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REVIEW

A review of domestic heat pumps

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Heat pumps are a promising technology for heating (and cooling) domestic buildings that provide exceptionally high efficiencies compared with fossil fuel combustion. There are in the region of a billion heat pumps in use world-wide, but despite their maturity they are a relatively new technology to many regions. This article gives an overview of the state-of-the-art technologies and the practical issues faced when installing and operating them. It focuses on the performance obtained in real-world operation, surveying the published efficiency figures for hundreds of air source and ground source heat pumps (ASHP and GSHP), and presenting a method to relate these to results from recent UK and German field trials. It also covers commercial aspects of the technologies, the typical savings in primary energy usage, carbon dioxide emissions abatement that can be realised, and wider implications of their uptake.

1. Introduction

Heat pumps are most commonly encountered in refrigerators and air conditioning units. In both cases they use electricity to remove heat from a cold location and pump it to a warmer one, providing the ideal temperature for food or people. They are able to provide heating as well as cooling by operating in reverse: extracting ambient heat from the relatively cold environment and upgrading its temperature for space and water heating. Although they require potentially high-cost and high-carbon electricity to operate, the majority of the energy harnessed is 'renewable' heat drawn from the environment. This heat is gained through sunlight, and so is zero carbon and virtually limitless.

Fig. 1a demonstrates how this makes heat pumps a very efficient form of heating. A typical system can produce 15 MW h of space and water heating from around 5 MW h of electricity, which in turn would be generated from around 13 MW h of primary energy in the form of coal, natural gas, uranium, *etc.* This gives a primary energy utilisation of greater than 1, as more heat is recovered from the environment than is wasted in generating the electricity for heating. When compared to the common alternative of a condensing boiler or furnace (as in Fig. 2), heat pumps can reduce primary energy consumption in the home by 15–50%.

The first functioning heat pump was built in 1856 based on the work of Carnot and Kelvin, but it was not until the 1930s that practical models began to be developed.[1] By the 1950s, heat pumps and reversible air conditioners had taken off in the US and Japan, driven by seasonal demands for air conditioning and space heating. As with the internal combustion engine,

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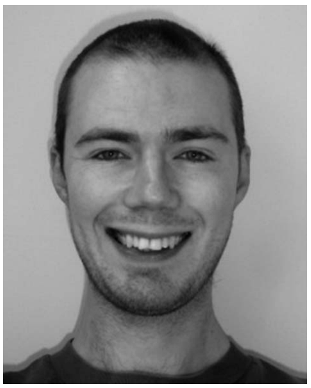
Broader context

Heat pumps have the potential to radically improve the domestic heating sector around the world. By combining high efficiency with (potentially) clean electricity, their widespread usage could cut global CO_2 emissions by a formidable 8% (1.8 GT annually), and allow future improvements in electricity generation to spill-over into the heating sector, magnifying national reductions to fuel imports and the overall cost of energy services. These benefits rely upon heat pumps operating to their full potential, which is only possible if they are adequately sized according to individual properties, installed according to best practices, and then operated correctly. This article addresses the lack of published material which critically reviews and analyses these vital issues. We examine the main technologies, their installation and operation, and review results from a survey of manufacturers and recent large-scale field trials. This work is a particularly useful resource for those considering the applicability of heat pump technologies to residential applications from both a technological and economic perspective, and helps to define the position of heat pumps within the portfolio of emerging microgeneration technologies.

the basic design has remained the same for nearly a century, undergoing gradual evolution to improve efficiency and comfort levels.[2]

Specific aspects of heat pump technology have been the subject of several previous works, for example: Omer[3] and Florides and Kalogirou[4] review the many configurations of geothermal heat pump systems, while Melinder's handbook[5] covers many aspects of system design and operation. Chua *et al.*[6] focus on recent component-level improvements and novel system designs, and Nekså[7] reviews CO_2 as a promising new refrigerant. Ozgener and Hepbasli[8] and Hepbasli *et al.*[9] review the applications of solar assisted and gas engine heat pumps, as well as heat pump water heaters.[10] Air conditioning units (*i.e.* heat pumps used only for cooling) are more mature, and so are the subject of many comprehensive textbooks.[11–13]

This paper reviews the use of heat pumps for domestic heating, an area where they offer substantial benefits, but face strong competition from fossil-fired incumbent systems. The following sections describe the technologies that can be used, their practical operation and durability; economic considerations (capital, installation and running costs); their performance, how it is measured, the factors influencing it, and how it can be simply estimated; and wider implications such as primary energy consumption and CO_2 savings, and their potential to act as low-cost electricity storage through demand-side management.



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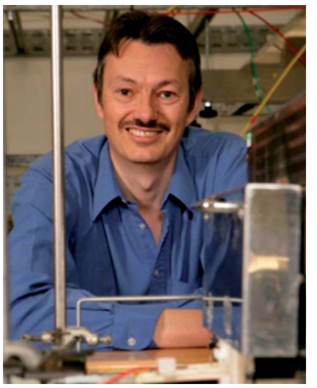

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Adam Hawkes

Dr Adam Hawkes holds a PhD in modelling energy systems for economic, environmental and policy assessment. He has developed a body of research on energy system change, distinguished by the characteristic that it considers decentralised technologies and the demand-side of the energy system as the driver of change. He has led research on small-scale energy systems for a decade focusing on technical systems, infrastructure, policy, economics and environmental impacts. Adam is a Subtask Leader in the IEA Annex 54 on Assessment of Microgeneration. He has developed new approaches and tools to study energy system change using optimisation and engineering-economic simulation techniques.

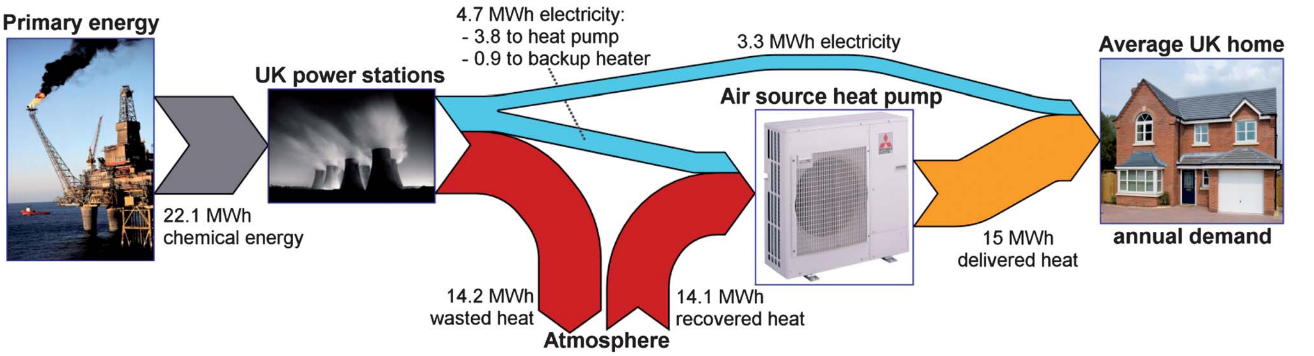


Fig. 1 A Sankey diagram showing the flows of energy required to heat and power a typical house for a year using a heat pump. Arrows denote the transfer of energy from one system to another, and their thickness is proportional to the amount of energy, based on representative UK data.[14]

2. Physical description

The underlying principle of a heat pump's operation is the reverse of a heat engine: using mechanical work to move heat against its natural gradient from a cold location to a hotter one, *e.g.* from outdoors into the home. A refrigerant fluid such as compressed CO_2 or an 'ozone-friendly' hydrofluorocarbon (HFC) is used to transport this heat, exploiting the physical properties of evaporation and condensation.

Fig. 3 depicts the four main components of a heat pump system:

(1) a compressor unit, which increases the pressure of the refrigerant and thus its temperature, making cool ambient heat into a useful commodity;

(2) an internal heat exchanger, or condenser, which distributes heat to the home or to hot water;

(3) an expansion valve to return the refrigerant back to below ambient temperature;

(4) an external heat exchanger, or evaporator, which collects heat from the environment.

Most heat pumps are capable of doubling up as air conditioners by reversing the direction of refrigerant flow. This swaps the roles of the two heat exchangers, drawing heat out of the home and expelling it to the atmosphere. This could be represented in Fig. 3 by reversing the arrows and swapping labels 2 and 4: hot refrigerant would be pumped outside, then expanded to a lower temperature in order to cool the home.

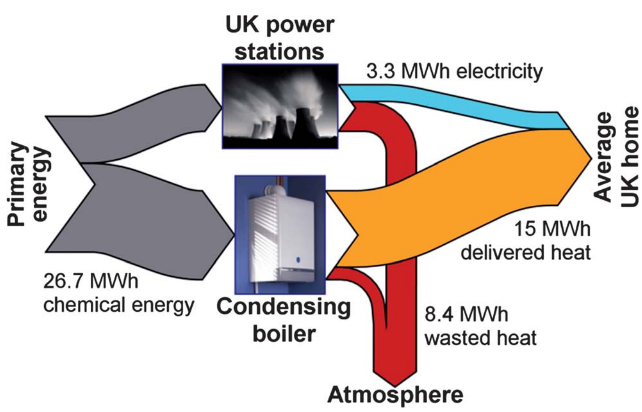


Fig. 2 A Sankey diagram depicting the provision of energy to the same house using a high efficiency condensing gas boiler.

According to the second law of thermodynamics, heat cannot be spontaneously transferred from a colder location to a hotter location without work from an external energy source being applied to the system. The thermodynamics of the ideal vapour-compression cycle is summarised in Fig. 4, which represents the change in temperature and entropy that occurs during the cycle. The area to the left of the bell-shaped curve represents the liquid only phase, vapour lies to the right, and under the curve is a two-phase mixture of liquid and vapour.

In process 1 (which corresponds to item 1 in Fig. 3), the working fluid in the dry vapour phase (A) undergoes isentropic compression, heating the gas to a superheated state (B). This is associated with the introduction of work to the system in the form of electrical power *via* the compressor. Process 2 first involves removing the superheat (B–C) and then the heat of condensation (C–D). This occurs at constant pressure and is where heat is harvested and delivered to the hotter location. The now liquid working fluid then goes through an expansion valve (3) where its pressure abruptly decreases, causing evaporation with associated absorption of heat from the low temperature reservoir. The liquid–vapour mixture is then completely vaporised by heat input from the cooler environment (4), returning the working fluid to a dry vapour.

Fig. 4 represents the ideal cycle; in practice frictional pressure drop, thermodynamic irreversibility during compression, non-ideal gas behaviour and the finite temperature difference across heat exchangers cause the cycle to depart from this ideal, and reduce the ratio of heat out to heat plus work in.

The compressor is the most significant component in terms of size, cost and energy consumption. The most basic heat pumps feature a fixed-speed reciprocating compressor which can only operate at full power, and so must regularly switch on and off in order to maintain a given internal temperature. These repeated start-ups and shut-downs inflict an energy penalty on the system that can reduce efficiency (although they can be beneficial to geothermal heat pumps),[15] and can lead the pump to overshoot the desired room temperature (or undershoot when cooling). The high compression ratio and inability to modulate outlet temperatures (reducing them when heating demand is mild) also reduce the performance of single-speed heat pumps.[6]

This basic design has undergone successive refinements with the introduction of scroll, screw, rotary vane, two-stage and fully modulating inverter driven compressors,[6] which have led to

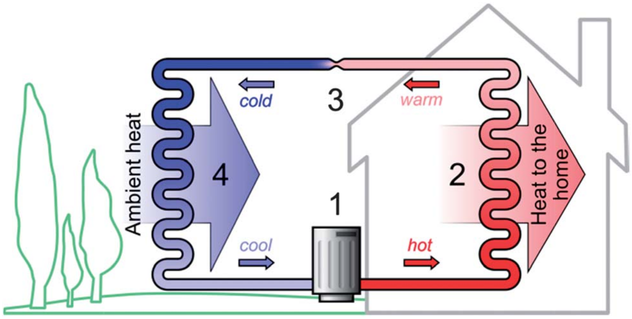


Fig. 3 Schematic of the vapour–compression refrigeration cycle used by heat pumps.

efficiencies improving consistently by 1% per year over the last two decades.[16]

Premium models in the US favour using a two-stage, or two separate compressors. This enables the system to run at two speeds, and so reduces the number of on–off cycles by running at low speed (around $^2/_3$ power) for the majority of the time, switching to full speed only for the coldest (or hottest) days of the year. This design improves efficiency by around 5–10% over fixed-speed models, at the expense of increased physical size and cost.[17,18]

Inverter driven (modulating) compressors became common in Japan in the 1990s, and improved both efficiency and comfort levels further by enabling the compressor speed to be varied smoothly.[19] This gives them the ability to reduce power output to any desired level, and thus precisely control outlet temperatures. Inverter models boast energy savings of 30–45% compared to fixed-speed models, but come with a similar cost premium.[20]

2.1 Air source heat pumps

Heat pumps are divided into two main categories based on the placement of the outside heat exchanger; either drawing heat from the air or from below ground. Air source heat pumps (ASHPs) are a familiar sight in many countries, using a small external ground or wall-mounted unit such as those pictured in Fig. 5. These are easy to retrofit into existing houses, and are practical in high-density urban areas with little surrounding land.

ASHPs come in two varieties: air-to-air and air-to-water systems. The first of these directly heats the air of a room using a slim wall-mounted box. Multi-split systems allow more than one indoor unit to be connected to a single compressor, allowing up to four rooms to be heated. This can become an expensive option in larger buildings as an indoor unit is necessary in every room that requires heating. Most air-to-air heat pumps are classed as reversible air conditioning units, as they perform both heating and cooling.

Air-to-water systems are instead integrated into a hydronic (water-based) central heating system to provide whole-house heating plus hot water. In addition to the outdoor compressor (Fig. 5), split systems require a compact heat exchanger and control unit located next to the hot-water cylinder to transfer heat from the heat pump's refrigerant. Mono-block (or mono-bloc) systems integrate these units with the compressor, giving a slightly larger outdoor unit. Air-to-water systems are common in Northern Europe due to the prevalence of water-based central heating, but are also popular in Japan as standalone water heaters.

Air-to-air systems must be installed by a trained refrigeration technician, as the refrigerant loop must be correctly connected, charged and tested. Leakage of the refrigerant gas is not only an environmental hazard (in previous decades because of ozone depletion, nowadays due to global warming potential), but is also liable to damage the system. Air-to-water heat pumps (as well as some pre-charged 'self-install' air-to-air models) have a factory-sealed refrigerant loop, and can be installed by regular plumbers and heating engineers.

2.2 Ground source heat pumps

Ground source, or geothermal heat pumps (GSHPs) use copper or plastic tubes buried underground as an external heat exchanger. This allows them to exploit a higher quality source of heat, but makes their installation more disruptive and expensive.

Open-loop systems extract water directly from, and reject it back to rivers or groundwater resources such as aquifers and springs.[3] These can provide a stable source of moderate temperature heat (5–10 °C) that is usually inexpensive to harness as only simple wells need to be sunk. However, resource availability is limited, acidity and impurities can lead to corrosion of system components, and in many countries there are complex environmental regulations covering the use of groundwater.[21,22]

Closed-loop, or ground-coupled systems are therefore more common, using a sealed loop to extract heat from the surrounding soil or rock. Direct expansion (DX) systems circulate refrigerant directly from the compressor through copper tubes, whereas indirect systems circulate water and antifreeze through plastic tubes, then transfer heat to the refrigerant circuit *via* a secondary heat exchanger.[21] This additional exchange step means DX systems are slightly more efficient, however the long underground refrigerant loop must be welded together *in situ*, and requires 3–10 times the refrigerant charge of an indirect system (around 750 g per kW of heating).[5,23] DX systems have therefore fallen out of favour in recent years as regulations on refrigerant leakage have tightened.

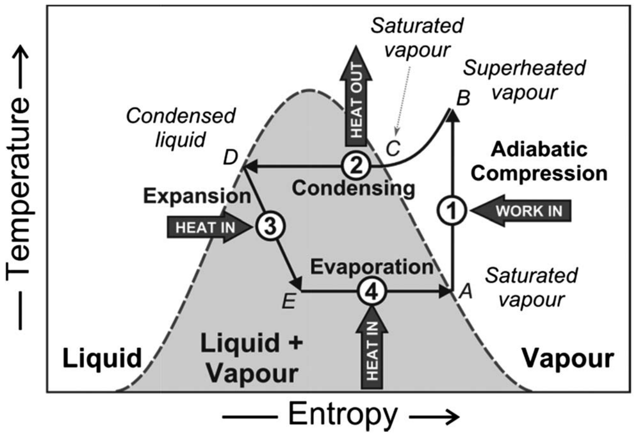


Fig. 4 Temperature–entropy diagram showing the ideal vapour-compression cycle for a heat pump.

The underground pipes can be laid in horizontal trenches at a depth of 1–2 metres, although this requires a substantial amount of land to be dug, typically 400–800 m^2 (0.1–0.2 acres).[24] The amount of pipe that must be laid depends strongly on the type of soil, due to differing thermal conductivities. Heat extraction rates for both horizontal and vertical pipes range from 10 W m^{-2} (20 W per metre of pipe) for dry sandy soil up to 30 W m^{-2} (60 W m^{-1}) for clay and rock.[25]

The pipes can instead be laid vertically in one or more boreholes around 100–150 m deep.[25,26] Borehole drilling is highly specific to the individual site as the underlying rocks, soils and sand must be treated differently. Drilling therefore requires a thorough geological survey, as well as planning permission in the UK. The physical size of drilling rigs can pose a problem, as they are at least 1.5 m wide, and access to the rear garden is limited in many properties. Boreholes are however an effective option for high density housing developments as multiple heat pumps can share the same set of holes.

Both horizontal and vertical options require heavy mechanical digging equipment and can cause significant disruption to the property, as pictured in Fig. 6. Many people view this as a great inconvenience unless the pipes are laid when the house is built.[27]

Installers and customers can be tempted to underestimate the required size of the heat collectors in an effort to reduce costs and disruption; however, this can lead to problems once the pump is installed. The heating output is directly related to the size of the underground collector, so under-sized pipes can result in a loss of thermal comfort in the depths of winter. Also, just as ASHP cool down the air surrounding the external unit, GSHP will reduce the temperature of the ground surrounding the pipes. If the ground is unable to recover the heat extracted with solar and geothermal gains, its temperature will gradually fall over decades of use, reducing the performance and output of the pump.[28] It is essential to ensure that horizontal pipes and boreholes are spaced far apart, and that around 20–40 m of pipe is sunk per kW of heating output – although there is no general rule of thumb that adequately covers the diverse combinations of geology, heat pump and building demand.[29]

The installation of the actual heat pump unit is relatively simple as with sealed air-to-water systems, and requires approximately one day's work from a plumber/electrician.[27] Most ASHP and GSHP are able to operate perfectly well with old hot water tanks and central heating systems, albeit with greater standing losses from the tank; however, it is important to ensure the capacity of the pump matches that of the distribution system, and the heat losses from the home.

2.3 Operation

Heat pumps aim to provide high user convenience, and are typically operated by a room thermostat or remote control unit. The indoor units (hydronic heat exchangers or warm-air distributors) are relatively unobtrusive and quieter than most household appliances (21–40 dB). European and Japanese outdoor units are slightly louder, ranging from 45–55 dB, although the larger American units are around 10 times louder at 69–74 dB. Air-to-air units can provide several additional services such as dehumidification and air purification (removing smoke, odours, bacteria and so forth).

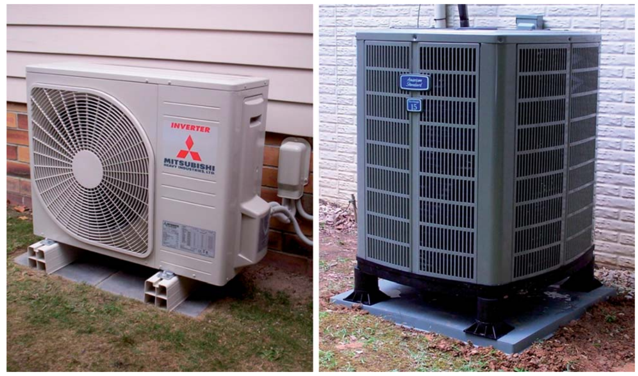


Fig. 5 Examples of air source heat pumps from Mitsubishi (left) and American Standard (right).

Like most microgeneration systems, heat pumps are usually undersized relative to the peak demand of the property to reduce capital cost and increase utilisation.[14] The pump is therefore supplied with a backup heater to provide sufficient heating on the very coldest days of winter. Some models (usually older ones) are not able to provide heat above 60 °C, and so the backup heater is also used to pasteurise stored hot water. Electric immersion heaters are often used for their simplicity and low cost, but their inefficiency can substantially increase running costs if used regularly. Choosing the right capacity of heat pump for a given house is therefore important to maximise the efficiency, and either requires the cost of consultation by an industry professional, or time and dedication by the customer.

The output of a heat pump reduces with external temperature, so there is a minimum temperature of around −15 to −25 °C below which the auxiliary heater must solely be used.[25,30] Only ASHP suffer from this in practical use, as underground temperatures are higher and more consistent than air temperatures between seasons. Freezing of the outdoor unit is also a disadvantage of ASHP: ice begins to form on the external heat exchanger below around 5 °C, as the air exiting the unit has been cooled to below freezing. Freezing is more of a problem in damp climates, but can be reduced by locating the heat pump in a sheltered or sunny area.

Freezing greatly reduces heat transfer into the heat exchanger, and so defrost cycles are regularly used throughout cold periods. The flow of refrigerant around the system can be reversed to draw heat back out of the house into the exchanger, although this can be an inconvenience to the occupants who may experience a cold draught for about 5 minutes at a time. Electric resistance heaters can otherwise (or also) be activated in the external unit to raise its temperature, although this greatly increases energy consumption during cold winters, which can also disappoint users who are not made aware of the requirement. ASHP are therefore generally considered unsuitable for colder climates with sub-zero winters; however, modern systems are able to maintain their full heating performance down to −15 °C.[31,32]

2.4 Maintenance and durability

Heat pumps exhibit longer lifetimes than conventional boilers, with high reliability and minimal need for maintenance. As electric heat pumps present no risk of natural gas leakage or explosion, servicing can be performed as little as once every three to five years, saving the owner from the expense of annual boiler services.[33] Besides component failures, such as compressor burn-out, equipment is serviced mainly when the heating (or cooling) capacity is too low due to loss of refrigerant from fugitive emissions.[34]

The compressor is the most complex and expensive component to replace, and typically has a lifetime of 15–25 years, while the plastic underground heat collectors of GSHPs are expected to last for up to 50 years.[21,35] It is now common for major manufacturers to offer 10+ year warranties covering the entire system. These long lifetimes are exemplified by the world's first commercial heat pump, which was installed in 1938 and still provides heat for Zürich city hall.[1,2]

Mean time between failure (MTBF) is reported as being between 20 and 40 years in small scale GSHPs,[36] and only 1.7% of compressors require replacing annually.[26] Coolant leakage from the ground coils is believed to be the most common fault, but this can be avoided by careful installation.[37]

Even though modern HFC refrigerants are not ozone depleting, it is still illegal in many countries to vent them to the atmosphere due to their high global warming potential. The most common refrigerant, R410-A, is 2000 times more powerful than CO_2,[38] which is itself emerging as a replacement refrigerant. Particular care must be taken when installing, repairing and replacing systems to ensure that leaks do not occur, and it is usually mandatory for a trained refrigeration engineer to carry out repair work on such systems.

2.5 Alternative designs

Several variations on the basic heat pump design have been proposed, with two of the more promising developments being heat pumps driven by gas engines or assisted by solar collectors.

2.5.1 Gas engine heat pumps. Gas engine heat pumps (GEHPs or GHPs) use an internal combustion engine to drive the compressor instead of an electric motor. They utilise the principle of combined heat and power (CHP) by moving the conversion of fuel into mechanical work closer to the end point of use, so that waste heat can be captured rather than lost to the environment.

Capturing heat from the exhaust gasses and engine body increases the total output by around 30%, which is particularly beneficial in colder climates.[9] Maximum heating capacity can be maintained with outdoor temperatures below −20 °C, as the engine becomes a direct source of heat, replacing the need for backup electric heaters and defrosting systems for air sourced heat pumps.[39,40]

Although the engine efficiency is not high (25–45%),[41] it is comparable to that of conventional power stations, and so the primary energy utilisation is better than for electric heat pumps.[9] GEHPs therefore benefit from lower running costs in countries with low gas prices relative to electricity (*e.g.* Japan and the US), and lower carbon emissions in most countries as natural gas and LPG are used instead of predominantly coal-derived grid electricity.

The combination of heat recovery from the engine and from the environment (as in Fig. 1) means that GEHP tend to produce 1.2–1.6 kW h of heat for each kW h of primary energy consumed.[42–44] This compares favourably to electric heat pumps, and represents a 60% improvement over condensing boilers.

Upfront and running costs for GEHP are currently too high, as the engine is an additional major component and requires regular maintenance every 10 000 hours.[40] GEHP are currently limited to larger commercial and shared apartment buildings with 25–100 kW demand. However, with the development of smaller gas engine CHP systems such as the 1 kW Honda Eco-will, domestic-scale GEHP could be brought to market within a few years.

Japan is virtually the only country developing this technology.[44] Japanese manufacturers have sold over half a million commercial units since 1995,[41] although sales have been steadily declining over the last decade.[45] Sales across Europe are gradually increasing, but stand at only 1% of Japan's total.[46]

2.5.2 Thermally driven heat pumps. Gas engines can also be used to power thermally driven absorption and adsorption reactions.[47] Known variously as diffusion–absorption (DAHP), gas adsorption (GAHP), chemical or thermo-chemical heat pumps; these systems predominantly use water–ammonia and zeolite chemistries in place of the vapour compression cycle, with comparable efficiencies to GEHP from a simpler, and therefore potentially cheaper system.[40,41]

As with GEHP, thermal heat pumps are currently available in the 50 kW+ range, and around 45 000 systems have been sold to date in Europe.[41] Several companies are developing smaller prototypes down to 1–5 kW for domestic properties, with several field trials currently underway in Germany.[41,48]

2.5.3 Solar assisted heat pumps. Solar assisted heat pumps (SAHPs) use glass or plastic heat collectors mounted on or embedded into the roof of the house, as with common solar thermal panels. These can be used separately from, instead of, or in conjunction with air or ground-based heat exchangers,[2] giving rise to the classifications of parallel, series and hybrid SAHP systems.[49]

This idea was first tested back in the 1950s,[50] but commercial products have only recently appeared in Europe[51] due to difficulties in correctly matching component sizes, and the cost premium of combining two microgeneration technologies.[44,52] The majority of systems available today are parallel, where the heat pump and solar panels separately supply a heat store. Series systems (where the panels act as the heat source for the pump) are slowly becoming available, and negate the problem of land disruption with GSHPs. Hybrid regenerative systems may offer the greatest performance, as excess solar heat from the summer restores ground temperatures, improving the GSHP efficiency during the following winter.

The primary benefits are that heat can be directly harvested from the panels and higher refrigerant temperatures can be attained on a property's roof, and thus SAHP can offer nearly double the heat output and efficiency of a conventional GSHP, with the greatest benefits seen during colder winter months.[6,51,53,54] By integrating a vapour-compression cycle into the traditional solar thermal design, they also achieve substantially higher heat output than from panels alone. However, complex hydraulic systems and unoptimised components can leave performance no better than a standard heat pump.[51]

3. Commercial aspects

Globally, heat pumps are one of the most widely used forms of microgeneration, due in part to their dual role as air conditioning systems. Air-to-air heating systems are ubiquitous across Asia and southern Europe, where water based central heating is not widely used and the climate necessitates both heating and air conditioning. For example, over 150 million air-to-air heating systems have been sold in Japan alone over the last 25 years.[45]

The American preference for whole-house heating, ventilation and air conditioning (HVAC) systems means that individual room heaters are less popular, and instead at least a third of US homes are heated by system-integrated ASHPs.[9]

Northern European countries lead the way with domestic GSHP usage, with Austria, Germany, Switzerland and Sweden pioneering geothermal systems for several decades.[8] Heat pump sales have topped 100 000 per year in several countries, growing steadily by 10–20% per year over the last two decades.[8,55]

The market for heat pumps in the UK was almost non-existent until 2005, but has grown rapidly since. By the end of 2010 annual sales stood at 18 000, ~1% of the market for replacement heating systems, and a total of 49 000 systems were in use giving a market penetration of ~0.2%.[56] The majority of companies who install domestic heat pumps in the UK only do so as a sideline to their main business of plumbing or borehole drilling, selling less than four systems a year.[57]

The leading brands vary from region to region: ASHP from Japanese multinationals (*e.g.* Daikin, Mitsubishi, Panasonic and Sanyo) are available throughout the world; several European manufacturers specialise in GSHPs (*e.g.* Dimplex, Vaillant, Viessmann and Worcester-Bosch); while American Standard and Carrier are the largest brands in the US; however, the world's largest suppliers by volume are now Chinese, for example Gree and Haier are among the hundreds of manufacturers that collectively produce 20 million air-to-air units annually.[58]

3.1 Capital costs

The capital cost of heat pump systems varies between regions and on the type of system; however, the underlying trend is that they are more expensive than the conventional heating systems they replace. The cost of an air-to-water or ground source heat pump in the UK is typically in the region of £2500–5000.[21,59–61] Capital costs for both technologies are similar, although the costs for installation are very different due to ground works.

There are however a small number of manufacturers who offer basic models in the UK for as little as £1100 for 5–10 kW capacity.[62,63] Lower capacity air-to-air room heaters are a more cost effective option for smaller dwellings that already have water heating. 4 kW models are available from £500–1000,[20] and go down to as little as £300;[64] however there is a trade-off between up-front cost and ongoing running costs, due to the higher efficiency of more expensive models. For example, comparing fixed-speed and "hyper-inverter" models from Mitsubishi reveals that 45% higher efficiency (and thus 31% lower running costs) can be realised for 54% higher upfront cost.[20] Similarly, two-stage models from American Standard and Trane are 8–13% more expensive than the nearest single-stage equivalents, and offer around 10% higher heating efficiency.

The cost per kW of thermal output decreases sharply with capacity, leading to reasonably similar prices for systems in the range of 7–15 kW, as seen in Fig. 7.

3.2 Installed costs

ASHPs are similar to standard heating equipment in terms of complexity to install, requiring around a day of labour. The total installed costs should therefore range from £1500–2000 for air-to-air systems up to £5000–7000 for air-to-water systems; although the Energy Saving Trust is less optimistic, placing the average cost of ASHP at around £6000 to £10 000.[33]

The additional labour required to lay the ground pipes for a GSHP increases the installation costs by around £500–800 per kW, bringing the total cost up to £8000–12 000 for a 10 kW system.[21,57,60,62,65] Again, the Energy Saving Trust suggests a more conservative range of £9000–17 000;[33] however, the actual prices paid in the UK during 2006–07 varied between £4000 and £14 000.[57]

Smaller systems using a horizontal ground-loop lie at the lower end of these price ranges, and vertical borehole systems, installed with a new storage tank and other ancillary equipment lie at the high end. It should be noted that these costs are significantly reduced when GSHPs are installed at the time of building a new house, or if several systems are installed together in neighbouring houses which can take advantage of communal holes.

Prices depend strongly on the system installed, and whether a suitable heat distribution and storage system is in place. For example, the popular Mitsubishi EcoDan retails for around £3000 for the 8.5 kW model, however it can cost over £7000 to have one installed with a new hot water tank by a "complete-service" company.[66] It is argued that the relatively small market in the UK has created less competition between manufacturers and installers, allowing profit margins to rise.[57] For this reason, prices are slightly lower across continental Europe: £1200–1700 for air-to-air, £6000–9000 for air-to-water, and £9000–12 000 for GSHP systems.[55]

Residents of the UK who do not use mains gas for their heating could apply for a Renewable Heat Premium Payment: a

Fig. 6 The installation of ground loops for GSHP systems using slinky horizontal pipes (left) and a vertical borehole (right).

one-off grant of £850 for installing an ASHP or £1250 for a GSHP.[67] These grants are available until March 2013, after which the Renewable Heat Incentive (RHI) will take effect for domestic users; although at the time of writing it is not clear how this scheme will work, or whether or not it will cover ASHPs.[68] The RHI is the world's first feed-in tariff for renewable heating, and analogous to the feed-in tariffs offered to electricity producing renewables, the scheme offers a fixed payment per kW h of heat produced.†

3.3 Running costs

Despite relatively high capital costs, heat pumps have in many cases passed the break-even point required to save money in the long run due to lower running costs and long operating lifetimes with minimal maintenance.[69] Systems that are installed and operated correctly can provide lower fuel bills than a condensing boiler, while operation and maintenance (O&M) costs are also lower than for gas boilers due to reduced safety regulations and higher reliability.[70,71]

Electricity tends to be 3 to 4 times more expensive than the cheapest available domestic fuel (natural gas); however, the use of discounted heat pump or night-time electricity tariffs will reduce this ratio (known as the spark gap) substantially. Given the average performance figures reported in the next section, spark gaps of less than 3.2 and 4.2 are required for the majority of ASHPs and GSHPs to become cost competitive with gas boilers.

The savings that can be made relative to a condensing boiler are relatively modest, leading to estimated payback periods of 30 years or more (*i.e.* annual returns of just 0–3%).[72–74] The five million homes in the UK which lack access to low-cost pipeline natural gas represent a much better target market for heat pumps, as payback periods fall to between 5 and 15 years when replacing oil or electric heating systems (7–20% annual returns).[73,75]

The UK government's introduction of the Renewable Heat Incentive will provide a substantial incentive to invest in heat pump technologies. With the current tariff of 4.7 pence per kW h of heat produced, this equates to an annual subsidy of ~£800 for a typical house.[68] This should be sufficient to reduce the payback period to just 8 years when compared with a new condensing boiler. ASHPs may become eligible for this support in the future, once technology costs and efficiencies have been characterised, and a method to reliably measure heat output has been developed.

4. Technical performance

The efficiency of the heat pump is the crucial factor in determining the savings it can offer. It can be represented by a number of measures which relate the amount of heat produced to the amount of electricity consumed. Strictly, it is incorrect to call these measures of efficiency as they do not take into account the amount of heat drawn from the environment, but as this heat is free, zero-carbon and plentiful, this is only a concern to those studying the thermodynamics and exegetics of the system.

A commonly used measure is the Coefficient of Performance (COP), which gives the heat output (in watts) divided by the electrical input (also in watts). The result is a dimensionless number which is simple to interpret: a COP of 3 means 3 units of heat produced for each unit of electricity consumed.

A system's COP represents its steady-state performance under a set of controlled conditions with defined input and output temperatures. It is common for heat pumps in Europe to be tested at 7 °C external temperature (dry bulb) and 20 °C indoor temperature, with 35 °C output from the pump.

The American standards body, AHRI, use different testing conditions: −8.3 and +8.3 °C external, 21.1 °C internal;[76] and the imperial Energy Efficiency Ratio (EER) in place of the COP. Heat output is measured in Btu h^{-1} and electrical input in watts, so EER values can be converted into COPs using eqn (1):

$$\mathrm{EER} = \frac{3600\ (\mathrm{s\ h^{-1}})}{1055.06\ (\mathrm{Btu\ W\ h^{-1}})} \times \mathrm{COP} = 3.41213 \times \mathrm{COP} \tag{1}$$

Another performance measure used in North America is kW per ton – the electricity consumed per ton of cooling (or heating). Confusingly the ton is a measure of power: the cooling provided by melting a ton of ice per day, equivalent to 12 000 Btu h^{-1} or $3.5168\dot{6}$ kW. One kW per ton is therefore equal to 12/EER and $3.5168\dot{6}$/COP.

The Seasonal Performance Factor (SPF) is a different type of measure which aims to represent the average annual performance in a given location, based on the average outdoor temperatures through the year. The steady-state COP is replicable and can easily be compared between brands, whereas the SPF will depend on the particular location and climate being considered in different tests. No matter where a *Brand X* heat pump is tested, it should operate with a COP of 3.5 under standard conditions, whereas it may have an SPF of 5 in Texas, 3 in New York, and 1 at the North Pole.

A second difference between COP and SPF values is with their system boundaries. The COP only accounts for heat production and electricity consumption by the heat pump itself (Q_{HP} and E_{HP}). The SPF can also include production and consumption by auxiliary heaters (Q_{aux} and E_{aux}), electricity used to circulate the coolant loop or outdoor air (E_{fan}) and to defrost ASHP systems (E_{frost}). Several system boundaries are used to define SPF in the literature, however the most complete picture is gained by including all of these aspects.[77,78] Eqns (2) and (3) summarise the differences between the two measures:

$$\mathrm{COP} = \frac{Q_{\mathrm{HP}}}{E_{\mathrm{HP}}} \tag{2}$$

$$\mathrm{SPF} = \frac{Q_{\mathrm{HP}} + Q_{\mathrm{aux}}}{E_{\mathrm{HP}} + E_{\mathrm{aux}} + E_{\mathrm{fan}} + E_{\mathrm{frost}}} \tag{3}$$

In North America, the Heating Seasonal Performance Factor (HSPF) and Seasonal Energy Efficiency Ratio (SEER) are used in place of SPF, to cover the heating and cooling functions of a heat pump (or air conditioner) respectively. As with EER, these

† Non-domestic customers currently receive 4.7 p per kW h of heat generated by GSHPs.[68] The newly proposed rates for domestic customers are far more generous, potentially lying in the range of 6.9–11.5 p for air-to-water (but not air-to-air) ASHP and 12.5–17.3 p for GSHP.[122]

are measured in Btu W^{-1} h^{-1}, and can be converted into SPF values using eqn (1).

There is an important distinction to be made between the two types of test: steady-state (as measured by COP and EER) and seasonal averages (as measured by SPF, HSPF and SEER); as the performance of a heat pump is highly dependent on the operating conditions and on electricity consumption by the ancillary components, which are not accounted for in COP values.

4.1 Dependence on temperature and technology

The performance of any heat pump is highly dependent on the 'lift': the temperature difference between the external heat collector and the output to the home. In practice COP drops by between 0.6 and 1.0 for every 10 °C difference, giving 0.6–1.0 kW less heat output per kW of electrical input. To maximise efficiency, the difference between these temperatures must be made as small as possible, and so a relatively cool heating loop and a warm external loop are desirable.

The first condition can be improved by using large area or fan-assisted radiators, or under-floor heating. By increasing the surface area over which heat is radiated to the room, these can be used with substantially lower water temperatures: 45–60 °C for radiators or 30–45 °C for under-floor. Heating the air directly with air-to-air room heaters can offer even greater performance as the outlet temperature is reduced further. For example, the Mitsubishi SRK-ZJX air-to-air series offers possibly the highest recorded COP to date for an ASHP: 5.56 at 7 °C external temperature, as its output temperature can be as low as 25 °C.[20] This ability to reduce the flow temperature to suit the specific situation is a key feature of inverter driven heat pumps.[31]

Despite this shift towards lowering output temperatures, modern heat pumps are still able to provide high temperature heat when required. Newer hydronic heat pumps produce hot water at over 65 °C, meaning they can be relied upon without an auxiliary water heater. It must be remembered that they do so at the expense of efficiency, and thus with increased running costs.

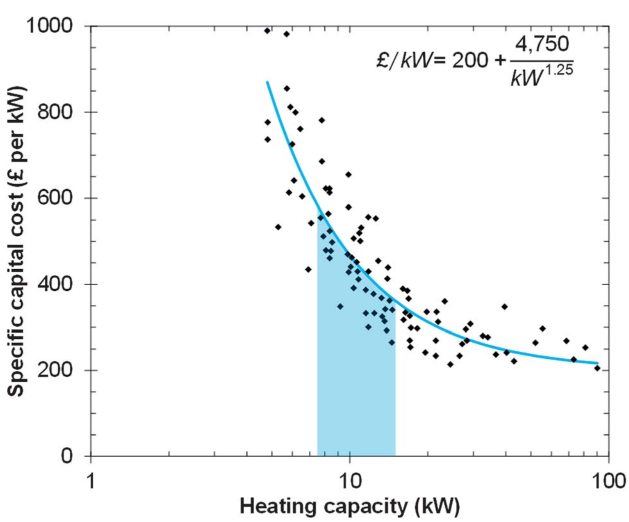


Fig. 7 Capital cost per kW of heating capacity for all types of heat pump from European manufacturers. The approximate range of capacity suitable for UK homes is highlighted. Based on data from MVV.[60]

The second condition exposes a fundamental drawback of ASHP relative to GSHP. The greatest demand for heating occurs during winter when air temperatures are at their lowest. Conversely, ground temperatures rapidly converge towards the annual average as depth increases, and show little variation during the year even at the shallow depths of horizontal ground-loops. Using the UK as an example, air temperatures average 0–8 °C during winter, whereas ground temperatures remain consistent at around 8–12 °C, as shown in Fig. 8.

GSHP therefore offer higher SPF/HSPF values averaged over the year, but they also tend to offer higher COP/EER values under nominal conditions. The process of extracting heat from the air is more energy intensive as its specific heat capacity (on a volumetric basis) is so much lower than that of soil or water. ASHP therefore have to expend more energy on shifting air through the heat exchanger, and thus use more electricity per unit of heat output under any conditions.

Fig. 9 plots the average COP of over 100 commercial models against the temperature rise across the heat pump – highlighting the clear dependence between the two. The range of performance that could be expected in the UK is highlighted, based on annual climate variations, and the results from eight separate field trials.

The variation in attainable performance is a source of confusion for users, as manufacturers can legitimately advertise COPs of up to 7, although these would never be experienced in practical usage due to the very low temperature difference required.[80] Although national and global standard procedures are widely used for testing heat pumps, their flexibility and complexity makes the results difficult to interpret. Prospective users generally need to conduct their own prior research, or face paying for expert advice in order to interpret manufacturers' data and estimate the performance that should be expected in their particular circumstances.

4.2 Real world performance

The numbers presented in Fig. 9 look good on paper; however, a common complaint from heat pump owners is that their systems do not perform so well, consuming more electricity than they had been led to expect. Several field trials from around the world have shown that SPF values for just heat pump units alone lie in the range of 3.0–3.5 for ASHP and 3.3–4.2 for GSHP when operated in real houses;[80] however, the whole-system SPF values (which include electricity consumption by immersion heaters and other losses) can be significantly lower.

This has perhaps been most prominently highlighted by on-going field trials in the UK. The Energy Saving Trust (EST) monitored 83 models from 14 manufacturers in British homes since 2008.[75,83,84] They found that while the best performing systems had SPF values of 3.2, the majority of systems "perform so badly they would not qualify as renewable energy under proposed European standards".[85] Average SPF values were 2.0–2.8 for GSHP systems, and just 1.5–2.1 for ASHP,[84] some 40–50% lower than the COP values presented in Fig. 9.

These results contrast with those from large-scale trials held in Germany. The Fraunhofer Institute for Solar Energy Systems (ISE) has conducted three separate programmes since 2005, each testing around 100 heat pumps in similar circumstances to the UK trials (annual averages of 9 °C and 14 MW h heat demand).

The first two projects considered heat pumps installed into newly built homes[86] and retrofitted into existing buildings,[87] while results from the third project will become available in 2013.[88] So far, ASHPs have attained annual average SPFs of 2.6–2.9 (higher than GSHPs in the UK trial), while GSHPs averaged 3.3–3.9; meaning that an average system installed and monitored in Germany can produce an extra 1.2 kW of heat per kW of electricity than a similar system operating in the UK.

The primary difference between the two countries appears to be the suitability and quality of the installations, leading some to argue that the English trial was "not so much a story about heat pumps, as one about the atrocious standard of building regulations in the UK".[85] The EST themselves state that systems were wrongly sized for the properties, had been set up incorrectly, and were operated in sub-optimal modes.[83,84] These problems are not unique to the nascent UK market though; as Energy Star report that half of heat pumps in the US suffer from problems with incorrect refrigerant charge, poor air flow, and leaky ducts.[89]

In contrast, Fraunhofer concluded that "very good efficiency can be reached if careful planning and installation is carried out".[90] The average efficiency of heat pumps installed in the Fraunhofer projects has been improving by 2.5% per year since 2007,[91] which could well be the result of learning effects among installers and users, as experience and best practices filter through the industry.

It is therefore clear that several aspects of a heat pump's installation and operation can have a severe detrimental effect on its overall performance.[84,86,92] Manufacturers, designers, installers and users all have crucial roles in ensuring strong performance from a system:

• building quality and insulation levels should first be improved to reduce the primary demand for heat;

• the installed capacity must be well matched to the heat demands of the property to prevent over-use of immersion heaters and excessive on-off cycling;

• boreholes and trenches must be correctly sized to the capacity of GSHPs to prevent ground freezing;

• pumps must be charged with the correct amount of refrigerant (or brine) and care taken to avoid subsequent leakage;

• heating circuits should be set to the minimum comfortable temperature, and users made aware of the implications of subsequently raising them;

• control algorithms and operating modes should be optimised to minimise parasitic losses and the need for defrosting ASHPs.

4.3 Estimating real world performance

Given the disparity between the COP values published by manufacturers and the SPF values experienced in real-world testing, it is vital to be able to estimate the performance that should be expected from a particular system installed at a given location.

Several heat pump simulations have been developed to enable this type of performance estimation, either integrated into building energy models such as ESP-r, EnergyPlus and TRNSYS; or standalone models with extensive libraries such as WP-OPT or the DOE/ORNL heat pump design model. Numerous academic models have also been developed since the 1980s covering all aspects of design, optimisation, and simulation.[10,93–95]

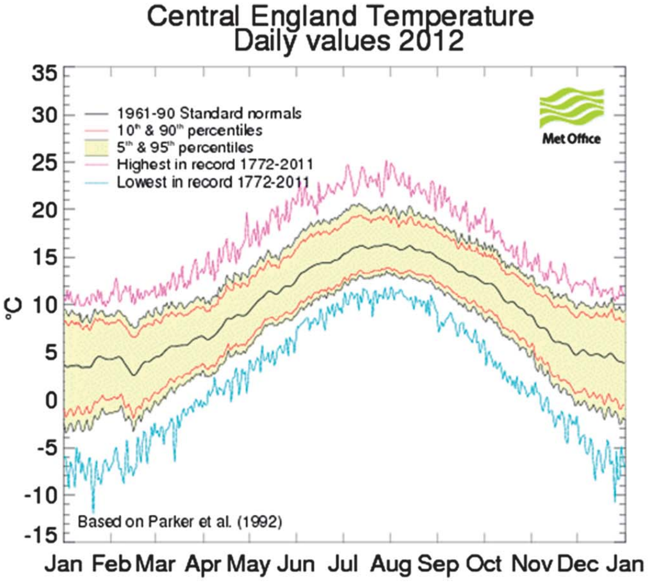
A simpler framework which can estimate annual heat pump performance without such detailed modelling is described below:

(1) compile the COP values for a given heat pump along with the corresponding temperature difference between the source and outlet (the lift, or ΔT);

(2) produce a linear or quadratic regression of these points, so that COP can be estimated for a continuous range of ΔT;

(3) determine the average output temperature from the pump, based on the ratio of space heating to hot water production, and the required outlet temperatures for each;

(4) determine the seasonal average temperature of the heat source (ground or air), weighted by the amount of heat demand across the season;



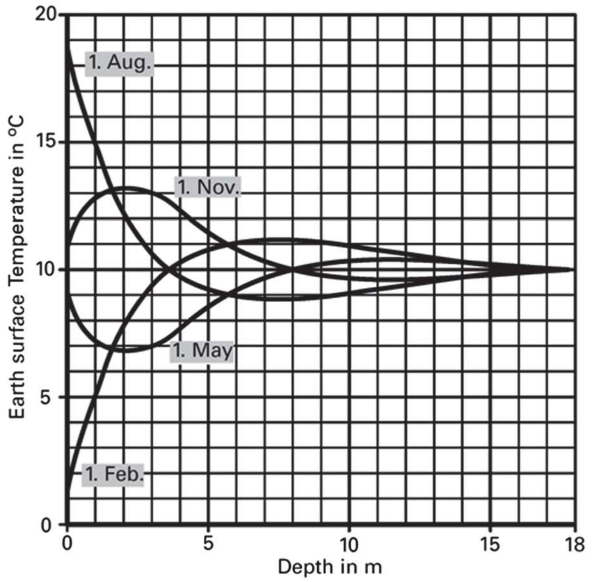


Fig. 8 Average air and ground temperatures (left and right, respectively) over the course of the year in the UK.[25,79]

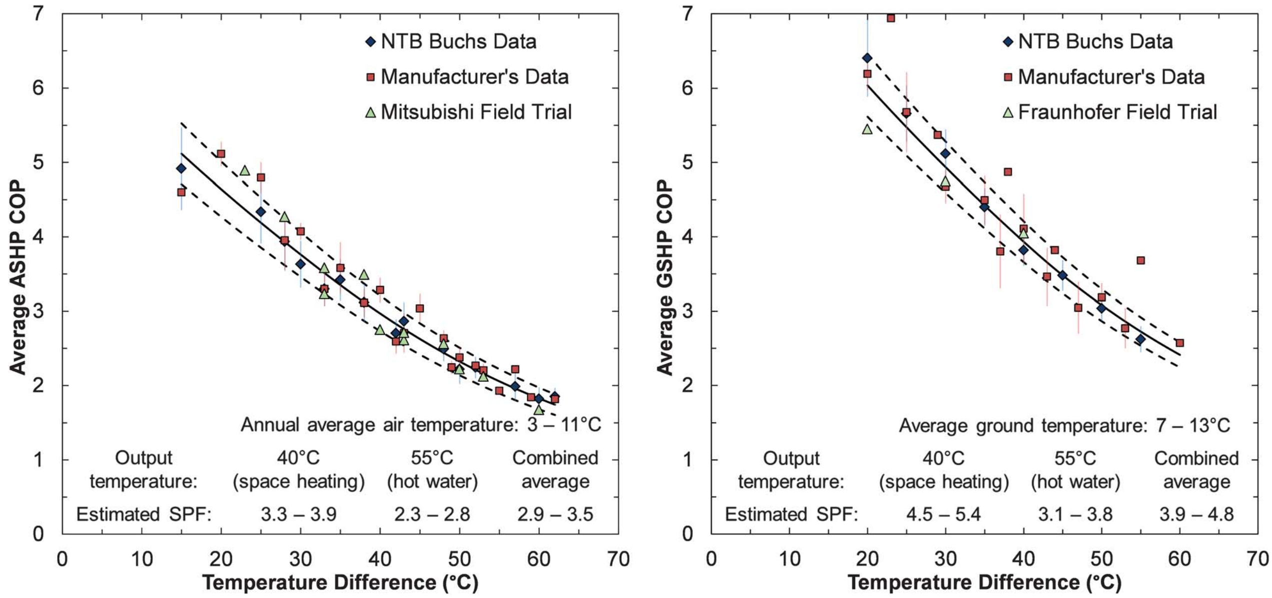


Fig. 9 Average heating coefficient of performance for air and ground source heat pumps (left and right, respectively) based on data taken from industrial surveys and field trials.[31,80–82] The inset tables show the expected performance for UK conditions.

(5) account for usage of a backup heater (if present);

(6) account for energy consumed during defrost cycles (for ASHP systems).

4.3.1 Regress COP against lift. Heat pump manufacturers are only obliged to publish a single value for a model's COP, although many of them voluntarily provide several values measured at different inlet temperatures. Obviously, the more data that can be found and the wider the range of temperatures covered, the better the resulting relationship between COP and lift. For reference, the industry-average data presented in Fig. 9 can be expressed as eqn (4):

$$\begin{aligned} \mathrm{COP_{ASHP}} &= 6.81 - 0.121\Delta T + 0.000630\Delta T^2 \text{ for } 15 \le \Delta T \le 60 \\ \mathrm{COP_{GSHP}} &= 8.77 - 0.150\Delta T + 0.000734\Delta T^2 \text{ for } 20 \le \Delta T \le 60 \end{aligned} \tag{4}$$

4.3.2 Estimate source and sink temperatures. Both internal and external temperatures change over the course of the year, meaning the lift provided by the heat pump (ΔT in eqn (4)) is constantly changing. In order to calculate the average COP over a whole year, these temperatures must be measured (or estimated) at regular intervals; the average COP can then be calculated for each period, and weighted by the amount of heat demand.

To calculate ΔT, the temperature of the air or ground (T_{in}) can be monitored or estimated from historic records, and the outlet temperatures for space heating and domestic hot water (T_{SH} and T_{DHW}) can be assumed. T_{SH} will primarily depend on the type of heat distribution system that is installed. Ideally, large-area or fan-assisted radiators will be used instead of conventional radiators, as the larger surface area for emitting heat enables them to operate with lower water temperatures; however, the gain in performance tends not to justify the additional cost of retrofitting these until the existing heating system needs replacement. Outlet temperatures can be reduced further by using under-floor heating (which was commonplace in the German field trials), or by heating the air directly (as with air-to-air models). Some heat pump models reduce their outlet temperature according to the external temperature (and thus amount of heat required), improving performance with all heating systems. The following temperature ranges are typical for each system:[14]

- direct air heating: 25–35 °C;
- underfloor heating: 30–45 °C;
- large-area radiators: 45–60 °C;
- conventional radiators: 60–75 °C.

Domestic hot water temperatures (T_{DHW}) tend to be around 50–60 °C due to comfort and hygiene considerations,[14] hence it is common to find that GSHP systems with underfloor heating exhibit a lower SPF in summer months than in winter, as they must produce a larger proportion of high-temperature water from relatively consistent ground temperatures.[77] The weighted average outlet temperature (T_{out}) can then be calculated from eqn (5), with the demand for space heating (Q_{SH}) and hot water (Q_{DHW}) acting as the weighting factors.

$$T_{\mathrm{out}} = \left(\frac{Q_{\mathrm{DHW}}\ T_{\mathrm{DHW}} + Q_{\mathrm{SH}}\ T_{\mathrm{SH}}}{Q_{\mathrm{DHW}} + Q_{\mathrm{SH}}} \right) \tag{5}$$

4.3.3 Account for auxiliaries. With careful sizing, use of the backup heater can be minimised to 3–6% of the supplied heat in domestic installations.[59,82,96] An under-sized system will rely more heavily on the backup heating (and thus reduce the SPF down towards 1), whereas an over-sized system will suffer from having too little demand, and will either run at part-load or repeatedly cycle on and off. Heat pump COP has been found to fall by 30% when the unit only runs for 5 hours a day, and to fall sharply below 40% rated power in inverter-driven models.[97]

The impact of defrosting on overall efficiency is not well characterised as it depends strongly on the usage pattern and climate. The exact position and sheltering of the outdoor unit must also be considered, as cold and damp conditions necessitate more regular defrosting. The reporting of its impact is not included in national standards, making it more difficult to compare systems from different manufacturers. For example, the COP values presented by Panasonic include the energy used for defrosting,[32] whereas figures from Nibe must be reduced by around 10% during defrosting,[98] and Mitsubishi suggest applying a series of correction factors to account for defrosting‡. A 4 kW Mitsubishi ASHP operating in London could, for example, be expected to consume an additional 100 kW h of electricity (3% of its total) on defrosting over the course of a typical year.[80]

Finally, the hot water produced by the heat pump must be transferred to the building's heating system and hot water tank. The water pumps consume around 150 kW h of electricity per year, adding a further 3–5% to the whole system's electricity consumption.[77] However, it must be remembered that similar pumps would be required by any hydronic heating system, and condensing boilers have been found to consume a similar amount of electricity per year.[99]

4.3.4 Estimate SPF.

In order to estimate the SPF over the course of a year, data on the pattern of heat demand is also required. A typical UK home has annual demands of 4 MW h for hot water and 13 MW h for heat, around 40% of which is demanded during the winter months, 25% during spring and autumn each, and 10% during summer.[100,101] The seasonal variation is much lower in new-build houses, as improved insulation greatly reduces the demand for space heating in winter.

The average annual SPF of the heat pump (SPF_{HP}) (also referred to as the seasonal COP) can then be calculated by weighting the COP for each period by the electricity consumed during that period (E_i). As $E = Q/COP$, this can be related to the more readily calculated heat demand of the property (Q_i) as in eqn (6).

$$SPF_{HP} = \frac{\sum_i COP(\Delta T_i)\ E_i}{\sum_i E_i} = \frac{\sum_i Q_i}{\sum_i Q_i / COP(\Delta T_i)} \quad (6)$$

Finally, the SPF of the whole heating system (SPF_{sys}) can be estimated using eqn (7). SPF_{sys} is related to SPF_{HP} by the fraction of electricity consumed by the auxiliary heater (e_{aux}) and the fraction of electricity consumed by the defrost function (e_{frost}). Alternatively, the fraction of heat delivered by the backup heater (q_{aux}) can be used with the appropriate multiplication factor, to account for the fact electric immersion heaters are less efficient than the heat pump.

$$SPF_{sys} = \frac{SPF_{HP}}{1 + e_{aux} + e_{frost}} = \frac{SPF_{HP}}{1 + (SPF_{HP} - 1)q_{aux} + e_{frost}} \quad (7)$$

Table 1 presents a worked example estimating the SPF for an air source heat pump operating in the UK. Source temperatures are taken from the Central England Temperature (HadCET) dataset,[79] sink temperatures are based on underfloor heating operating at 40 °C and hot water production at 55 °C, heat demands are modelled on a typical semi-detached property,[101] and the COP of a typical ASHP was modelled using eqn (4).

The data from Table 1 gives a weighted average performance of $SPF_{HP} = 3.19$. If this is modified according to eqn (7), assuming that 4% of the final heat is supplied by the backup heater and that defrosting consumes an additional 3%, the average annual SPF is estimated to be 2.86, which matches the average results for ASHPs in Germany.

If these calculations are repeated with 60 °C space heating (radiators rather than underfloor) and assuming 8% supply from the backup heater (due to less appropriate matching of capacity to the home), the predicted performance of the exact same heat pump model falls to $SPF_{HP} = 2.19$ and $SPF_{sys} = 1.92$; matching instead the results of the English trials.

Auxiliary systems not considered in official COP measurements are in both cases estimated to lower the SPF by around 10%. This closely matches the findings of the Fraunhofer field trials, which showed that average ASHP SPF reduces from 3.17 to 2.89, and GSHP SPF from 4.19 to 3.88, when these auxiliaries were included.[77] New testing procedures that incorporated these aspects would help to raise consumer awareness of these issues, and reduce the potential for disappointment at unmet expectations.

4.4 Primary energy consumption

Despite the inefficiencies of auxiliary systems, and more importantly of generating electricity in thermal power stations, heat pumps provide the most effective utilisation of primary energy for space heating when installed and operated correctly.

It is possible to calculate the minimum SPF required to give lower primary energy consumption than a competing heating system by using the generic eqn (8):

$$SPF_{min} = \frac{\eta_{heater}}{\eta_{grid}\ \eta_{trans}} \quad (8)$$

Using the UK as an example, the efficiency of the most commonly used condensing boilers (η_{heater}) is 86% w.r.t. higher heating value (HHV),[14] central electricity generation (η_{grid}) is on average 38.9% efficient, while transmission and distribution losses average 7.1%, meaning the transmission efficiency (η_{trans})

Table 1 Example data used to estimate the SPF of an air source heat pump operating in central England

Month	Source temperature T_{in} (°C)	Sink temperature T_{out} (°C)	Lift ΔT (°C)	Heat demand Q (MW h)	Estimated monthly COP
Jan	3.4	42.0	38.6	2.56	3.08
Feb	3.7	42.1	38.4	2.35	3.09
Mar	5.5	42.1	36.6	2.35	3.22
Apr	7.8	43.7	35.9	1.36	3.28
May	11.3	44.9	33.6	1.02	3.45
Jun	13.9	50.9	37.0	0.46	3.19
Jul	16.0	55.0	39.0	0.33	3.05
Aug	15.7	52.5	36.9	0.40	3.20
Sep	12.9	49.9	37.0	0.50	3.20
Oct	9.9	44.2	34.3	1.20	3.40
Nov	6.0	42.5	36.5	2.01	3.23
Dec	4.2	42.0	37.8	2.46	3.13

‡ Mitsubishi suggest that defrosting begins to affect COP when external temperatures fall below 5 °C; COP is reduced by a maximum of 14% between −1 and +1 °C, and then recovers to 95% of its full value below −10 °C.[123]

is 92.9%.[102] Therefore, a heat pump operating with an SPF above 2.51 would consume less fuel than a condensing boiler in the UK.

Thus, taking the readily attainable SPF values from the Fraunhofer ISE studies, ASHP could be expected to produce 0.94–1.05 kW h of heat from 1 kW h of primary fuel burnt in UK power stations, while GSHP should produce 1.19–1.41 kW h. When compared to a new condensing boiler producing just 0.86 kW h of heat from 1 kW h of natural gas, heat pumps represent a substantial improvement.[14]

These figures improve further when the network of electricity generators' operation is considered in more depth. The majority of domestic heat demand occurs during winter when wholesale natural gas prices are at their highest.[103] Electricity generation from combined cycle gas turbines (CCGTs) is therefore frequently more expensive during winter months than generation from coal-fired boilers, in which case coal provides the baseload generation alongside nuclear, while CCGTs are the marginal plant that operate part-loaded and vary their output in response to changes in demand.[104,105] The additional power required when a heat pump turns on in winter is therefore likely to be generated by a CCGT with an average efficiency of 47%.[102] Air and ground source heat pumps could therefore realistically be expected to produce 1.14–1.27 and 1.44–1.70 kW h of heat per kW h of fuel burnt – saving 25–50% relative to condensing boilers.

In practice, the savings realised by households switching to heat pumps may not be so drastic due to indirect and rebound effects.[106] Owners of heat pumps choose to enjoy room temperatures half a degree higher than those without, due to the cost of heating being lowered and partly through heating more areas of their house (the effect of central heating).[107] Households also tend to start using more energy because heat pumps offer previously unavailable services such as dehumidification or air conditioning in the summer. This trade-off between saving energy and increasing standards of living should be factored in to estimates of national savings potentials.

A final consideration is that significant uptake of heat pumps would be reliant on an expansion of the electricity generation network, either with new centralised baseload plants or a similar penetration of electricity-producing microgeneration technologies such as solar PV and micro-CHP.[14] A 10% penetration of heat pumps in the UK would consume 12–17 TW h of electricity per year,§ requiring additional generating capacity equivalent to one large nuclear or coal plant. However, as the demand from these heat pumps would be heavily biased towards winter months, two or three times more capacity would need to be built to cope with the increase in winter peak demand.

4.5 Demand shifting and smart grids

Heat pumps are viewed as an enabling technology for the development of smart grids, as they electrify our demand for heat which is relatively flexible on short timescales. The fabric of the building and its heating system act as a thermal buffer, meaning the production of heat can be delayed or brought forwards without a noticeable loss of thermal comfort. Heat pumps can therefore be used to effectively store electricity as heat at much lower cost than using batteries, vastly increasing the potential of demand side management (DSM).[108]

By coordinating this flexibility in dispatching a large fleet of heat pumps, electricity systems operators gain a low-cost tool for balancing supply and demand, and heat pump users gain a preferential tariff for offering their services. Utilities around the world already manage thousands of heat pumps with traditional ripple control load management technology.[109] The value of this will become more pronounced with increasing levels of intermittent wind generation, opening up new opportunities for load shifting and peak shaving (reducing the maximum morning or evening demand), and thus for energy arbitrage (buying cheap and selling – equivalent to not using – dear).

British houses are heavy but poorly insulated, so high thermal masses (40–60 MJ K^{-1}) and heat loss rates (200–300 W K^{-1}) are typical.[110,111] Over-warming a house by 0.5 °C (barely perceptible to occupants) would therefore require around 7 kW h of heat input, and in winter it would take around two hours for this heat to be lost again. If the home has a hydronic heating system (typically circulating 50–100 L) and a 200 L water cylinder, these can safely be over-heated by 10 °C as well, adding an extra 3.2 kW h of storage and half an hour of buffer time. A COP 3 heat pump could therefore turn a typical semi-detached house into a 10.2 kW h thermal battery, and thus 3.4 kW h of electrical storage. Adding a large thermal buffer to the house (*e.g.* a 750 L heat store) would more than double this capacity at a relatively low cost.

Testing of such systems is in its infancy, but results are promising. EDF demonstrated the ability to shed 1.8 kW of load per house for up to 90 minutes (2.7 kW h) using ASHPs connected to 200 L storage tanks, with only 0.5 °C deviation in internal temperatures.[112] Scaled up nationally, a 10% penetration of smart heat pumps in the UK (2.6 million homes) would be equivalent to the £3.4bn (in 2010 terms) Dinorwig pumped-hydro storage plant which holds 9 GW h.

4.6 Carbon emissions

The carbon dioxide emissions from operating a heat pump are directly linked to the carbon content of the electricity used to power it. When operating in the UK, where 0.54 kg of CO_2 is emitted per kW h of electricity,[102] ASHP and GSHP could be expected to produce up to a third less CO_2 than a new condensing boiler. When operated in nuclear, hydro and renewable rich countries such as France and Brazil, their average emissions are less than a tenth that of burning gas.

Numerous case studies of heat pump installations have shown that CO_2 emissions from domestic heating are reduced by around 50% (1–2 tonnes a year per house) when displacing oil, solid fuel or electric heating.[31,37,83,94,96,113] Emissions reductions are more modest when displacing lower-carbon gas boilers, but still stand at 10–35%, or 0.3–1.5 tonnes per year. Similarly, Eco Cute heat pumps are estimated to cut domestic hot water emissions by 50–65% in Japan when they displace standard electric water heaters, each saving around 800 kg of CO_2 per year.[114,115]

There is however a downside for the carbon footprint of heat pumps which use R410-A and other fluorocarbon refrigerants with high global warming potentials (GWPs). Refrigerant gradually leaks from the system during usage, and can be

§ Assuming 2.6 million homes requiring the UK average of 13 MW h of space heating and 4 MW h of hot water per year.[100]

released in bulk during installation and at the end of life. The IPCC estimate that in developed countries 1% of a heat pump's refrigerant is lost to the environment each year,[34] which for a typical 10 kW system would mean around 25 g of R410-A, or the equivalent of 50 kg of CO_2. If, as the IPCC estimate, the refrigerant from a fifth of all heat pumps is dumped to the atmosphere rather than being recycled, then the equivalent of four tonnes of CO_2 can be released at the end of life (averaging out to 800 kg per system).[34,116] These combined releases increase the total equivalent warming impact (TEWI) by 2–4% relative to electricity consumption alone.[117–119] Enforcing better standards for maintenance and disposal of air conditioning equipment, or a move to 'R744' carbon dioxide refrigerant (already used by some Japanese models) would obviously negate this problem.

Despite this, it has been concluded that "there is unlikely to be a potentially larger mitigating effect on GHG emissions and resulting global warming impact of buildings from any other current market-available technology".[3] The International Energy Agency estimate that if heat pumps gained a 30% market share world-wide, they would cut global CO_2 emissions by 8%, or 1.8 GT annually.[120] This is possibly the largest contribution to global GHG mitigation that could be made by a single technology.[121]

Conclusions

This review aims to increase the awareness and understanding of heat pumps for the domestic sector. To this end, the physics, technologies, modes and practical aspects of operation are discussed, the capital and running costs are considered, and the commercial landscape explored.

In order to derive a better understanding of the actual performance of heat pumps, the various ways of describing efficiency are presented and used to examine the performance that can be obtained in real-world operation, surveying the published efficiency figures for hundreds of air source and ground source heat pumps. A straightforward method to relate these to the actual performance measured in UK and German field trials is presented, accounting for climate, the building's heating system and auxiliary components of the heat pump.

The striking difference in results from these trials highlights the importance that non-technical factors, such as design, installation and operation have on the energy and CO_2 savings that heat pumps can attain. There is much that can be learnt from both the best and worst performing systems. Awareness of these issues within government, industry and people's homes must be heightened in order to reap the substantial benefits that heat pumps can offer.

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