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Home Truths about Heat Pumps

Report prepared by Dr. David Strong, independent author, who was comissioned on behalf of Calor to share his views on the performance of ASHP in the UK climate conditions.

Home Truths about Heat Pumps

Over the past decade a number of UK Government reports have repeatedly stated that *"Most low carbon pathways suggest that heat pumps will play a large role in decarbonising the UK economy[1]."* Furthermore, the Committee on Climate Change (CCC) has suggested that the overall cost-effective uptake of heat pumps in UK homes could reach "2.3 million by 2030[2]."

The current UK market for heat pumps is relatively small, with around only 17,700 (mostly domestic) Air Source Heat Pumps (ASHP) being installed per annum. To achieve the CCC uptake by 2030, an order of magnitude increase in the rate of installation will be required. This begs some important questions; "Are heat pumps always the best technology? Do they live up to the performance claims? What are the potential benefits and pitfalls? Is a headlong rush to install millions of heat pumps the most prudent way forward"?

Domestic heat pumps broadly fall into two system types; Ground Source Heat Pumps (GSHP) and Air Source Heat Pumps (ASHP). There are a number of variants including; solar assisted heat pumps and heat pumps for special applications, such as heat recovery from exhaust ventilation air, swimming pool heating etc.

The adoption of GSHP's is likely to be limited, as a consequence of high cost (when compared with a conventional boiler or ASHP) due to the requirement for a deep vertical borehole or a suitable area of land to accommodate an in-ground heat exchanger. GSHP take-up is currently mostly limited to rural areas, where sufficient space for the ground coil is more likely to be available. As with any heating system improper specification, installation, operation and control can have a significant impact on performance. For example, inadequately sized ground coils can cause (in extreme cases) the ground to freeze; resulting in 'permafrost', low heat output, very poor seasonal performance and an extremely low return on investment.

However, I am becoming increasingly concerned by some of the claims being made by manufacturers and installers of ASHPs. I was involved in the development of the first generation of ASHPs in the late 1970s. Although invented over 100 years before, ASHPs were marketed in the early '80s as an exciting new technology - a simple way to absorb heat from outdoor air, to warm the inside of buildings, with the added benefit of being smaller, cheaper and easier to install than GSHP's. It is fair to say that ASHPs have come a long way since then, with more efficient variable speed compressors, improved heat exchangers and microprocessor control systems.

The technology came in for serious criticism during the 1980s because of reliability & technical issues, poor performance and failure to deliver the promised reduction in heating cost. The basic physics and thermodynamics remains unchanged and the climate hasn't changed much, but, regrettably some of the lessons learnt from the 1st generation of ASHPs have been forgotten.

There are many applications where heat pumps can help contribute to the energy efficiency of our buildings, providing excellent performance and real carbon saving benefits. For example, when used for swimming pool heating in spring, summer and autumn months, a well-designed system can be very cost-effective and deliver major carbon savings. Air source systems can also be very effective in recovering energy from building extract systems and from some industrial processes.

As awareness of the potential benefits of heat pumps has increased, so inevitably have the marketing promises being made. There is an often repeated assertion by those with a commercial interest in selling heat pumps that ASHPs *'provide a low-carbon technology for all our space heating needs'*. Before believing the hype it's important to consider, as objectively as possible, the potential drawbacks so that informed and pragmatic choices can be made regarding the type of heating system to be specified.

About the author:

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David Strong is an internationally recognised expert in energy efficient sustainable building design and refurbishment. He has a wealth of knowledge associated with low/zero carbon buildings and is a specialist in whole system thinking, building physics & integrative design. He has a particular interest in eco-minimalism and bio-mimicry – exploiting and optimising the use of natural systems for heating, cooling, ventilating and illuminating buildings. He applies an integrative approach to the design and construction of sustainable/low energy buildings, to deliver significant reductions in capital & operational cost.

Source: www.davidstrong.co.uk

[1] Evidence Gathering – Low Carbon Heating Technologies Dept, for BEIS November 2016.

[2] Sectoral scenarios for the Fifth Carbon Budget, Technical report, Committee on Climate Change, November 2015.

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Performance Claims

The first important issue to consider are the performance claims – most manufacturers state that their ASHPs will achieve a Coefficient of Performance (COP) of at least 3.5 (NB the COP is defined as the ratio of heat output to electricity input).

However, rather like car manufacturers' fuel consumption claims, **there is a world of difference between the performance of a heat pump measured under idealised laboratory conditions and actual seasonal performance 'in the field'**.

To make things more complicated, there are currently at least three different ways of expressing the performance of a heat pump:

1 Coefficient of performance

The coefficient of performance (COP) is determined by laboratory testing at defined source and heat flow temperatures, for example, a 7°C ambient temperature and flow temperature of 45°C. The temperatures at which the COP is measured must always be quoted, otherwise the concept is meaningless.

2 Seasonal coefficient of performance

The seasonal coefficient of performance (SCOP) is a modelled estimate of the efficiency of a heat pump in a given climate. It is based on laboratory measurements of coefficient of performance, combined with the climate data for a given location. The relevant European Standard is EN 14825.

3 Seasonal performance factor

The seasonal performance factor (SPF) is the measured annual efficiency of a heat pump at a particular location. Measuring System Efficiency is based on the **se**asonal **pe**rformance factor and **mo**nitoring (SEPEMO) methodology. This starts from the core HP components only (**SPFH1**), with expanding boundaries covering the supply air fan, or ground loop pump power into the HP (**SPFH2**), backup heaters, including electric immersion for domestic hot water if present (**SPFH3**) and finally, system circulators, or pumps (**SPFH4**). **SPFH2** and **SPFH4** are of particular interest because:

SPFH2 is used as the basis for deciding if the heat pump meets (or exceeds) the definition of being deemed to be a renewable energy technology

- The EU Renewable Energy Directive considers heat pumps as providing renewable energy provided that SPFH2 ≥ 2.54.

SPFH4 Is the most realistic indicator of the HP's actual in-situ performance, since it includes the energy used by all ancillary equipment and thus provides a realistic indicator of likely savings.

Understanding which definition of performance is being used is critical to success. Most manufacturers claim performance based on measuring the COP, under a standard testing procedure defined in EN 14511 and generally provide one headline value – **the COP achieved at an ambient temperature 7°C and a central heating flow temperature of 45°C.**

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Performance Claims

The manufacturers' data provided in Table 1 is typical – a headline COP of 3.69 is claimed at an ambient (outdoor) air temperature of 7°C and a central heating flow temperature of 45°C – however, this falls by over 40% to 2.20 when outdoor air temperature is -15°C. As is often the case, the manufacturers' data is silent regarding the performance under more extreme conditions (e.g. at -15°C outdoor ambient and a central heating flow temperature of 55°C). Other factors will further reduce the COP, so that the Seasonal Performance Factor is always significantly lower than the idealised laboratory COP performance claims – these issues are considered in greater detail below.

Table 1: Manufacturers' specified COP values at different ambient and central heating flow temperatures for a typical ASHP

Ambient Temperature (°C)	Central heating flow temperature (°C)		
	35	45	55
-15		2.20	
-7		2.65	
2	3.84	3.28	
7	4.39	3.69	3.18

It is important to note that heat pump performance is directly linked to a number of factors, including;

- The difference between outdoor air temperature and the temperature heat is delivered at within the building. This is known as the 'temperature lift' – the greater the temperature lift, the lower the overall seasonal performance. **This is why heat pumps work best with low temperature heat distribution systems (such as underfloor heating) and why performance reduces dramatically when a heat pump is required to supply heat at high temperature for conventional radiators and/or to supply domestic hot water.**
- Ice build-up on the evaporator of an ASHP in the UK is a serious problem, with **icing typically occurring whenever outdoor air temperatures fall below about 5°C** (however, this can be as high as 7°C for some systems)
  - The most common method of removing the ice is for the heat pump control system to switch the unit into a reverse cycle mode. When this happens the outdoor heat exchanger (evaporator) becomes the condenser, with hot refrigerant being used to remove the ice. When operating in this mode, electricity continues to be used by the compressor and heat is **removed from inside** the building (i.e. the condenser temporarily becomes the evaporator).
  - Alternatively, some systems use hot-gas bypass or direct acting electric elements to undertake defrosting. **Whatever type of de-icing system is used, the energy requirements to remove the ice can have a dramatic effect in reducing the seasonal performance.**
  - ASHP evaporator ice-up is particularly problematic in the UK because a **significant proportion of winter temperatures fall within the range -5°C** to +5°C coupled with high humidity/air moisture content. Perversely, the energy consumption associated with de-icing is less of an issue in colder locations such as Scandinavia, since the relative humidity (and hence moisture content) of the outdoor air is significantly lower than much of the UK.
- Other factors can also have a major impact on the seasonal performance of ASHPs, including;
  - auxiliary heating (to augment heat pump output under low ambient temperature conditions,
  - the electricity used by an immersion element to provide (or top-up) the production of domestic hot water,
  - parasitic losses such as; pumps, fans, crankcase heaters,
  - poorly insulated and/or excessively long pipework etc.
- Also, of critical importance, is heat pump sizing and control, since rapid on/off cycling of the heat pump will adversely impact on performance and could result in premature component failure.

Independent Performance Trials

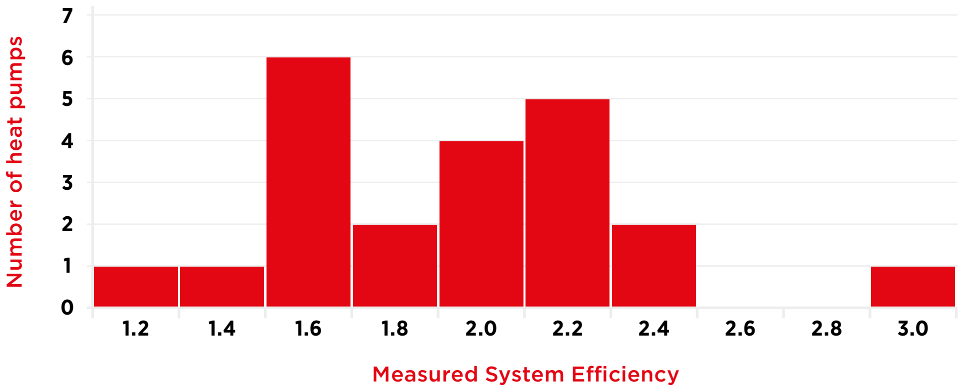
Two major studies have been undertaken in the UK to establish the actual seasonal performance of domestic heat pumps in the field.

The first major field trial was managed by the UK Energy Saving Trust (EST)[3] between 2009 and 2012. The initial (Phase 1) results were published in 2010 - the average system efficiency of 22 ASHPs with monitored data was only 1.94 (see Fig. 1 below).

This result caused much consternation, with manufacturers claiming that the monitoring methods used were unrealistic and with policy makers and specifiers starting to question the veracity of the performance claims. 21 of the 22 heat pumps in the Phase 1 trial had a monitored system efficiency of 2.4 (or less). For a heat pump to claim to be a 'renewable technology' it must achieve a Seasonal Performance Factor (SPFH2) of at least 2.54 to satisfy the requirements of the EU Renewable Energy Sources Directive[4].

Fig. 1 EST Phase 1 Heat Pump trial results[3].

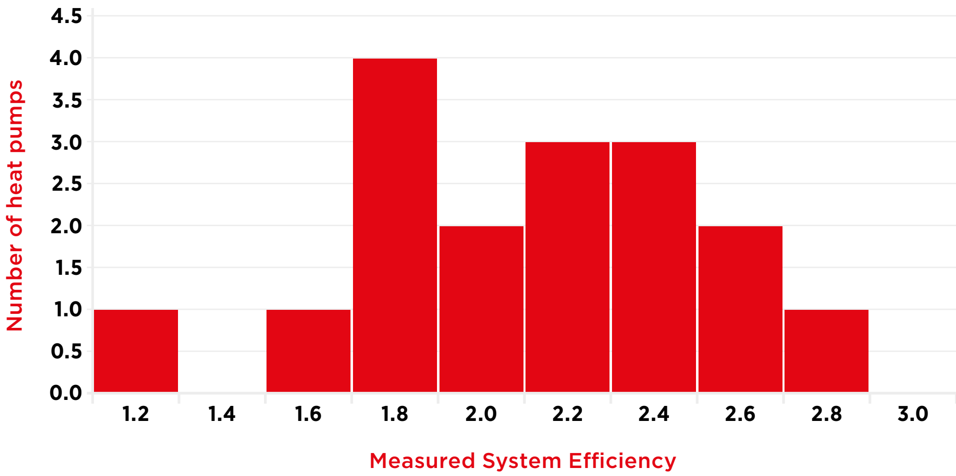
Average System Efficiency = 1.94



A second round of monitoring was undertaken (Phase 2) with some of the very poor performing Phase 1 heat pumps being removed from the trial and with several interventions (some major) being made at other sites in an attempt to enhance performance. The results of the second trial are not encouraging[5]. Monitoring results were provided for 17 ASHPs with the average system efficiency having increased marginally from 1.94 to 2.11 (see Fig. 2 below). These results gave significant cause for concern, since if they are representative of typical ASHP performance, the operational costs and carbon savings claimed by manufacturers and installers are unlikely to be achieved in practice at the majority of sites.

Fig. 2 EST Phase 2 Heat Pump trial results[5].

Average System Efficiency = 2.11



[3]Getting warmer: a field trial of heat pumps. EST 2010.

[4]Directive 2009/28/EC of the European Parliament and of the Council of 23rd April 2009 on the promotion of the use of energy from renewable sources.

[5]Detailed analysis from the second phase of the Energy Saving Trust's heat pump field trial EST & DECC May 2013

Independent Performance Trials

It should be noted that manufacturers and installers were fully engaged and involved in the EST heat pump trials. The trial was not 'blind' – the participants were fully aware that their systems were being monitored, so every effort will have been made to ensure the systems were correctly specified, installed and controlled. **Despite this, most of the systems failed to achieve the criteria to be considered a 'renewable' technology and as a consequence should not have been eligible for support under the Renewable Heat Incentive**. The trial results were very concerning, since if they are representative of best practice achievable by the heat pump industry, it begs the question "what level of performance was being achieved by the thousands of heat pumps which have been specified and installed, with much less scrutiny than the EST's field trial systems?"

As a consequence of the EST trials a second large scale Renewable Heat Incentive Premium Payment (RHIPP) field trial was funded by The Department of Energy and Climate Change (DECC), (subsequently incorporated into The Department of Business, Energy and Industrial Strategy). The resultant RHIPP field trial covered a total of 700 heat pump sites, with 2 minute heat and electricity data collected between 31st October 2013 and 31st March 2015. DECC commissioned RAPID-HPC at the UCL Energy Institute to analyse the data and to publish a final report[6].

The key findings from this trial are as follows:

- The initial dataset used (B2) consists of results from 318 ASHPs and 99 GSHPs. This dataset showed SPFs between 0 and 5.5. The report is silent regarding the distribution of SPF's based on the raw B2 dataset and provides no average values for ASHPs or GSHPs.
- UCL/RAPID-HPC researchers 'cropped' the initial data set to eliminate outliers (i.e. heat pumps which have either very high, or very low performance)
  - Cropping the data was undertaken by RAPID-HPC in 2 ways:
    - **Cropped B2 dataset** – this filtered out data where SPH4 was less than 1.5 or greater than 4.5 – these limits seem somewhat arbitrary and the report provides no clear explanation as to why the HPs performing at less than 1.5 were removed from the analysis
    - **B2 Tukey dataset** – this is (arguably) a more statistically robust way of dealing with outliers – in this case the data was filtered out where SPH4 was less than 1.19 or greater than 3.52 (for ASHPs) and less than 1.47 or greater than 3.98 (for GSHPs)
- Based on the B2 Tukey cropped data the report found that 40% of the ASHPs **failed to achieve the minimum SPFH2 of 2.54 to qualify as a renewable technology** (the value for GSHPs was somewhat better, with 21% failing to qualify. This result for GSHPs is replicated in a further study published in February 2018[7] which found that of the 19 ground and water source non-domestic heat pump installations for which performance results could be presented, only 15 had a performance better than SPFH2 ≥2.5, i.e. 21% failed to qualify).
- It is regrettable that the UCL/RAPID-HPC does not provide a detailed breakdown or distribution curve for the B2 Tukey dataset. The only data presented is the median SPFH2 and SPFH4 values – it is not clear why the median value is reported, but NOT the more highly relevant and revealing average (mean) SPFH2 and SPFH4 values achieved.
- The UCL/RAPID-HPC includes detailed Case Studies from 21 properties. A key finding was:
  - *"…at least 10 out of the 21 cases had experienced some significant problem since installation. Issues as described by occupants included faulty HPs or faulty sub-system, installation and antifreeze problems, condensation dripping from external ASHP units, blockages, a "faulty motherboard", and unintentional use of resistance heating resulting in excessively high electricity bills .... HPs in three out of the seven RSL cases suffered a major breakdown, with heating systems out of action for periods of up to two months."*

[6]Final Report on Analysis of Heat Pump data from the Renewable Heat Premium Payment (RHPP) Scheme, UCL Energy Institute, March 2017.

[7]Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source & Water-Source Heat Pumps Final Report Prepared by GRAHAM Energy Management for BEIS (Department for Business, Energy & Industrial Strategy) February 2018.

Other evidence regarding performance and reliability

There is an increasing body of evidence from Housing Associations, developers and consumers that ASHPs are failing to deliver.

Problems reported include; poor return on investment, insufficient heat output, noise levels and reliability issues and extremely high maintenance/repair costs for component failures outside the warranty period.

Deciding the best type of heating system to specify is not an easy task.

Many factors come into play, each requiring careful consideration, for example:

- Is mains gas available and if not, what are the options?
- Does the existing electricity network have sufficient capacity to support a heat pump?
- Is the optimum heating system for new build the same as an existing dwelling?
- Does the development consist of multiple new dwellings?
- If new build, how highly insulated is the dwelling (i.e. is the space heating demand very small/de-minimis)? If so, is the cost of installing a heat pump prohibitive?
- If an existing house, how difficult (or practical) is it to reduce the space heating demand?
- Is there sufficient land for a ground source heat pump?

These factors (and many others) should be addressed before any decision is made regarding the preferred heating solution for a particular location.

Since average UK domestic electricity cost (16.27/kWh) is about 4 times the cost of mains gas (3.98p/kWh) or 5 times the cost of domestic fuel oil (3.23/kWh) and about 2.6 times the cost of LPG (6.52p/kWh), the actual seasonal system efficiency achievable by a heat pump becomes a critically important issue[8]. If the seasonal system efficiency of a gas or oil system is assumed to be 88%, a heat pump would have to achieve the following system efficiencies to break even against the following alternative fuels on a running costs basis:

Table 3 Minimum Heat Pump System Efficiency required to break-even against different fuel types

	Mains Gas	LPG	Oil
Minimum Heat Pump SPFH4 value required to break-even	3.60	2.20	4.43

If, as suggested by the EST field trials, the actual average SPFH4 being achieved in the UK by ASHPs is around 2.0, then all conventional boiler heating fuels are competitive in operational cost terms against ASHPs. Furthermore the capital cost for a conventional central heating system will be significantly lower than an ASHP.

[8]Fuel cost data based on average 2017 supply costs. Source: Electricity, Mains Gas & Oil BEIS Retail Fuel Price data (Tables 4-8) LPG data based on Sutherland Tables Weighted Monthly Average Price Domestic Bulk supply. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/666406/Data_tables_1-19_supporting_the_toolkit_and_the_guidance_2017.xlsx

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Other evidence regarding performance and reliability

Other factors which should be considered when comparing an ASHP against a conventional central heating system include:

- To achieve high seasonal system efficiency a heat pump requires low operational temperature heat emitters, implying either underfloor heating and/or oversized radiators. This requirement does not exist with a boiler.
- Some form of supplementary heating may be required associated with an ASHP to ensure adequate output in cold weather and/or to provide domestic hot water – such as with a hybrid heat pump system where a boiler is combined with the heat pump.
- An ASHP requires space for the outdoor unit in a location which permits free air movement.
- Noise (from the fan and compressor) of ASHPs can be very problematic in domestic/urban locations.
- The local electricity network may require reinforcement/upgrading before a heat pump can be used.
- If used to also produce domestic hot water an ASHP will require connection to a hot water storage vessel – a combi boiler does not require a hot water cylinder, with benefits in terms of a reduction in space and the elimination of hot water cylinder standing losses (NB in 2010 74% of boilers sold in the UK were combi's[9]).
- Heavy snow can completely block the airflow around an air source heat pump, preventing system operation unless it's manually removed - clearly this is likely to be unacceptable to many householders (particularly the elderly or infirm).
- Conventional boiler systems are easier to control and more responsive than ASHPs
- If gas is available (either mains gas or LPG) utilising the gas for cooking is also an option.

In locations where mains gas is not available, LPG and oil are viable options, however, the high CO_2 emissions, NOx and particulates associated with the combustion of oil gives serious cause for concern. The publication of the Government's Clean Growth Strategy in October 2017 made it clear that it is likely that oil systems will be subject to greater regulation over the next decade, possibly resulting in oil systems either being banned, or becoming prohibitively expensive to achieve the compliance requirements.

LPG remains an attractive option in locations where mains gas is unavailable. Furthermore, the recent introduction of biopropane (derived from waste residues and sustainably sourced vegetable oils), provides new opportunities for carbon reduction. With 40% of the LPG (propane) being from renewable sources and 60% being conventional propane, a carbon saving of between 15 and 32% (depending on the feedstock used) is achievable. Also, new housing developments with multiple dwellings, are increasingly sharing a single bulk LPG storage vessel.

[9] UK Market Update Abdel Eljidi BSRIA 2010

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Summary

Considerable care is required in the selection and specification of any heating system. Heat pumps have high installed costs with requirements for larger heat emitters and the need for a hot water storage vessel.

The EST trials have highlighted serious concerns regarding the seasonal system efficiency achievable in practice and the UCL/RAPID-HCL report identified significant concerns regarding faults and reliability. Heat pumps do have a role to play, but considerable care is required to ensure effective operation and despite the manufacturer's claims, they are not a panacea, or 'magic bullet'.

The optimum approach should always be based on 'fabric first' – reducing the demand for space heating to a minimum and then meeting the heating and hot water demand in the most efficient and cost-effective way possible. In 'hard to treat' dwellings, where high levels of insulation and air tightness are difficult to achieve, a well-designed and competently installed air or ground source heat pump may be a viable option, however, caveat emptor!

In highly insulated new dwellings, with low air permeability, the space heating demand becomes almost de-minimis (particularly if mechanical ventilation with heat recovery is also specified). About 50% of the domestic hot water requirement can be met cost-effectively from solar thermal. The small residual space heating requirement is often best delivered by a highly controllable, fast response, conventional condensing boiler, linked to low water content radiators.

If you would like to find out more about Calor's independent report on Heat Pumps simply email contactcalor@calor.co.uk or call 01926 318 571.

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