Domestic Energy Solutions Primer

Energy and heat generation

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September 2023 (Originally published)

April 2024 (Revised version 2)

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Introduction

A building can draw energy from the grid as electricity or natural gas, and also from grid-equivalent ‘bottled’ sources, such as propane or fuel oil, delivered to on-site tanks. With these energy sources, the building is able to supply its energy needs – for both electricity and heat. The building can also have self-generation capabilities (e.g. photovoltaic panels).

In this document the topic of energy and heat generation has been split into four sections:

- Generation (i.e. delivered energy)
- Self-generation (i.e. from PV, wind and solar thermal)
- Transformation (i.e. transforming one form of energy into another)
- Distribution (i.e. how energy can be moved from one location to another).

Acknowledgements

We would like to thank lead author Andrew Jeffryes, and Chris Brierley from Active Building Centre/Energy Systems Catapult for supporting this work.

Active Building Centre

This guide was developed as part of phase 2 of the Build Net Zero Now campaign which has been kindly supported by Ecology Building Society, Passivhaus Trust, SNRG, Sustainable Development Foundation and Velux.

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Thank you to our Energy working group participants for their input and feedback:
Active Building Centre, Basingstoke Council, BCP Council, Bioregional, CEPRO, Greencore Construction, Oxford City Council, PureHaus, Sero, SNRG, South West Net Zero Hub, Southampton Council, Traxis, Vertigo and Verto Homes.

Build Net Zero Now campaign led by GHA team - Julian Brooks, Richard Broad and Larry Tate.

Generation

Electricity

Electricity is generated at power stations, distributed at high voltage across the grid, and then to buildings via the local DNO network, at lower voltage. The range of power sources has increased over the years – as renewable power has become cost effective, and there has been an increase in interconnector capacity, allowing for power to come across the North Sea and the Channel. In future, solar power may be connected from North Africa.

All the power sources have a generation efficiency. For wind, solar and nuclear, this is not significant to the end price of electricity, as there is no other way to use the source energy, except via electricity. For fossil fuels the power station efficiency is more relevant; a gas-fuelled station operates at approximately 49% efficiency. The implication of this is that, if a non-renewable electricity tariff is based on the purchase of gas-derived electricity for 50% of its supply (as is likely), and the gas/electricity conversion is only 50% efficient, then a direct electric heating appliance is consuming the same gas, in practice, as a gas-fuelled heater.

Therefore, converting to electric heating (space and DHW) can be no 'greener' than burning gas. To reduce fossil fuel use, electricity has to be renewable and/or the heating appliance needs to have a Coefficient of Performance (CoP) greater than 1 (e.g. a heat pump).

Gas

UK gas was supplied for many decades from gas-production plants derived from coal (i.e. 'coal gas') and made up, approximately, of 50% carbon monoxide and 50% hydrogen. In 1965 natural gas was discovered in the North Sea, and in the 1970s the UK gas network was converted from coal gas to natural gas (i.e. > 95% methane).

There are moves to reintroduce hydrogen into the gas network without conversion of appliances. Many appliances converted easily from 50% hydrogen to near 100% methane during the 1970s, and a small (5–10%) hydrogen blend is possible without any equipment modification. The potential next step would be to replace natural gas with hydrogen. There would be no point in doing this using 'blue hydrogen' (i.e. derived from fossil fuels – coal, natural gas, oil etc.) as energy would be wasted in the conversion and it is more efficient to use natural gas directly.

'Green hydrogen' is produced by electrolysis, from water, the term 'green' signifying that it uses electricity from renewable sources. However, the conversion efficiency is approximately 30%, that is, if the electricity is used directly in a home rather than to electrolise water and then burn the hydrogen in the home, there is a saving of 70%.

Green hydrogen only makes sense when it can be used as a form of battery, if surplus electricity can be converted to hydrogen at times of grid supply/demand mismatch, stored, and then pumped out into the gas grid.

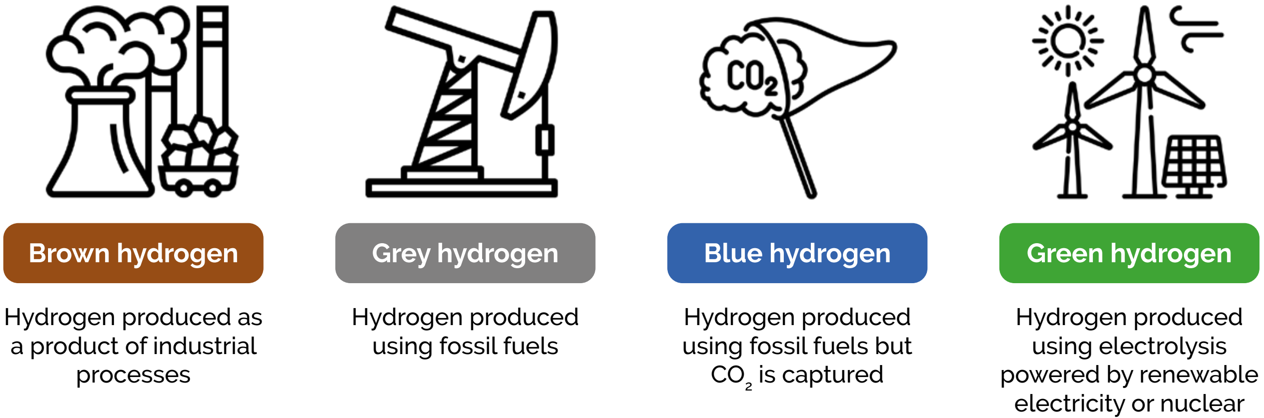


Figure 2 - Types of hydrogen fuel

The problem for the UK is the current dependence upon gas for heating, since the majority of homes have gas boilers, and in recent years these have typically been ‘combi’ boilers (i.e. gas instant hot water heaters). This means that weaning the UK off gas is difficult and costly, and there has not been a government programme to do this until recently. To change over 23 million gas boilers to electric heat pumps at the subsidised rate of 30,000 per annum will take 766 years. It is likely that the phase-out will only happen with political actions, for example banning gas for new homes and increasing the minimum price for gas in order to make it uneconomic.

Oil

Central heating oil (kerosene) is delivered by tanker, has to be stored local to the building (in a double walled/bunded tank) and can vary greatly in cost depending upon time of year, supplier and world oil pricing – i.e. it can be an economic fuel in good times, but costs can change rapidly. Oil should be phased out in the move to net zero. As an oil system requires storage space for the fuel, it is likely that oil-fuelled systems will have room for a heat pump replacement.

Coal and wood

Coal, wood and biomass (wood pellets) all need to be delivered to a property and stored securely to ensure they remain dry. This requires space, so it is often only feasible in rural locations or for larger detached properties. Costs are variable, as they are bought from dealers rather than on a standing contract.

Costs

Historically, costing was relatively simple. Each energy source had a price per kWh. Electricity was available on single- or dual-rate tariffs. Economy 7 was the most common dual-rate tariff (cheaper for a designated seven hours in the day, more expensive in the other periods) and used by homes with night storage heaters – otherwise most people were on the standard variable single-rate tariff.

The cost ratio of gas to electricity has been of the order of 1:5 (i.e. gas was 20% of the cost of electricity, per kWh). This has meant that electricity was never cheaper to use than gas – even with a heat pump on Economy 7, and this was the reason why gas became the preponderant energy source for the UK.

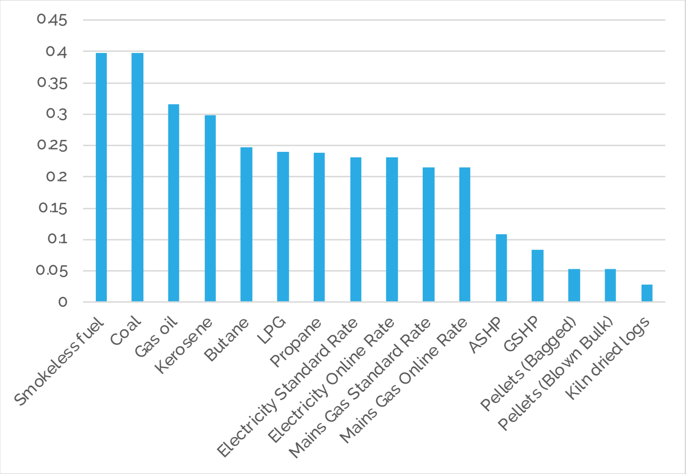
Oil, coal, biomass/wood and propane have been the fuels for off-grid use, purchased at the locally available price, usually more expensive than gas, but cheaper than electricity

In more recent years, costs have changed:

- Electricity tariffs have become more complex. The wholesale price of electricity varies widely by time of day. With the advent of smart meters, it is now possible to offer a tariff that reflects this and flex the price based on the wholesale rate, with safeguards to prevent too large a swing. There have also been new multi-rate tariffs aimed at the flexible electricity users and those with the ability to flex their main energy demands (e.g. timing their heat pump use to suit the tariff, storing heat in thermal batteries and storing low-tariff electricity in home batteries).
- The shock to the energy market in 2022/2023 caused many of these new tariffs to be withdrawn and the majority of domestic customers went over to the government-set tariff. This year innovative tariffs have started to return but the challenge for the consumer will be how to make best use of them. A common feature is likely to be the need for whole-house energy demand control, that is, letting the building decide what to draw, and when, to optimise the energy systems and minimise running costs.
- Gas became relatively more expensive in 2022. From a gas:electricity ratio of 1:5, it has now become 1:2.3. Wholesale gas prices in 2023 have fallen back, but the political challenge for governments is whether to allow the ratio to rise back up again or keep gas relatively expensive. The climate change advice is to make the ratio even smaller to move people off gas but this conflicts with the problem of averting fuel poverty.

Fuel	Fuel price (p per unit)	Unit	Pence per kWh (after boiler efficiency)	Energy content (kWh per unit)	KgCO2e per kWh*
Electricity Standard Rate	39.21	kWh	39.21 (100%)	1	0.231
Electricity Online Rate	38.41	kWh	38.41 (100%)	1	0.231
Mains Gas Standard Rate	11.52	kWh	12.81 (90%)	1	0.215
Mains Gas Online Rate	11.06	kWh	12.29 (90%)	1	0.215
Kerosene	81.23	Litre	9.23 (90%)	9.8	0.298
Gas oil	115.49	Litre	12.71 (90%)	10.4	0.316
LPG	55	Litre	9.04 (90%)	6.66	0.24
Butane	191.2	Litre	29.34 (90%)	7.97	0.247
Propane	158.55	Litre	26.53 (90%)	7.07	0.239
Kiln dried logs	40.01	Kg	11.21 (85%)	4.2	0.028
Pellets (Bagged)	60.9	Kg	14.10 (90%)	4.8	0.053
Pellets (Blown Bulk)	60.17	Kg	13.93 (85%)	4.8	0.053
Smokeless fuel	67.22	Kg	13.38 (75%)	8.51	0.398
Coal	76.4	Kg	12.81 (75%)	6.2	0.398
GSHP	39.21	kWh	11.20 (350%)	1	0.083
ASHP	38.41	kWh	14.23 (270%)	1	0.108

Table 1 - Energy cost comparison – March 2023



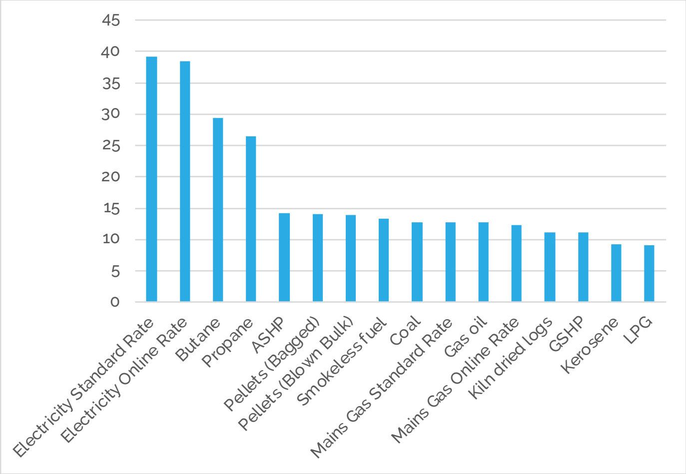


Figure 3 - KgCO2e per kWh by fuel type

Figure 4- Pence per kWh (after boiler efficiency)

*CO2e emissions are based on UK Government GHG Conversion Factors for Company Reporting Scope 3, which includes emissions from transmission and distribution. See https://nottenergy.com/resources/energy-cost-comparison/.

Self-generation

Solar photovolatics (PV)

Photovoltaic (PV) conversion is the primary method to produce electricity from sunlight. Many different chemistries have been developed but the majority of PV systems are based on silicon, with much smaller numbers using Cadmium Telluride. Silicon units are either thin film (silicon deposited on glass/polymer) or monolithic (silicon wafers cut into squares and mounted in a closely packed grid). PV units are typically a composite of a glass faceplate (to protect the active circuitry), a small air gap and then the active layer, with reinforcement behind. The sheets are encased in an aluminum extrusion based 'picture frame' with the electrical connections on the rear of the panel. Panels are mounted using clamps.

Each PV conversion method has an efficiency, that is, the percentage of sunlight falling perpendicularly on the panel that is converted to electricity. Silicon-based panels (2023) are typically 21% efficient while older panels were 16% efficient. Some modern designs are up to 23% efficient.

The three main improvements are:

- Silicon type – most panels were based on P-doped silicon. Newer N-type silicon tends to have about 1% extra efficiency.
- Use of IBC cells – N-type silicon combined with a higher silicon packing density by area to remove busbar shading losses.
- Tandem perovskite cells - Tandem units are not yet on the market and the launch date of production cells has been put back in recent years. Tandem cells differ in using two active layers – an outer layer based on Perovskite and a back layer of standard silicon wafers. The perovskite converts some of the light to electricity but is effectively semi-transparent. Light that passes through the perovskite film is then 'seen' by the silicon cells. It is anticipated that the resulting twin film conversion will be approximately 25 to 28%.

The importance of efficiency improvements is in maximising the output per unit area. For a roof-mounted system the available area is often limited (by building size, roof orientation, and roof/shading obstructions) and for field-mounted large-scale solar farms the area is defined by the land purchased. System mounting costs are constant – per panel – so more efficient panels make the most of the fixed costs.

Key factors in the usability of PV generation on buildings, especially for domestic premises, are:

- Roof orientation and azimuth (slope). South-facing roofs generate the most electricity per area, while East/West roofs generate more energy if both an East and West face can be used. However, they require more panels, as each panel collects about 20% less than a South facing unit. A feature of East/West pairing is that the power is generated over more of the day, at a more constant rate, which is generally of greater use to a building occupant. For flat roofs, more panels can usually be mounted based on high-density East/West mounting systems. South-facing panels create self-shading of the rearmost rows, so waste space.
- Panel optimization. A PV panel generates DC power which is converted to mains voltage AC using an inverter. Panels are connected in ‘strings’ (e.g. six panels in series). To maximise the output, the inverter has to balance the voltage and current relationship of the panel (‘MPPT’). This is done in one of three ways.

  - Inverter-based optimisation – typical inverters run two strings. Each string is optimised based on the worst performing panel in the string. This minimises hardware costs.

  - Panel-based optimisation – each panel, or pair of panels, is connected to a local optimiser and the series DC output from the string is then converted to AC at the inverter. This increases the hardware but allows for panel-to-panel variation.

  - Panel-based optimiser/inverters – the local optimiser output is mains voltage AC and there is no central inverter.

The market is mainly split between string inverters and panel optimisers/central inverters. The lowest-cost string units are suitable for simple/non-shaded applications, while the local optimisation solutions are more cost effective when there are potential mismatch/shading problems.

A side effect, and bonus, of the local optimisation route is that the inverter typically controls the local units and only allows DC to be generated when the system is safe. This means that if the AC power is isolated at the inverter, the roof wiring can be voltage-free, whereas string-based units have live high-voltage DC (700–800 V) on the roof wiring at all times when there is solar insolation – important for both safe maintenance and also in case of fire/fire fighting.

Most domestic installations are single phase. UK DNOs do not generally allow systems to be installed with a rated output of more than 16 A (i.e. about 3.68 kW). When panels had a low rating, a 12-panel roof at 200 W per panel was 2.4 kW – not an issue. Now, with higher power/higher efficiency panels, and with a trend towards making better use of East/West roofs, a home may be able to run 18 panels at 420 W per panels (i.e. over 7.5 kW capacity). To be able to fit these, there are two options:

- A three-phase system – the building needs to be connected to the grid via a three-phase connection. For a new build, this is not normally a cost obstacle but it is unlikely to be feasible as a change for an existing building.
- Export limitation – many inverters can be configured to operate with an export limit. The inverter 'detunes' the panels to ensure that the AC power output cannot exceed a set value (i.e. 3.68 kW). Use of export limitation is likely to be become more prevalent, especially once higher efficiency/output tandem perovskite panels become common.

PV panels on sloping roofs can be mounted 'on-roof' (on aluminium frameworks above the slates/tiles of the existing roof), or 'in-roof' (mounted flush with the roof surface, so that the panels become the roofing material). On new builds that have been designed to maximise PV output, full coverage of a roof surface is desirable – making in-roof mounting cost effective and more attractive. There is a small efficiency loss with in-roof systems – the panels run hotter and PV efficiency drops as the panel temperature rises.

Case study - Solshare

Allume Energy is unlocking solar energy for flats with SolShare; the world's only technology for connecting a single rooftop solar system to multiple flats and sharing the energy fairly between residents, without requiring tenants to sign up for additional billing services or solar trading platforms.

Find out more at https://allumeenergy.com/technical.

Solar thermal (ST)

Solar thermal (ST) is the general term for heat recovery from solar gain. It covers:

- Vacuum tube ST – a set of evacuated glass tubes contain reflectors, and a central heat pipe absorber. The fluid in the heat pipe boils, as it is heated by the sun, and is condensed at the 'cold' end – water cooled. Water is heated, and the hot water is then pumped to a heat exchanger (coils in a tank or an external plate heat exchanger). The circulating 'water' is a pressurised water/glycol mix, to prevent freezing and to allow the 'water' temperature to rise to 150 °C without boiling.
- Flat plate ST – one or more large area (typically 2m^2) flat absorber units, glass faced, with a copper or aluminum serpentine water circuit built into a flat highly absorbent plate. The fluid is water/glycol and is used in the same manner as for vacuum tube ST.
- Roofing-based ST – based on absorber plates that are mounted underneath a roofing surface (e.g. slate). The absorber is usually invisible – the roofing material acts as the solar radiation absorber, and in turn heats the lower plate.

The key differences between the methods are:

- Efficiency under high radiation/summer air temperatures - The flat plate ST units are most efficient per gross area (the vacuum tubes are individually more efficient, but do not fully cover a given area of roof).
- Efficiency under low radiation/winter air temperatures - The vacuum tube ST units are most efficient and have much lower heat losses, due to the vacuum insulation. The flat plate/roofing-based units cannot reach operating temperature under low sun conditions, so stop 'working' for most of the winter.
- Operating position - Most vacuum tube units require the tubes to be inclined, collector at the top, on a sloping roof. A few units are made that can be horizontal, for flat roofs. Flat plate and roofing units can be inclined, vertical or horizontal.
- Stagnation temperature - This is the temperature at which a ST unit 'tops out' – the heat gain = heat losses – without circulation. If a ST unit is not required (e.g. a thermal store is at max temperature, the home is unoccupied), then the circulation will stop. The ST unit now stagnates. For vacuum tube units, this can be at 150–200 °C.
- Some flat plate units also have a special absorber that changes its emittance as it heats and turns off the absorption automatically. These units stagnate at less than 150 °C, so can be run without precautions. Roofing based units stagnate at less than 100 °C – they are inherently lower temperature units.

Solar thermal units can be used in two ways:

- Direct heat – the 'coolant' fluid is circulated, until it reaches about 60 °C. Vacuum tubes can operate in this mode all year, while flat plate/roof units can only use this mode for full sun periods, so are often unusable in winter.
- Indirect heat – the coolant fluid is circulated via a buffer tank stabilising at about 15–25 °C. A ground source heat pump is coupled to the buffer tank, which is the source for the heat pump. The heat pump speed and ST circulation flow are modulated to keep the buffer temperature in range. The advantages of this are that the ST unit operates a low temperature and that the heat pump operates with a relatively high 'source' temperature.

Flat plate and roofing-based units may be plumbed to be Direct in summer, and Indirect in winter – the system automatically changing mode depending upon the insolation level and achievable temperatures.

Combined solar electricity and heat

Combining PV and Solar Thermal creates a PV-T module (PV-Thermal). A PV panel is bonded to a flat plate ST panel. The PV panel is heated by the sun, and in turn heats the ST panel. The ST panel is cooled by the circulating fluid, extracting heat energy, in addition to the PV panel producing electrical energy. In theory, this is a win–win because:

- The same roof area is used twice, once for the PV panel, and once for the ST panel
- The PV panel is more efficient in summer (as it is cooled).
- Reduced installation costs – only one panel is installed on a framework (although both electrical and fluid connections are needed).

However, there is a downside. If the ST panel is run with a low flow, then heat will be extracted at 'high' temperature (60–70 °C). This will produce DHW but does little for the PV panel efficiency – it is not being cooled significantly. If the ST panel is run with a higher flow – to cool the PV panel effectively - then the cooling fluid will be less than 30 °C. This is good for the PV system but cannot be used for space heating or DHW.

Early PV-T systems were high temperature but more recently there has been a move to the lower temperature mode – a hybrid system in association with a ground source heat pump. Just as a ST system can be used as a lower temp heat source for a heat pump, so can a PV-T system.

There is a limitation on the system usage, in winter. On a cold cloudy/misty day, the insolation may be negligible. The PV output will be trivial and the ST panel hardly heats up. If there is snow the panels turn off completely. If the heat pump has no other possible heat source it turns off. In contrast, an air source heat pump will run at zero air temperature.

Wind turbines

Small wind turbines have been marketed for many years but have failed to sell in large numbers. This is because they are not well matched to building use.

Wind turbines are most efficient when the turbine is raised well above the ground and when the turbine is large, so a small unit only 5–10 metres above the ground is likely to be obstructed by other buildings, airflow is reduced, and the air is turbulent/confused.

The rotating turbine is a potential hazard/vibration risk, especially if the system becomes loose in high winds, therefore siting is critical, and the support mast /ground anchors can cost more than the turbine. The result has been that small wind turbines are mainly only installed at remote off-grid rural properties and in windy areas such as the Scottish Highlands. They are not a mainstream energy source.

Water power

It is rare for a building to be able to install water-powered generation capacity (a hydropower turbine to generate electricity). Converted/renovated water mills may still have a functional mill pond, but elsewhere the combination of local geography and licensing restrictions make this difficult to achieve.

Water power requires a head of water – a low head can only be used with large volume (to compensate for the lack of head), and the equipment size increases. High head supplies are only possible in hilly areas and the cost of pipework from higher ground is unlikely to be economic. Use of river water is controlled by the Environment Agency and it is not possible to divert water from a river through a building hydropower plant without a license. This can be expensive to obtain. Licensing is more likely where there is a history of use, for example for disused mill buildings being brought back into use.

Transformation

Heat production

Electricity

Direct electric heating is efficient and has a relatively low cost, but has the disadvantage of no CoP improvement, which means it uses the most expensive energy source. Direct electric heating is often marketed as being economic when used with PV self-generation (i.e. ‘free’ electricity) and/or low cost off-peak grid tariff electricity. This is likely to become an irrelevance in the coming decade, due to EV use. Once electric vehicles become the norm, it is likely that home occupiers will need to use their spare PV output for EV charging. If it is used for direct electric heating, then grid tariff power is needed for the EV charge (i.e. effectively the heating is being run on the grid tariff). Low-cost tariffs (25–30% of standard) may not exist at such a high ratio in years to come. As nighttime EV charging becomes more prevalent, the grid balance will change and the EV tariff cost will rise.

In an ideal world, very little use would be made of direct electric heating – if it is needed, it should be restricted to those situations where it is unavoidable or used at low power/occasionally, especially once the cost of heat pumps falls.

Resistance heating of water/liquids

Most thermal storage units are fitted with electric resistance elements (typically 2–3 kW per element, 1 or 2 elements). The element is embedded in the storage (e.g. an immersion heater inside a hot water tank), so energy transfer to the storage medium is close to 100% efficient.

Immersion elements are low cost and fast acting but only heat the storage medium directly where it is in contact with the element, therefore some form of circulation (convective or forced) is required to distribute the heat throughout the unit. An immersion heater element can be mounted in the output pipework of a heat pump to boost the output temperature if the desired temperature is higher than the heat pump can achieve.

Almost all heat pumps include a booster element but using an expensive heat pump to house a CoP=1 direct electric heating element is wasteful of both the investment and energy, so they are normally only used for occasional backup purposes. The problem occurs when they are used to boost the upper-end temperature output of a heat pump. For example, if a HP is normally only run with a 55 °C maximum output and 65 °C is demanded, then the HP will use the element to boost from 55 °C to 65 °C. This mode of operation could be the norm but the bill payer will then find that their HP is apparently much less efficient than they had thought. It is advisable for use of the element to be made transparent to the HP user so they can see and understand when and why it is being used, and potentially modify their demand/temperature settings to minimise usage.

Electric boiler

An electric boiler is a unit that typically resembles, and is interchangeable with, a gas boiler. The boiler contains a circulation pump, controls, a very small local tank and high-power electric elements. It can be used as a system boiler (i.e. pumped flow to and from a hot water tank/thermal store) or an instantaneous (combi-style) boiler plumbed direct to the load (DHW and space heating). The limitation for combi use is likely to be its power rating – many are approximately 15 kW, and high-power versions are 24 kW, about 30% less than equivalent gas units.

Resistance heating of air/surfaces

Any air-handling system can include a heating element section in the supply ductwork. This can be the primary heating method or a top-up to other heating systems. The advantage of applying the heat into the ductwork is that one heating element may be able to heat a whole home without any additional distribution system (assuming the ductwork is already in place for ventilation purposes). It also minimises the controls and wiring: the element is typically linked to the air handling unit, so there is no need for thermostats in individual rooms.

Electric space heating units have traditionally been 'radiators' – convective units mounted low on the wall. The element is either directly in the airflow, or heats a storage medium such as ceramic bricks, that in turn heat the air.

More recently, domestic heating units have been launched that are branded as 'Radiant' or IR (Infrared) systems. These 'heat the person', and objects, by radiation, rather than heating the air – meaning that the room air temperature can be 3–5 °C lower than would be expected.

Case study - Herschel

Herschel Infrared is the UK market leader in electric infrared heating. Their UK-manufactured heaters are highly controllable, easy to install, and maintenance free. Their newest Comfort range has been tested to the IEC 60675 standard, certifying their radiant efficiency.

Find out more at https://www.herschel-infrared.co.uk/infrared-heating-panels.

In reality, the distinction between convective, conductive and radiant heat transfer is not straightforward, and all three exist for every heat emitter – the balance changes with different designs and surface temperatures.

Radiant transfer is governed by the Stefan-Boltzmann Law – energy transfer is proportional to the fourth power of the absolute temperature. The person and the heater are both radiating, so the temperature difference between the surfaces is critical. The energy transfer from a 100 °C radiant body to a 20 °C clothed person is approximately four times greater than that from a 40 °C radiant body (e.g. a 'radiator' surface).

Heat pumps

One or more heat pumps exist in almost every household – they are at the heart of refrigerators and freezers. A compressor pumps a 'working fluid' between two heat exchangers – high pressure in one exchanger, lower pressure in the other, with an expansion device between them. The low-pressure exchanger will be colder than the high-pressure exchanger – heat is transferred from one to the other. In a freezer, this means that the cold section (built into the freezing compartment) transfers heat to the hot section (metal coils/fins in the air, behind the freezer).

The key feature of a heat pump is that it has a Coefficient of Performance (CoP) greater than 1 – i.e. the heat emitted from the hot section is greater than the electricity consumed by the device, the ratio of the two is the CoP.

If a heat pump is used in a building, it can be used to provide:

- space heating (SH) – the hot section is in the building.
- space cooling (SC) – the cold section is in the building.
- domestic hot water (DHW) – the hot section is heating the water.

Working fluid/global warming potential

The dominant working fluids were hydrofluorocarbons ('F gases', e.g. R134a). All working fluids are rated for their Global Warming Potential, which is the ratio of how much worse they are for global warming, compared to CO_2. R134a, based on a 20-year time horizon, has a GWP of 3400. In the UK, in 2025, new heat pumps and air conditioning units will be banned if they contain working fluids with a GWP of more than 750. In anticipation of this, many older fluids have or are being phased out from heat pump designs. Designs based on R410a (GWP 2088) and R134a (3400) are effectively obsolete.

The main fluid being used in the short term is R32 (GWP 675) but this is only a stop gap since it is likely that by 2030 the EU will have a limit of GWP 150, and possibly even less. This means that the future-orientated working fluids/heat pumps are those based on R744 (CO_2, GWP 1) and R290 (Propane, GWP < 5), the so called 'natural refrigerants'. They are both highly effective but are currently less common for technical and regulatory reasons.

R290 is flammable – it is propane. The EU bans heat pumps from being mounted indoors if they contain more than 150g of R290 fluid. Work is being done to develop highly compact/low-volume systems, but currently only one R290 ground source system (6 kW output) is indoor rated. This does not affect monobloc air source heat pumps, as they are outdoor units anyway, but there is a trend towards having at least some of the unit indoors in many situations. More development work is needed before this is feasible.

R744 is used as a transcritical fluid. It requires a higher-pressure system (so must be constructed to a higher integrity) and operates in a significantly different manner to the other fluids. R744 is most efficient when the output water flow/return temperature differential is high (e.g. 20–35 °C) – this means it is optimal for DHW rather than space heating use.

Heat source

There are two potential heat sources for domestic HP systems – air and water. Air is either the air outdoors, or air within the building envelope (e.g. ventilation system exhaust air). Water can cover a much wider range of options:

- water cooling of the ground, via ground loops, pile loops or bore holes.
- water cooling of fresh water – lakes/rives/streams.
- water cooling of solar thermal systems (PV-T, solar thermal units).
- water cooling of outside air (i.e. an intermediate water loop between the air and the working fluid).

The most common and lowest-cost systems are those based on Air Source (i.e. ASHP) – the technology is shared with air conditioner units made in their millions, worldwide, and the systems are relatively simple to install.

Water-based systems are generally considered to have the potential for higher efficiency and can be used in more versatile ways but have much more limited sales due to the majority of them requiring a ground loop or borehole – both expensive to install.

The reason why water sources (WSHP or GSHP) are more efficient is based on the source temperature. In winter (when heating demands are highest), the average ground temperature in Northern Europe is higher than the average air temperature, so a GSHP is working with a heat source advantage of 5–10 °C. In summer, the situation is reversed and the air temperature is 5–10 °C above the ground temperature but the HP demand is usually less as it is only providing DHW, not space heating. The result is that the winter GSHP usage gives an overall efficiency saving.

However, the optimum system is neither of these but a solar thermal source WSHP with a water/air fan unit backup. The HP uses a water-based source heat exchanger and in winter extracts heat from a solar thermal (ST) system operated in low-temperature mode (15–25 °C) – giving a very high HP CoP. If the ST system is unable to provide enough heat, switching in a simple air/water fan unit can effectively convert the HP into an air source unit. In summer the system will shut down, as the ST system operates in high temp mode. These systems give the highest efficiency/lowest heating cost but demand a systems approach to the design – rather than the supply of a single packaged solution – so are currently rare.

Heat output

Just as for the heat source, the heat output can be based on either air or water. Heating air means the HP is only for space heating. These systems are most commonly based on air conditioning technology. The CoP is relatively good, as room (duct) air is not heated to a high temperature, and Air to Air systems are the lowest-cost heat pumps on the market.

The majority of domestic heat pumps heat water, enabling them to be used for both space heating and DHW.

Heat pump format

The main types used in domestic buildings are:

- **Air to Air**: Mostly derived from single-room air conditioner unit.
- **Air to Water**, which can be:

    - Monobloc: External fan and compressor unit – all in one. Simpler to install compared to split units.

    - Split system: External fan unit and internal compressor unit. Easier for compressor maintenance, with an internal unit but more complex to install.

    - Exhaust air system: Most systems installed have no heat exchange component and the result is that they can be expensive and wasteful to run. The unit extracts heat from a continuous extract and this requires the same volume of fresh air to enter the building (which then needs heating). An alternative format is to couple the unit with an MVHR system. This has the advantage of always working with air that is warmer than the outside temperature, but only by a few degrees.

- **Water to Water**: Compact unit, typically internal, heat exchangers are small and low volume. The complexity, and variations, are in how the unit gets heat from water sources – including ground loops/boreholes, roof solar thermal, and potentially waste heat from other locations.

Source/output temperature difference

The temperature difference between source and output is the fundamental efficiency parameter for a heat pump – the smaller the difference, the more efficient the unit will be (higher CoP). In designing a system, the aim is to minimise the output temperature, and maximise the source temperature. Strategies include:

- Output – for space heating, using low-temperature-based emitters such as underfloor heating and fan-assisted radiators. For DHW, using a thermal store with a FriWa unit and 55 °C output. High-temperature emitters should be avoided as well as DHW storage systems (hot water tanks/PCM stores) that require 65 °C or greater.
- Source – for air source heat pumps, aiming to time shift the HP operation to the warmest time in the day. For water source heat pumps, solar thermal should be used as the hottest heat source.

Output temperature flow/return difference

Most heat pumps, using working fluids other than R744, are optimised for a flow/return temperature difference of 5 °C. This is well suited to space heating but is a problem for DHW.

R744 systems are the reverse – they are matched to DHW duty but become less efficient when run with low Delta T space heating. There is no HP setup that is optimal for both duties.

Compressor operation/control

Older heat pumps ran the compressor at a single fixed speed – i.e. full speed. The majority of modern HP use inverter control of the compressor, allowing for a turn-down ratio of between 1:3 and 1:6, depending upon design. These units will typically have an Auto mode – the unit runs at full speed when first switched on, and then as the target temperature is neared/duty load is reducing, the inverter slows down the compressor to an idle speed. The aim is to run the HP for a longer period, without stop/start periods – in theory, more efficient, and less wear on the compressor due to less startups. However, the optimal CoP speed for a HP is often neither of these speeds – i.e. if the optimal speed is 50%, then running at 100%, then dropping to 30% speed could lead to a CoP reduction of 20%. Running with an optimal speed requires detailed knowledge of the CoP/Speed mapping and an energy management controller that is able to use this data to run the HP in a more optimal manner.

Boilers

Gas boilers

Modern condensing gas boilers are relatively low cost and highly efficient when run correctly. They are capable of producing high-temperature water but to maximise efficiency the output should be limited to 65 °C, if possible, and the flow/return temperature differential should be at least 11 °C – the higher the differential, the more efficient the condensing action.

The problem with gas boilers is that they have become almost too good. They are low cost, easy to install and are often fitted as combi units (i.e. high power, 30–40 kW, without any hot water tank, acting as a DHW instant hot water heater). This causes three issues, for the low-carbon economy:

- The majority of homes use gas boilers. If the UK is to be weaned off gas soon, the obvious replacement (heat pumps) is not a straightforward swap.
- Gas boiler-based heating systems are able to run with small heat emitters and relatively hot water. Although hot water is now considered unsafe (due to the risk of burns from 60–70 °C pipework), this is the way most homes have been plumbed. Conversion to a lower temperature mode requires, at minimum, larger heat emitters.
- New homes are mostly being fitted with combi boilers (i.e. these homes have no hot water tank and no room set aside for one). Therefore, when a heat pump is retrofitted and needs a thermal store/hot water tank, and probably also a space heating buffer cylinder (to allow time shifiting/use of nighttime low tariffs), the challenge is where to put it. An immediate need is for new homes to at least be installed with thermal stores, so that they are heat pump ready.

Hydrogen boilers

No hydrogen boilers are currently sold/used in the UK, as there is no piped hydrogen supply, though the gas industry is working on a route to keep 'gas', under the auspice of hydrogen. This could be done in several phases. First, green hydrogen could be injected into the grid (5–10%), without converting appliances. To go further, a reverse of the coal gas/natural gas conversion programme would be needed, though this could be minimised by making all new gas boilers 'hydrogen ready', that is, either directly able to run with hydrogen or designed to be changed over with minimal attention.

This all assumes that there is an economic route to using green hydrogen, but the problem is that green hydrogen is always going to be more expensive than off-peak electricity. In addition, the amount of electricity needed to produce green hydrogen to satisfy the UK ‘gas’ market is disproportionate to the available supply. The changeover from petrol/diesel to EV for cars is already going to cause an electricity supply issue and there will not be huge surpluses of power that can be used to make hydrogen. The reality is that the green hydrogen economy is unlikely to happen.

Fuel cells

Fuel cells have been touted as an alternative to the hydrogen boiler and their advantage is that they can be used to produce both electricity and heat. However, using electricity to produce hydrogen, and then turning the hydrogen back into electricity, is not an efficient cycle when the alternative is to just use grid electricity directly. Moreover, fuel cell appliances are costly and have only been installed where there are government incentives to do so.

Oil boilers

Normally oil boilers are only fitted in off-grid/off-gas rural locations. They were common in the past but are now declining and likely to be replaced by heat pumps.

Coal boilers/stoves

These were very common decades ago but have been mostly replaced, usually with gas. They require a periodic coal delivery, coal storage and manual refilling.

Biomass boilers/stoves

Biomass boilers have been promoted by UK government schemes on the basis that they are low carbon (like PV). However, there are now major concerns about the validity of these claims. Biomass boilers are fuelled with factory-made wooden pellets. These have a low-energy density by volume, so a large storage bunker is required on site, usually with an automatic pellet transfer mechanism, making them only suitable for rural locations with space for the storage system. The claim is that they are made from tree carbon that is released back into the atmosphere as CO_2 when burnt, but is then converted back into more trees by a circular process that does not increase overall atmospheric carbon. It is claimed that mostly waste wood is used to make the pellets, but a large proportion of biomass pellets are actually made from virgin timber and are imported from the USA. They are not waste and have used energy to produce and transport the pellets.

For these reasons, most biomass boilers have to be considered as fossil fuel equivalent – not to be installed in a net zero economy. The only wood biomass that is ‘renewable’ is that made from 100% waste that would have otherwise rotted to become atmospheric methane and has been sourced relatively locally in order to avoid excessive wasted transport energy. In practice this market does not exist on any scale.

Distribution

Water based (in building)

Water-based distribution uses pipework to send DHW to taps, either copper or plastic, 10 mm to 28 mm diameter. Heat losses will stay inside the building envelope, adding to the space heating Autumn to Spring, but pipes should be well insulated and appropriately sized to minimise losses.

The main issue is 'time to hot' – if a hot tap is opened in a cloakroom basin, the person may have washed their hands before any warm water has come through or wastes water waiting for the heat. When DHW is supplied at 3 bar (i.e. managed mains pressure), 10 mm radial piping may be better for many taps.

Pipework needs to be sized based on real flow rates, usage and distances rather than the historical tendency to oversize (based on low-pressure vented hot water tank supply). Most of the pipework is hidden in the building fabric, so it is important that it is well insulated.

All pipework should be inspected, leak tested and signed off prior to being hidden by subsequent trades. Lack of insulation (cold and hot), incorrect sizing, poor mounting and minor leaks/weeps are all near impossible to correct later in most situations.

Water based (local area)

Heat network (HN) pipework, flow and return, can provide a hot water resource to local heat interface units and extract (metered) heat from the main for use in local space heating/DHW.

HNs have gone through multiple technical 'generations':

- 1st Generation – 1880 onwards, 200 °C steam, coal fired.
- 2nd Generation – 1930 onwards, > 100 °C pressurised hot water, coal/oil fired.
- 3rd Generation – 1980 onwards, 80–90 °C, from coal/oil/biomass/gas/waste heat.
- 4th Generation – 2010 onwards, 50–60 °C, wide variety of sources, including high-temperature heat pumps.
- 5th Generation – 2017 onwards, 5–25 °C, based on the use of both central plant (heat pump, solar thermal, waste heat etc.) and local plant (heat pump per building).

The key difference between the 1st to 4th generation systems, and 5th generation networks, is that the 5th generation involves local heat pumps. The first four systems supply heat 'ready to use' and require high-temperature heat sources and very highly insulated hot water distribution pipework with the attendant losses (and costs). Using a lower-temperature distribution system almost eliminates losses since the network becomes a controlled heat source for a local water source heat pump. 5th generation networks can also be used for cooling – the local heat pump can be reversed in one building, in summer, so that heat is dumped back into the main and in turn used by other buildings for DHW production.

A commercial issue with district heating/heat networks is that they tie residents into the network costings for maintenance and energy pricing. An apartment resident on a 3rd or 4th generation network is not able to buy their energy on the open market. They have to buy heat at the set price from the network which means that they may not be able to take full advantage of off-peak electricity tariffs, seasonal price variations, fixed-period offers and so on. A 5th generation home has to pay for their base heat source (the network), but they manage the electricity supply for their local heat pump.

Air based (in building)

Air heated within air handling units (air conditioning, MVHR etc.) is then ducted to wall/ceiling/floor terminals. Increasingly rigid 'branch' ducting is being supplanted by semi-rigid radial ducting connected to a distribution box. Radial ducting is much easier to install, is leak-free for life and removes cross-talk between terminals (e.g. sound transmission between neighbouring bedrooms).

Flows need to be balanced, ideally by design (calculated duct sizing with tuning discs at the distribution box) to negate problems with terminal adjustments, especially post-installation. Pre-insulated ductwork should be used for cold air inlet ducts and where ducting passes through uninsulated zones within a building (e.g. a cold attic void).

Electricity based (local area)

The current electricity distribution method is for central and local generation to all be 'sent' to the grid, and for consumers (domestic and commercial) to purchase electricity from an energy supplier who pays the local DNO for the local network costs/provisioning. This does not allow for peer-to-peer sales.

For example, if a school had extensive PV on the roof, it will only uses the power for approximately 160 short days per annum – weekends, holidays and the end of the afternoon are all going to result in low-income export to the grid. At the same time, houses around the school, within the same local transformer zone, are purchasing full-price electricity from the grid. Ideally, there would be a mechanism for the school to resell surplus power to local consumers at a price between the two extremes, and make a contribution to the relevant DNO costs. This is not allowed currently, although trials have been carried out to test the principle. It is likely that a form of peer-to-peer supply will happen but only when the market matures and the regulations are revised.

An example of innovation in this area is a multi-site business tariff – a business can register all of their sites with one supplier and create virtual exports/imports from one site (PV roofing, freehold) to another site (no PV, leasehold).

A single building variation on this, that is currently possible, is to use PV/V2G/battery exports. An energy supply company purchases electricity (at times of peak national demand) from consumers (discharged from Vehicle to Home EV batteries/domestic building battery systems, exported from surplus PV). They are also the electricity supplier to the property – charging the battery when the grid has surplus energy and providing the normal electricity supply. The home occupant would then be billed for the difference between their exports and imports from the grid at the appropriate rates. If the consumer is able to use a large EV battery effectively, they may even become a net supplier rather than consumer. Export tariffs are now available at about 60% of import costs – i.e. the whole country becomes a 'battery' for the household, at a cost of about 14p/kWh. Once V2H EV battery systems become the norm, this is likely to be a growth area. This is being piloted in Germany and some trials have been done in the UK. There are implications for battery lifetime and a successful system will require active/intelligent battery management to ensure that the home or EV battery is not degraded prematurely.

Conclusion

The move to a low carbon/Net Zero economy is going to mean an all-electric generation and supply system with self-generation (PV and heat) becoming increasingly cost effective. Widespread EV use will increase household electricity demand, electricity prices will probably rise faster than general inflation, and there will be a drive to maximise efficiency.

Direct use of electricity, for space heating and DHW, will be expensive compared to the use of heat pumps, especially once heat pump prices fall. The next decade is a time of change – new houses will need to be built and equipped to a much higher energy standard but the result should be increased comfort, lower carbon use and lower running costs.

The challenge, beyond new homes, is the existing housing stock – i.e. the majority of homes. Better integrated energy systems are needed, designed for the retrofit market. There is a real need for more comprehensive data from systems suppliers – far too many systems are marketed based on slogans, not facts. The days of low running-cost, high-temperature gas combi-based energy systems are gone, and the replacements will cost more to buy, with greater potential for poor system design leading to excessive running costs.

About Build Net Zero Now

The Build Net Zero Now campaign, led by the Good Homes Alliance, aims to empower progressive local authorities, housing associations and housebuilders, and their supply chains, by providing them with the knowledge and tools to deliver net zero housing.

Following a year-long series of topical events and targeted outputs, including new and freely available net zero case studies and design briefs, phase one of the campaign concluded at the GHA Build Net Zero Now Conference in October 2021.

For phase two, three new working groups on net zero finance, energy solutions and planning & placemaking have been launched and tasked with delivering a targeted and much-needed output that will help accelerate the delivery of net zero housing.

Outputs include comprehensive guidance on energy solutions, a 'mini manifesto' and report on how the finance sector should adapt to accelerate the delivery of net zero homes, and a new web portal showcasing the progressive work of local authorities in setting net zero and Passivhaus planning policies.

The campaign outputs have proved vital for the 30+ members of our fast-growing Vanguard (Local Authority), Pathfinder (Housing Association) and Net Zero Developer (SME developer) networks from across the UK, who collectively represent 350,000 existing homes and 120,000 new build homes to be developed in the next 10 years.

Despite the success of the campaign to date, the need to accelerate the delivery of net zero housing is more urgent than ever.

To find out more about the campaign and phase 3 outputs, please visit https://goodhomes.org.uk/campaign/build-net-zero-now or contact Richard Broad: richard@goodhomes.org.uk.

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