespread use of heat pumps is inevitable.

1. Fire and Hot Water

We still teach the Greek myth of Prometheus who stole fire from the Gods and suffered an agonising and eternal punishment as his reward. And from a cultural perspective, the persistence of this myth reflects the significance of fire in every human civilisation.

There are many reasons why control of fire is considered culturally significant, but with regard to the interests of *Waterline's* readers, there are three reasons of especial significance. Historically, fire enabled us to heat our homes; to heat water for our homes; and to heat water for cooking and other processes. In the parlance of modern engineering, fire enabled space heating, and the production of both domestic hot water and process hot water.

In the modern world, fire (in boilers) is still widely used for these processes but is supplemented by electrical heating. However, since a significant fraction of electricity is still derived from burning things, there are still deep historical and technological links between fire and hot water.

But in recent years, the seeds of renewable energy technologies have grown into a nascent energy transformation. This represents a technological revolution of comparable significance to the first industrial revolution. In this transformation new technologies will replace old technologies not because they are 'greener', or represent a 'more moral choice', but rather because they are simply cheaper. Electricity generated using solar photovoltaic panels and wind turbines is the cheapest electricity that there has ever been. And eventually, both industrial and domestic habits of consumption will inevitably adapt to exploit the new patterns of availability of this cheaper resource.

So, as I write in 2023, not only is it now possible to heat water electrically without burning any fuel at all, but these renewable technologies have also become the cheapest way to heat water. And accompanying progress in these renewable *generation* technologies, heat pumps offer a way to dramatically reduce the cost of heating water even further. Depending on the temperature through which water is to be heated, the cost could fall by a factor somewhere between 2 and 5. So even as immersion heaters offer 100% efficient conversion of electrical energy into thermal energy, heat pumps offer efficiencies between 200% and 500%.

In this article I will look at *what* heat pumps do and *how* they do it (Section 3), and then look at some details of their design (Section 4). I will then (Section 5) describe a typical domestic installation of a heat pump and its role in space heating and the preparation of domestic hot water. I will then (Section 6) discuss the costs of a domestic heat pump installation. Finally (Section 7), I will briefly outline applications of heat pumps for process heating in different industrial sectors.

But before embarking on this journey, I hope you will please allow me to explain briefly why this matters as much as it does. In every audience I have addressed over recent years I have found that there are people who feel – despite the indisputable facts of the warming globe – that our climate crisis is a hoax of some sort and that – to quote our former Prime Minister – renewable technologies are just 'green crap'. This section is addressed to those people reading this who choose to disbelieve the overwhelming evidence of the harmful effects of carbon dioxide emissions and who apply to themselves the label: *'climate sceptic'*.

2. Why heat pump deployment is so important

The combustion of fossil fuels in air results in the inevitable emission of the gas carbon dioxide (CO$_2$). **Figure 1** on the next page shows the approximate amount of carbon dioxide in Earth's atmosphere measured in billions of tonnes – gigatons (Gt) – over the period 1750 to the present day. When the climate stabilised after the end of the last 'ice age' (~8,000 BCE), the atmospheric concentration of carbon dioxide stabilised at approximately 0.028% – which corresponds to roughly 2,000 Gt of atmospheric CO$_2$ and is shown as a horizontal dashed line.

The black line shows the original amount of CO$_2$ in the atmosphere plus an estimate of the cumulative amount of carbon dioxide emitted by human beings. Currently emissions are increasing at approximately 36 $GtCO_2$ per year, a trend shown as a dotted line. To appreciate the astonishing magnitude of these emissions, one might reflect that the rate of increase amounts to more than four tonnes of CO_2 emissions per year for each of the 8 billion people on Earth.

Of the CO_2 emitted into the atmosphere, within one year roughly half is removed by increased plant growth and absorption into the oceans, and so the residual amount of CO_2 in the atmosphere follows the trend in emissions but is rather lower. Currently, the amount of CO_2 in the atmosphere is around 3,000 Gt CO_2, a 50% increase over the pre-industrial quantity.

We have known about the effects of CO_2 on the surface temperature of the Earth since the pioneering investigations by John Tyndall in London in the 1850s [2]. Using an extraordinary apparatus (**Figure 2**), he investigated the transmission of visible and 'obscure' light – what we now call *infrared* light – through optically transparent gases. He was astonished to find that infrared transmission through air was dramatically affected by the presence of *tiny* amounts of water vapour and carbon dioxide. Considering its meteorological effects, he concluded: *"... the atmosphere admits of the entrance of the solar heat; but checks its exit, and the result is a tendency to accumulate heat at the surface."* In short, he had discovered what we now call the 'Greenhouse Effect'. When my father was born in 1914, the Greenhouse Effect warmed the Earth by approximately 33 °C: this figure is now a little more than 34 °C.

The warming effect of the CO_2 on the Earth's surface was first calculated quantitatively by Svante Arrhenius in 1897, who suggested that doubling the concentration of CO_2 would warm the surface temperature of the Earth by approximately 4 °C [3]. In 1937. Guy Callendar detected the early warming and re-calculated the effect of doubling CO_2 concentration as being approximately 1.5 °C [4, 5]. Both these authors looked upon global warming as a curiosity: an interesting phenomenon with minor, largely beneficial, effects.

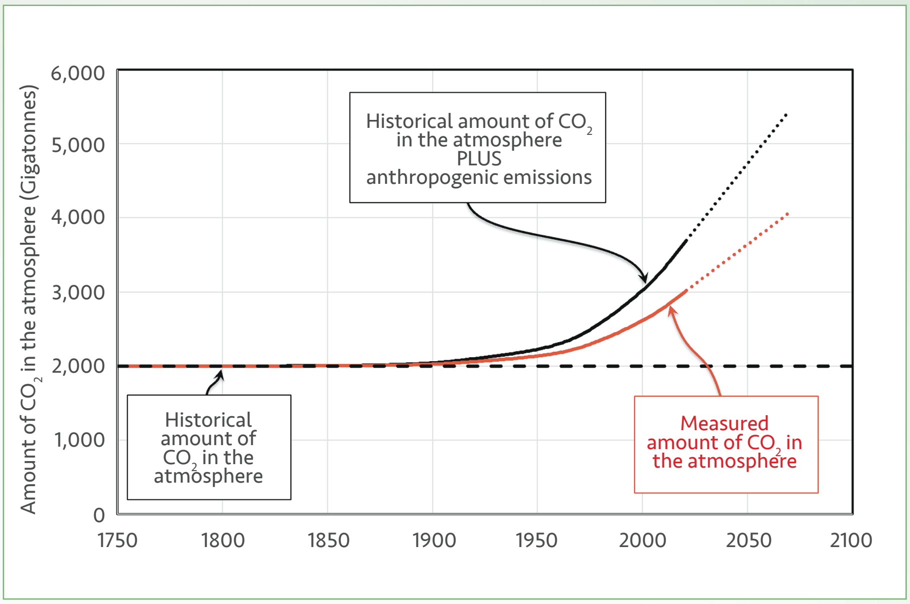


Figure 1: *Estimate of the amount of carbon dioxide in the Earth's atmosphere from 1750 to the present day and beyond. [1]*

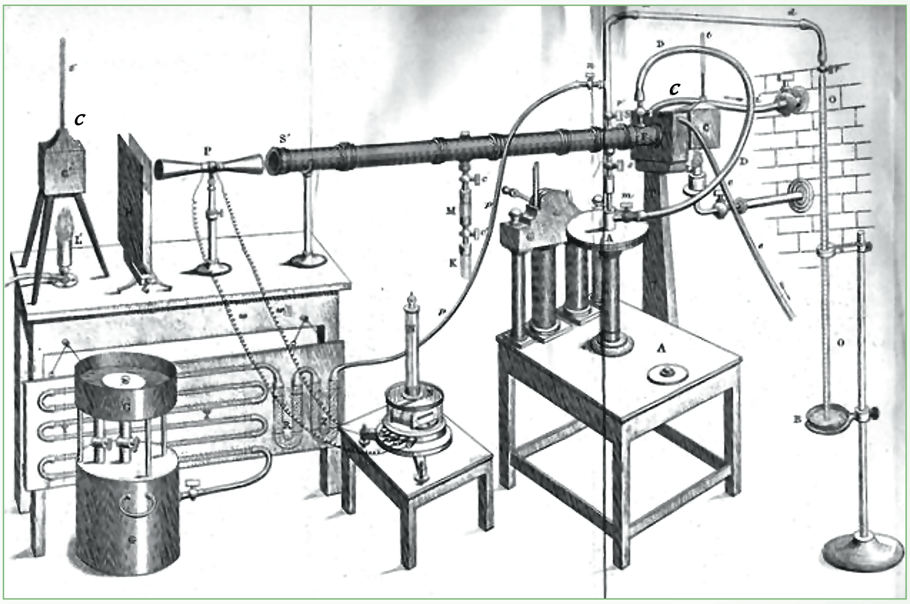


Figure 2: *The apparatus used by John Tyndall to investigate the transmission of infrared light through air and other gases and vapours. A heated, blackened surface (labelled C) emits infrared light into a long tube containing the gas under investigation. The ends of the tubes are sealed with windows made of large single crystals of salt – glass does transmit infrared light. The infrared light emerges into thermopile P whose reading is offset by infrared light from second heated surface C'. [Ref Tyndall]*

It was not until the 1980's that the first serious warnings of the negative effects of increasing CO_2 concentration emerged, and the establishment of the *Intergovernmental Panel on Climate Change* (IPCC) in 1988 stimulated more sophisticated calculations of the likely effect of doubling CO_2. The latest estimate in the *IPCC 6th Assessment Report* is 3.5 °C with an uncertainty of ± 1.8 °C [6]. This is striking: the modern estimate considers many effects that were ignored by Arrhenius and Callendar, and yet the estimated warming is similar. This suggests that the calculations of Arrhenius and Callendar had captured the essential physics of the problem.

The IPCC have dire warnings of the effect of a 3 °C change in the average temperature of the Earth's surface and warn that it is essential to reduce emissions to zero in order to stabilise the atmospheric concentration of CO$_2$. If we manage to achieve zero emissions, then – providing we have not passed any critical tipping points – Earth's temperature is expected to stabilise, but it will not cool. Sadly, the climate we grew up in is gone forever.

In 2022, domestic heating was responsible for about 17% of total UK emissions [7], so finding ways of heating our homes without emitting carbon dioxide is a significant but essential challenge. Ideally the solution would be not only environmentally superior, but also technologically superior, resulting in lower operating costs as well as lower associated carbon dioxide emissions. This is what heat pumps provide.

Using heat pumps to provide domestic heating allows us to de-carbonise this sector with the least possible amount of renewable or nuclear generation. Installed as a replacement for a gas boiler, a heat pump can deliver exactly the same amount of heat, but reduce emissions from typically 2.8 tonnes per dwelling per year to just 0.8 tonnes per dwelling per year, a 70% reduction. And as the electric grid becomes greener in coming years these emissions will be reduced still further. This scale of reductions is what we need in order to avoid warming the planet even further, and no other technology can achieve this as rapidly or as cheaply.

3. Heat Pumps: What heat pumps do & how they do it

There is a fundamental difference between heating with heat pumps and heating with electrical or gas boilers. Boilers and electrical heaters *convert energy* from *one form to another*. For example, a boiler converts *chemical energy* stored in a fuel to heat energy and an electrical heater converts *electrical energy* to heat energy. In contrast, heat pumps *move thermal energy from one place to another.*

There are many heat pump designs adapted to where they gather heat from, and where they deliver it to. Air source heat pumps (ASHPs) gather heat from environmental air and transfer it either to internal air (an Air-to-Air heat pump) or to water (an Air-to-Water heat pump). Ground source heat pumps (GSHPs) gather heat from coolant flowing through underground coils and typically transfer this to water in a heating system (a Ground-to-Water heat pump). In the UK, the most common heat pump types are Air-to-Water (**Figure 3**) and Air-to-Air.

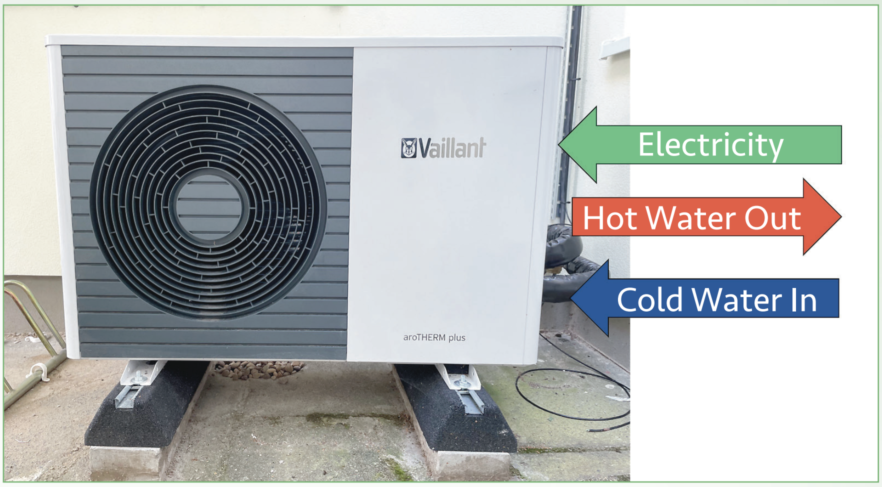


Figure 3: *Photograph of a monobloc Air Source Heat Pump (ASHP). Monobloc means that the working fluid and all associated heat exchangers are contained within a single box. This is means it can be installed without the special skills of a licenced F-gas installer. Typically, there are just four connections: a cold-water inlet; a hot-water outlet; an electrical power connection; and some electrical control wires.*

Air-to-Water heat pumps extract heat from air outside a residence and use it to heat water for space heating via under-floor heating or radiators, and for domestic hot water. In many cases these devices can be used to straightforwardly replace a gas boiler. Air-to-Air heat pumps – also known as air conditioners (AC) – are widely used in commercial premises for both heating and cooling. When used for heating, these devices extract heat from outside air like Air-to-Water heat pumps, but transfer this heat to fan-blown air in interior fan-coil units.

There are three essential components of any heat pump: a *compressor,* a *flow restriction,* and a *working fluid*. Additionally, a heat pump has two heat exchangers which transfer heat to and from the internal working fluid. The working fluid – sometimes called a *refrigerant* – is selected so that on pressurisation by the compressor, the fluid is heated – typically to 50 °C – but when squeezed through the flow restriction, the fluid cools – typically to -20 °C.

The heat pump extracts heat from the environment by blowing environmental air (perhaps at 0 °C) over an air-to-liquid heat exchanger – a labyrinthine arrangement of tubes containing working fluid (perhaps at –20 °C). Because the air is warmer than the working fluid, heat is extracted from the air (cooling it by typically 3 °C) and captured in the working fluid.

On compression, the working fluid is heated to perhaps 50 °C and then passed through a liquid-to-liquid heat exchanger where the heat is transferred to pipes carrying domestic hot water at typically 40 °C. Because the working fluid is warmer than the water, heat flows from the working fluid into the water.

The net effect of these processes is that as working fluid flows around its closed circuit, heat is extracted from the air and transferred to the water.

The amount heat energy delivered to the household water divided by the electrical energy used to power the compressor is called the *Coefficient of Performance* (COP) and has a typical value of around 3 i.e. the heat pump delivers 3 times more heating than the electrical energy it consumes. This is the key attraction of heat pumps. It is important to note that the extra heat delivered by the heat pump has not been created, it has simply been *moved* from a colder place to a hotter place.

When first encountered, the idea that any heating device can be more than 100% efficient, or that it can move heat from cold places to hot places strikes many people as being impossible. But this is just a matter of unfamiliarity. Heat pumps play a key

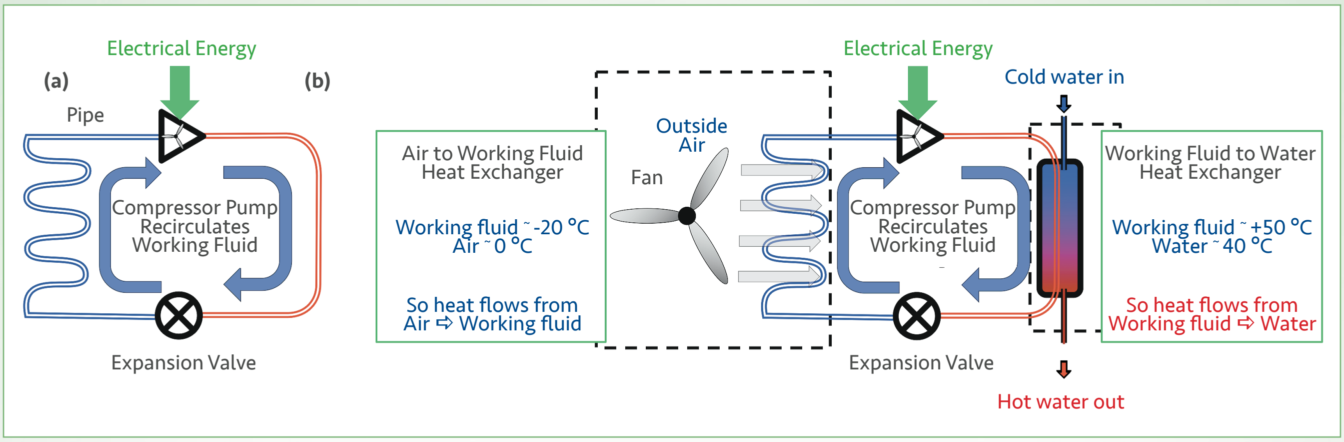


Figure 4: *A schematic illustration of the functioning of an air source heat pump. (a) A simplified picture and (b) a more complex picture. (a) Essentially a heat pump is a pipe containing a specially-chosen working fluid. A compressor pump recirculates the working fluid, and a flow restriction known as an expansion valve restricts the circulation. This establishes a high-pressure hot region and low-pressure cold region. (b) shows the features in (a) but adds details of the two heat exchangers which allow the heat pump to gather heat from its environment and deliver it to the domestic hot water.*

role in modern lives but are often not recognised because different names are used to describe the technology in different applications. For example, refrigerators are simply a different application of the same underlying heat pump technology.

After a little exposure, the idea that mechanical device can 'pump heat uphill' against its natural tendency to flow 'downhill' from hotter to colder, is no odder than the idea that a mechanical device can pump water 'uphill' against its natural tendency to flow 'downhill'.

4. Heat Pumps: More details

The key technology that enables high COP values in heat pumps is the *vapour compression cycle* that I described briefly in the previous section. This technology enables the cold source of heat to be physically separated from the hot heat-delivery part of the pump, which allows for very effective pumping. But the efficiency of heat pumps is limited by the laws of thermodynamics (ultimately) and also by the more practical considerations.

In particular, increasing the temperature difference between the cold source and the hot end reduces the maximum COP.

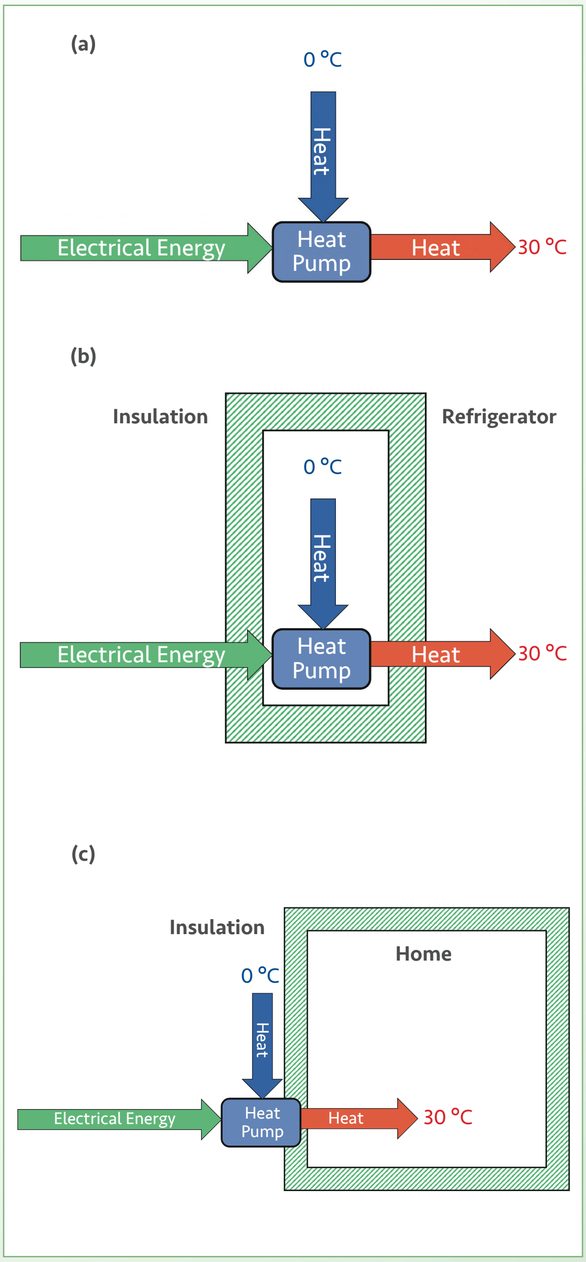
Additionally, the maximum temperature of the heat delivery and the minimum temperature of heat collection are limited by the thermophysical properties of the working fluid. To operate efficiently the working fluid should be a liquid in

Figure 5: Heat Pump Technology.

(a) A heat pump moves heat from a region at a lower temperature and moves it to a region at a higher temperature.

(b) In a domestic refrigerator insulation is placed around the cold end of the heat pump and the internal temperature is maintained below the level of the environment.

(c) In an Air Source Heat Pump (ASHP) insulation is placed around a dwelling at the hot end of a heat pump and its internal temperature is maintained above the level of the environment.



the cold section of the heat pump and capture heat by *evaporating* rather than by simply warming up. The heat is then captured in the so-called *latent heat of evaporation* of the working fluid. This dramatically improves heat transfer in the cold heat-exchanger which is thus known as the *evaporator*. When the working fluid (as a vapour) is subsequently compressed, the fluid condenses releasing the latent heat captured at the cold end. This dramatically improves heat transfer in the hot heat-exchanger which is thus known as the *condenser*.

Historically working fluids have consisted of fluorinated hydrocarbons – substances which if released into the atmosphere have a global warming potential hundreds or thousands of times worse weight-for-weight than carbon dioxide. More recent developments have focussed on using propane (R290) and carbon dioxide (R744) as working fluids, both of which are relatively benign if released. Although technically more difficult to use, these working fluids have the additional benefit of allowing heat delivery at temperatures up to 70 °C.

The maximum amount of heat that can be delivered by a heat pump is perhaps its most important specification. The maximum amount of heat that can be delivered will be needed when the outside temperature is lowest – and it is in these circumstances that the COP is lowest (**Figure 6**).

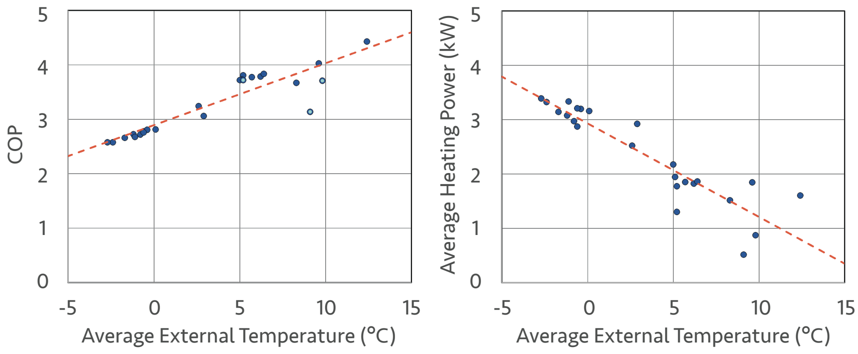


Figure 6: *Data from the author's home in December 2022 showing daily averages of (left) COP and (right) heating power versus the average external temperature. During this period the internal temperature was kept constant at 20 °C. The heating power (right) is seen to increase as the outside temperature falls, reaching a peak of approximately 3.5 kW when the average external temperature fell to approximately -3 °C. At the lowest temperatures, the COP (right) fell to approximately 2.5 compared with a COP of 4 when the external temperature was ~ 10 °C. This means that at the lowest temperatures 3.5 kW of heating was provided by 3.5/2.5 = 1.4 kW of electrical power.*

Figure 7: *Heat Exchanger size versus heat pump power. If we wish to harvest heat from air at a greater rate, it is necessary to have physically larger heat exchangers. The graphic shows a range of heat pumps from Vaillant and their maximum rates of heat delivery. Heat pumps of all manufacturers are of a similar size.*

The heat delivered to a dwelling is captured in the latent heat of evaporation of the working fluid. So, *the amount of working fluid* and its rate of circulation must be sufficient to deliver this power. But in most circumstances the power is limited by the *amount of air* which can be drawn over the cold heat exchanger. For example, to capture 3.3 kW of heat at 0 °C requires an air flow through the heat exchanger of approximately 0.9 cubic metres of air per second, with the air being cooled by 3.5 °C. For domestic installations it is essential to minimise noise, which arises primarily from vortices generated at the tips of the rotating fan blades. Thus in order to maintain quiet operation, the rotational speed of the fan must be kept low. Thus a heat pump with a higher power requires heat exchangers with physically larger areas (**Figure 7**).

5. Heat Pumps: In a domestic setting

Heat pumps in UK domestic installations are now most commonly of so-called *monobloc* construction. In this design the working fluid, compressor and heat exchangers are contained in a single external unit (**Figure 3**) with just four connections: a cold-water inlet; a hot-water outlet; an electrical power connection; and a data connection.

From a householder's perspective, heat pumps work similarly to a gas boiler – heating water in a closed circuit and either circulating it around radiators to provide space heating, or through a heat exchanger in a storage cylinder to provide domestic hot water. However, the heating characteristics of a heat pump are quite different from those of a boiler in three key ways: *heating power: heating flow rate: and heating flow temperature.*

Heating Power (kW): A domestic gas boiler has a typical power of between 20 kW and 30 kW – far in excess of the maximum rate of heat loss from a typical UK home which is around 7 kW. Gas boilers can modulate their heat output to some extent, but typically cycle on and off frequently. In contrast, the maximum heating power of a

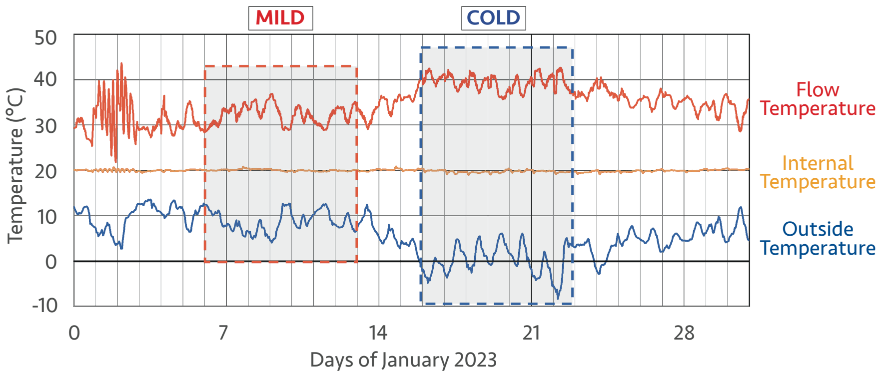


Figure 8: *Graph showing the outside temperature, internal temperature, and flow temperature in the radiators in the author's home during January 2023. Notice that throughout the month the Internal Temperature is maintained close to 20 °C. When the external temperature falls, increasing heating demand, the so-called weather compensation control increases the temperature of the water flowing in the radiators. See text for a detailed description.*

heat pump is chosen to match the maximum heat loss of the dwelling which is typically in the range 5 kW to 10 kW when the exterior temperature is -3 °C. Heat Pumps are designed to operate *continuously* using weather compensation (**Figure 8**) to adjust their heating output to match the heat loss from the house. For a dwelling in the southern half of the UK which uses gas for both space heating and domestic hot water one may guesstimate the required maximum heating power (in kW) from a year's consumption of gas (in kWh) by dividing by approximately 2,900 [8]. For example, if annual gas consumption was 15,000 kWh, one may estimate that a heat pump with an output power of 5.2 kW would be required.

Heating Flow (l/hr): The heating circuit for a gas central heating installation is typically set to return water to the boiler approximately 10 °C colder than the water leaving the boiler. Heat pumps operate more efficiently when this return temperature is only 5 °C colder than the water leaving the heat pump. This requires a heat pump to circulate water through the radiators at twice the rate of an equivalent gas installation. For most installations this is not problematic, but in some cases, it may be necessary to install a so-called *Low-Loss Header* with an additional hydraulic pump.

Heating Flow Temperature (°C): Gas boilers can heat water to 70 °C with little difficulty and modern heat pumps can also recirculate water at 70 °C, but doing so will reduce the COP for the heat pump. In order to maximise the COP – and thus minimise the energy required to provide a given level of heating – heat pump installations focus on delivering the required heating power with water flowing at lower temperatures. At lower flow temperatures, the efficiency of radiators is reduced and so when switching from a gas boiler to a heat pump it is sometimes necessary to replace some radiators. [9].

The differences in these three 'hydronic' characteristics (*heating power: heating flow rate:* and *heating flow temperature*) make the installation of a heat pump more technically challenging than the installation of a gas boiler. In order to ensure that a heat pump will be able to provide sufficient heat at lowest temperature it is essential to conduct a heat-loss survey to estimate the heating power required in each room at the lowest likely exterior temperature.

Figure 8 shows data on my own home during the month of January 2023. The graph shows the internal temperature in the house barely deviates from 20 °C throughout the month. This is typical of the steady heating at which heat pumps excel. The graph highlights a 'mild spell' of typical UK winter temperatures (with exterior temperatures ~10 °C) and a 'cold spell' (with exterior temperatures ~0 °C). In the mild spell, the weather compensation system met the heating demand by flowing water through the radiators with an average temperature of approximately 33 °C. In the cold weather the average flow temperature was increased to 40 °C. The average COP during the mild spell was 3.9 and during the cold spell was 2.8. Over the entire winter, the seasonally averaged COP (SCOP) was 3.5.

Domestic Hot Water (DHW) is supplied by intermittently interrupting space-heating duty and diverting the heat pump flow through a heat-exchanging coil inside a DHW cylinder. In older heat pumps, to exceed a hot water temperature of 50 °C required the use of an auxiliary immersion heater, but in modern heat

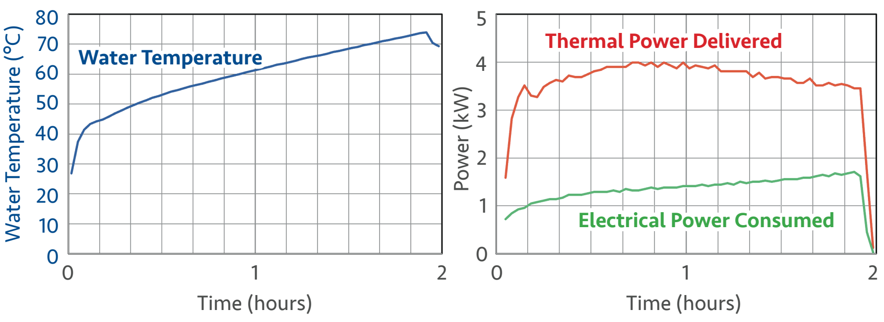


Figure 9: *Graphs showing how various quantities vary during the course of a 2-hour anti-Legionella heating cycle. The left-hand graph shows water temperature in °C and the right-hand graph shows power in kW. One can see that the electrical power is approximately 1.5 kW, while the heating power delivered is over 3.5 kW. Note that the water temperature rises to more than 70 °C without the use of an auxiliary immersion heater.*

pumps, temperatures up to 70 °C are possible without such assistance (**Figure 9**).

My appreciation of the hazards of *Legionella* infection is much less than those of *Waterline's* readers, but my general understanding is that in most circumstances, a DHW temperature of 50 °C is sufficient to prevent growth of *Legionella*. To kill *Legionella*, heat pump systems typically include a weekly Anti-Legionella cycle which heats the cylinder to 60 °C.

So far I have discussed Air-to-Water heat pumps that are suitable for boiler replacement in most UK houses. But many people live in apartments which may not be immediately suitable for Air-to-Water heat pumps. There are many heat-pump solutions depending on whether we consider heating dwellings individually or communally.

If we consider dwellings individually, many apartments are well-suited for air-to-air heat pumps, commonly sold as 'air conditioning'. These are nothing more than heat pumps with heat exchangers optimised for direct heating of internal air. These are not *monobloc* designs and the working fluid flows around a circuit which includes the external air-handling unit and typically up to five internal so-called fan-coil units. These devices have outstanding COP performance for heating – commonly over 4 – and also offer comfort cooling in summer, a feature which is likely to be of increasing importance.

For domestic hot water, heat pump solutions are likely to take up too much space for easy installation in most apartments. But hot water can be made available by using cheap-rate electricity to store heat in phase-change storage devices [10]. These devices can store heat at twice the density of a standard DHW cylinder, and are available in a convenient cubical rather than cylindrical form-factor. In operation, the solid phase-change material is heated to typically 55 °C where it transforms to a liquid. When cold water passes through pipes embedded in the material, the liquid freezes releasing latent heat which rapidly heats the water to typically 45 °C. By avoiding storing water at elevated temperatures, the risk of *Legionella* growth is reduced.

If we consider dwellings communally, then there are many opportunities for heat pump heating. Given the smaller areas available in urban settings, the heat source would typically be a number of boreholes drilled near to the apartments, with a typical 20 m deep borehole being able to extract around 6 kW of heat. One of the advantages of extracting heat from underground is that at depths below 2 metres, the temperature of the earth changes very little during winter. So on the coldest days – when air-source heat pumps must extract heat from very cold air – ground source heat pumps have an advantage.

In suitable locations other sources of low temperature heat can also be used as a heat source. For example, an installation at Kingston upon-Thames extracts heat from water in the Thames and returns it to the river up to 3 °C cooler. This provides up to 2.3 MW of heating, sufficient for 56 homes, 81 apartments and 145 hotel rooms [9]. Or alternatively, the Bunhill facility in Islington heats local homes by upgrading waste heat from the London Underground system [10].

6. Heat Pumps: Cost versus Gas

One of the common objections to heat pumps is that they are more expensive than gas boilers. And if one considers the hardware and installations costs alone this is correct. A gas boiler installation might cost perhaps £3,000 while an air-source heat pump installation would be more typically £13,000, or £8,000 after the current government subsidy. Additionally, at August 2023 prices, a kWh of electricity costs almost 4 times the cost of a kWh of gas, so running a heat pump installation with a COP of 4 is likely to be only slightly cheaper than a gas boiler. For people with limited capital, there is little financial incentive to switch.

However, for a typical household a gas boiler might easily be the largest single source of CO_2 emissions. And as I explained in Section 2, emitting CO_2 is causing the temperature of the Earth to rise. If one were to consider the ongoing and continuing costs of the droughts, wildfires, crop failures, sea level rise, and extreme weather events arising from CO_2 emissions, then the balance of costs would differ substantially. There is simply no way to substantially reduce emissions using gas boilers.

The gas industry advocate [13] the use of hydrogen gas instead of natural gas (methane) for home heating. They suggest this might be a way in which we could continue to burn gas in our homes in relatively familiar appliances. They argue that the cost of a hydrogen-burning boiler would be only slightly more than the cost of an existing boiler, and certainly less than the cost of a heat pump. While correct, this argument does not consider the cost of building the plant to generate the hydrogen.

To understand the magnitude of the cost of a hydrogen-based heating system for the UK, I invite you to first imagine a hypothetical future in which renewable energy is plentiful and able to supply the *average* winter UK heating demand of approximately 70 GW. To do this wind turbines (mainly) and nuclear power stations would generate 26 GW of electricity which would be turned into 70 GW of heating by heat pumps with a COP of 3. Deploying renewable generation and heat pumps on this scale would represent a significant national challenge.

If we wished to similarly supply 70 GW of heating with renewably-generated hydrogen (so-called 'green' hydrogen), we would need approximately *six times the generation capacity* of a heat-pump-based solution i.e. around 150 GW of electricity generation. Approximately 50% of this generation would then be immediately wasted during AC/DC conversion (5%), Electrolysis (25%), Gas Compression (10%), Gas Transmission (10%) and combustion (10%). I estimate that the capital cost of this massive generation is close to £100,000 per household, which of course would have to be paid for eventually [14]. Such an approach would also create a decades-long delay in even *beginning* to respond to our urgent need to reduce emissions. Developing hydrogen technologies for energy storage and chemical applications will be a key part of the energy transition, but using hydrogen gas for home heating would be enormously wasteful and costly.

In short, heat pumps are not as cheap as one might wish, but they are the only practical and sustainable solution to the problem of heating our homes without emitting carbon dioxide. And if we choose to follow this path, the problem of the cost per individual household is not insurmountable: deployment of heat pumps is widespread throughout northern Europe.

On a personal note, I feel obliged to add that my own gas-free home is extremely cheap to heat. In winter I use a domestic battery to download cheap-rate electricity at night and then run the heat pump from the battery during the day. Combining this with electricity from solar panels means in 2022 I was able to power and heat my 160 m^2 house for less than £400/year i.e. about £33/month.

7. Heat Pumps in industry

Process heating is a significant cost for a wide range of industries, and historically the cheapest way to provide that heat has been through burning gas. Heat pumps are set to change this, providing cost reductions while simultaneously reducing associated carbon dioxide emissions. A 2021 estimate of the market for industrial heat pumps identified the largest potential as being in the chemical, food, refining and paper industries [15].

These four sectors have two things in common: the first is that they use process heating up to 200 °C; and the second is that they also generate prolific amounts of 'waste heat' that is currently dissipated into the environment. The waste heat is typically embodied in a fluid at temperatures below 100 °C, and the action of a heat pump is to extract heat from the waste stream and transfer it to another fluid at a higher temperature. suitable for process applications.

As with domestic heat pumps, there are limitations such that typically 'upgrading' heat by more than 100 °C is unlikely to be economical – the investment cost is unlikely to justify the savings because of the reduced COP when pumping heat across this large temperature differential. And the heat pump supply market is still developing. Heat pumps operating up to 90 °C at megawatt scale can be readily purchased, but heat pumps with upper temperatures extended to 160 °C still require custom design. Heat pumps operating up to 200 °C do not yet exist outside laboratories.

Despite these limitations, the heat pump transformation has already begun. I am not in a position to comment authoritatively on this field, but skimming the web I find multiple reports [16, 17] of the use of heat pumps in chocolate manufacturing. The revised process uses waste heat from the necessary cooling systems to power the modest 60 °C heating requirements. A similar trick can be used to upgrade waste heat from a data centre to pasteurise milk at 85 °C. [17].

Even in apparently inaccessible processes such as brick manufacturing, the waste heat from the kilns can be captured by a high-temperature heat pump that dries out bricks before firing. If the savings are sufficient, a gas fired kiln can be replaced by an electric kiln which can in principle be powered with renewably generated electricity rather than gas.

Deutche Welle [17] notably reported that multinational chemical company BASF are planning to install a heat pump with an output of 120 MW at their main plant in Ludwigshafen. The pump would use waste heat from the factory's cooling water to produce up to 150 tons of steam per hour. And international food group AGRANA is already using a high-temperature heat pump to extract water from wheat starch at up to 160 °C, with the dry powder being used in the food industry as a binding and thickening agent.

8. Summary

Despite the many benefits that humanity has obtained by burning fossil fuels, the impact of the concomitant emissions of carbon dioxide has created a grave climate crisis. Responding to the need to drastically reduce emissions of carbon dioxide presents a massive challenge to all sectors of society. But having failed to respond to our first warnings, we now need to respond rapidly. Fortunately, we have technologies available which will allow us to respond on the scale required.

In recent years, the energy landscape has been transformed, with renewable generation technologies now being the cheapest way to make electricity. Wind and solar generation, used alongside conventional nuclear generation, make it possible to produce electricity with zero proximate emissions of carbon dioxide. By electrifying as many processes as possible, we can 'de-carbonise' processes that previously used fossil fuels. Applying this *'electrify everything'* principle to heating, heat pumps offer us the chance to electrify – and hence de-carbonise – our heating in both domestic and industrial settings. The energy savings available are so large that the widespread use of heat pumps is inevitable.

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