PO Box 32, Llandysul, SA44 5ZA Tel: 0845 4569773 Web: www.aecb.net

Air Source Heat Pumps - Friend or Foe

A review of current technology and its viability

A peer reviewed article for the AECB by John Cantor
Editor: Kate de Selincourt

27th July 2011

Background

John Cantor has 30 years experience with heat pump systems. His enthusiasm to experiment combined with a hands-on approach has led to a broad and detailed knowledge of the topic. He now mostly acts as an advisor and consultant.

Heat pumps have for a long time been presented as a 'green' and 'cost effective' heating technology, but there seem to be at least as many sceptics as proponents. Tales of poorly performing systems are not uncommon, but equally, there are plenty of satisfied customers.

There is no shortage of gadgets that don't actually do what the salesmen claim, and it's clear that heat pumps are often over-hyped. Do over-optimistic claims fuel the sceptics' mistrust? What do heat pumps deliver in reality?

In this article we look at heat pump technology and air source heat pumps in particular, since these seem to be gaining in popularity. We look at possible reasons why the reality seems to have fallen short of the claims, reveal some common pitfalls and advise how to avoid (or remedy) them, and offer some pointers to assessing when a heat pump might be good option – and when something else might be the better option.

What is a heat pump?

Heat pumps gain their status as 'renewable' technology because they draw 'renewable' heat from the wider environment (which is ultimately provided by the sun). However heat pumps do also require an input of non-renewable mains electricity in order to function.

The process that a heat pump uses to transfer heat energy from outside to inside is the same one that is used in a fridge. It involves the evaporation and condensation of a refrigerant within a sealed system (see diagram). As with the fridge, heat is transferred from 'cold' to 'hot'. Electricity is required to drive the compressor, but the total heat available is generally two to four times greater than the electrical input.

In the case of air-source heat pumps (ASHP), a large slow-running fan draws outside air through the unit, from where heat energy is absorbed. In the case of ground source (GSHP), antifreeze solution collects the (low temperature) heat as it is being pumped around pipes buried in the ground, either in horizontal trenches, or deep boreholes. The ‘up hill’ heat transfer is made possible by the compressor that enables a pressure difference between the ‘cold’ and the hot’ side of the ‘system. In essence: heat energy is absorbed by the evaporating refrigerant at low pressure, and heat is ejected as it condenses in the high pressure side of the system.

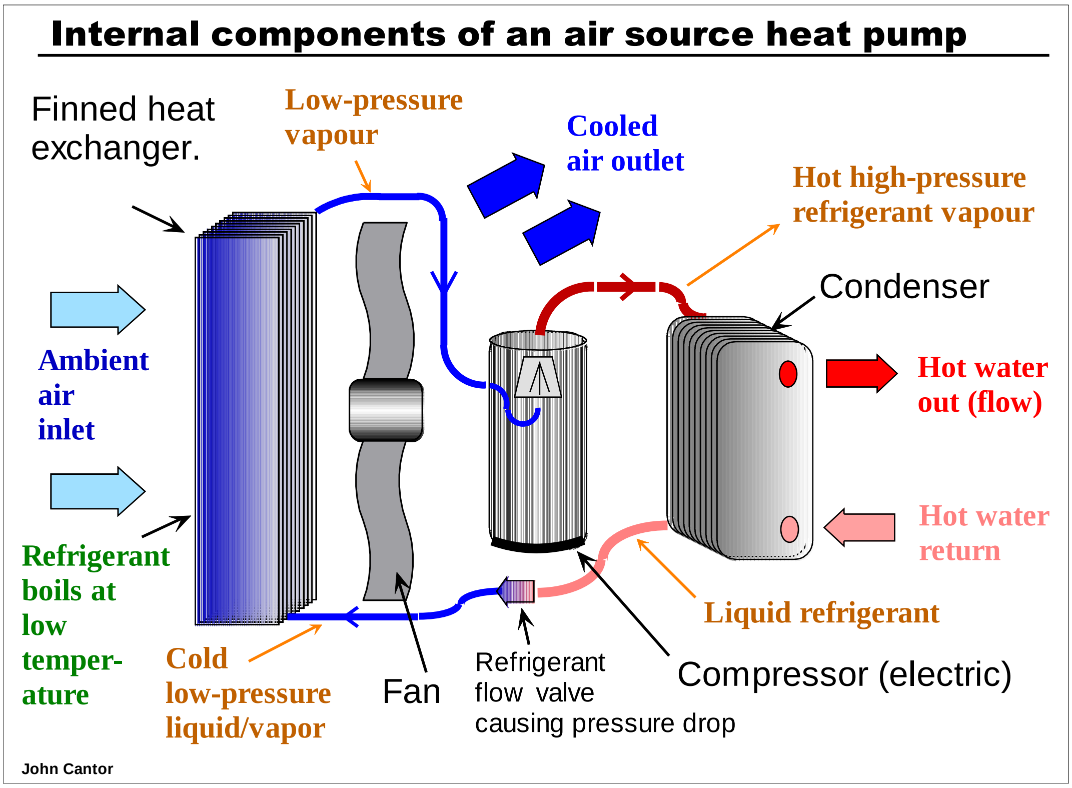

Figure A: Schematic diagram of an air source heat pump illustrating the component parts.

How is efficiency expressed – and can we trust the figures?

COP

COP (coefficient of performance) is a measure of energy efficiency. It's the useful heat output divided by the electricity input. However, the COP is an instantaneous reading. Since the COP will vary dramatically depending on the operating conditions, it should always be quoted for a fixed set of conditions (For air-source these are the outside temperature, and temperature of the heated water produced by the system).

SPF

Because the efficiency of a heat pump varies depending on those conditions – and the conditions of course vary, we really need to consider the average over the year. This is given by the SPF (seasonal performance factor), which is the total useful annual heat produced divided by the total electrical input. The electrical input should include any direct electric 'top-up' heaters which might be necessary to cover any short-fall in the heat output, or to elevate the hot water cylinder temperature, in the case of pasteurisation for legionella protection for example. It will also include any energy used to defrost the heat exchanger in cold weather.

COP values quoted in the data sheets are measured in laboratory conditions and if the conditions are the same, then they can be used to make comparisons between units for those conditions.

However once you get to SPFs (seasonally averaged COPs), 'real world' measurements need to be done, and these are much harder to standardise.

The SPF would be measured by placing a heat meter in the system. This measures the liquid flow rate (liquid being either water or a glycol mix) and also measures the temperature rise (or fall) of the liquid flowing through the system. The heat output is automatically calculated and recorded in kWh. The electrical consumption is also recorded. The ratio of these two values gives the SPF. Since this figure is derived from four variables, and each has its own inaccuracy, the end result can have a considerable error. Heat meters must be calibrated, and the accuracy should be known. Some skill may be required to position the sensors correctly so as to capture the actual useful heat delivered accurately.

Heat is often measured at the heat pump, i.e. the heat given out from the heat pump. However, in the largest set of UK performance data published to date, the Energy Saving Trust field trials, they did something a bit different. EST measured the heat going into the heating system, and measured the heat coming out of the hot water tank. They called this measure the **system efficiency,** and in reality, this is more representative of the whole picture since it includes system losses. Clearly if a boiler system was also tested in this manner, it would produce hot water (at tap) with an efficiency figure far lower than the 90% that might be cited for the boiler. In fact, cylinder losses aside, some recent results from Carbon Trust field studies indicate that boilers fall short of their SEDBUK rated efficiency by around 4-5%. [Micro-CHP Accelerator - Interim Report (CTC726)]

What have we been led to expect?
The selling point for heat pumps is that despite the fact that they use electricity -- a high-carbon, high-cost energy source -- because they use so little of it, they still end up being greener and cheaper to run than conventional heating methods.

Since their first conception, a COP of 3 has been considered the norm for a heat pump - you get 3kW of heat for 1kw of power input (see box – How is efficiency expressed). This general expectation seemed to creep up around 10 years ago, and maybe due to the optimism of salesmen, a COP 4 became the expectation (discounting any highly inflated claims of COP 5 or more!). And as more air-source heat pumps came on the market (also claiming COPs of up to 4), many hoped these would offer a cheaper and easier-to-install way to make similar energy and carbon savings.

However, as described in the box, it is the SPF that we really need to consider. An SPF of 4 is certainly achievable for space heating with a good GSHP, connected to a well designed underfloor heating system in an insulated building. But what are UK ASHP users generally getting overall?

Last year the Energy Saving Trust (EST) published the long-awaited findings of one of the few field trials of heat pump installations in the UK, (http://www.energysavingtrust.org.uk/Media/node_1422/Getting-warmer-a-field-trial-of-heat-pumps-PDF) and this appeared to be something of a reality check. The results, expressed as 'system efficiencies' (see box), showed that for almost all the ASHP installations (heating and hot water), the performance was well below 3.

Of the 22 ASHP installations evaluated, 50% fell within the range of 1.6 to 2.2, with one as low as 1.2, and only one achieving a measured efficiency of 3. While GSHPs performed better, the middle 50% still fell between 2.0 and 2.6.

Studies in Germany and Switzerland, where the technology is better established, have shown SPFs for ASHP installations generally clustering around the 2.5-2.9 mark, with some as low as 2.2, and GSHP installations usually above 3.

	UK	Germany	Switzerland
Air source	• 60% of installations: SPFs **1.7 – 2.2** • 30% of installations: SPFs **2.3 - 3.2**	• Range of SPFs **2.3 – 3.4** • Cluster of SPFs around **2.5 - 2.6** (retrofit) and **2.9** (new build).	• Range of SPFs **2.2 – 3.0** • Half the units in the range **2.5 – 2.8**
Ground source	• Range of SPFs **<2.0 – 3.2** • 30% of installations: SPFs **2.3 - 3.2**	• Range of SPFs **2.6 – 5.0** • Nearly all of which above **3.0**	• Range of SPFs **2.7 – 4.0** • Average SPF **3.4**

Source: Energy Saving Trust; Fraunhofer Institute ISE, Swiss Federal Office of Energy

Figure B Seasonal Performance of heat pump systems recorded in field trials

Figure courtesy of Delta Energy & Environment, www.delta-ee.com, based upon data from Energy Saving Trust; Fraunhofer Institute ISE, Swiss Federal Office of Energy

The EST results were taken by some commentators as 'proving' what a disappointment heat pumps in general, and ASHPs in particular, had turned out to be. Given the high cost of installing any heat pump system, and the relatively high cash and carbon costs of the electricity they use, doubts began to arise as to whether heat pumps really did offer benefits, either to the consumer, or to the wider environment. To cap it all, tales were coming in of dissatisfied people experiencing inadequate levels of comfort, and people in the countryside with electricity bills higher than their previous oil condensing boiler.

What can we realistically achieve?

The first thing to note is that, for reasons we'll go into below, a heat pump can't work at 'optimum' efficiency when delivering hot (tap) water – so in systems producing both space heating and tap water, like most of those in the table above (in all 3 countries), the overall efficiency is bound to be lower than the impressive-sounding COPs cited in some of the adverts.

On top of that, as explained in the box, the EST (UK) results were not a direct measure of the seasonal performance factor, because they added losses from the hot water system to the load, so the actual SPFs (the standard comparison measure) might in practice have been a little more favourable.

However and perhaps most significantly, the way many heat pumps have been installed and set up in the UK falls short of the ideal, so it is little wonder that some performances have been disappointing.

Unlike established technologies like gas central heating, there has been little or nothing in the way of standards for heat pump installations to adhere to. Heat pumps need to be installed to a more exacting standard; they are less 'forgiving' than the technologies that we are used to. So as the industry has been finding its feet on the 'learning-curve', it is no surprise that some installations have had problems

The EST has not published much detail about the installations in their study, but according to a report by Delta energy and Environmental, most of the heat pumps on the EST trial were retrofitted into existing buildings (some recent, some older) – and it is reasonable to assume these installations might be typical of the wider UK picture

The crucial fact is that any heat pump is very sensitive to the way that it is utilised. Its real-world performance will only be as good as the system it is part of. This not only relates to the way the heat pump is installed, but also to the way it is used.

In other words, a heat pump on its own can't give a predictable, guaranteed performance (whatever it might say on the tin). A heat pump only has a <u>potential</u> efficiency. The <u>actual</u> performance is that of the entire system, of which the heat pump is only one element.

By 'system', we mean heat pump, space heating system (heat emitter system), hot water system (tank, pipe-runs), integral electric back-up heaters (if used), heating and HW controls, building fabric – and also the building users. (The weather also plays a role, though of course this cannot be modified!) Any one of these system elements can impact on the overall performance, and in the authors' experience, they often do, and they can in some circumstances impact very badly. There are some very poor systems out there.

The good news is that in many cases, it would be relatively easy to improve things significantly – as discussed below. There are also some excellent installations that take on board the special requirements that heat pumps call for.

That being so, what could ASHPs really deliver in the UK? The short answer is, we cannot yet know, until we start setting up and using them properly, and monitor and report on the performance.

However, combining the data there is from UK and abroad, plus some practical experience, we could take as a starting point that an ASHP correctly installed into an existing UK home, and supplying both space heat and hot water, might achieve on average an SPF of around 2.6. In a new-build dwelling with a lower heat load, and more freedom to specify a heat-pump friendly system, it might be reasonable to expect SPFs of around 3.0.

The SPF of any system has a correlation with the installation cost. If money were no object, systems could be better, and SPFs could be much higher. Systems tend to be a compromise between capital cost and operating efficiency – this applies not only to heat pump installations of course, but many other aspects of building design.

We will discuss below how this level of efficiency matches up to other approaches to heating, in terms of cost and 'greenness'. But if we allow for now that that these SPFs would make an ASHP worthwhile to at least some users in some circumstances, how are these levels to be achieved in practice? In a moment we will discuss how to tune the system to avoid the common pitfalls, and enable the best performance from a heat pump. But first, we will look at why the 'system' matters so much.

Don't torture your heat pump!

The key difference between a heat pump and any other heating system is that a heat pump's energy efficiency is affected greatly by the temperature rise (temperature difference) between the source and heat sink. A heat pump is at its most efficient when heat is supplied to the house's heat-distribution system at a relatively low temperature.

If the pipes from the heat pump are hot, the COP is likely to be low, while a heat pump operating at a very high COP will have relatively cool pipes.

This may at first seem a little perplexing, but it is because the heat pump operates most efficiently when the heat pump 'sees' a low water temperature. In effect, if the heat is transferred away from the heat pump's condenser efficiently, the compressor has less work to do, so the system is more energy efficient. Let us look at a simple graph that illustrates how the COP is affected by the working temperatures that the heat pump compressor 'sees'.

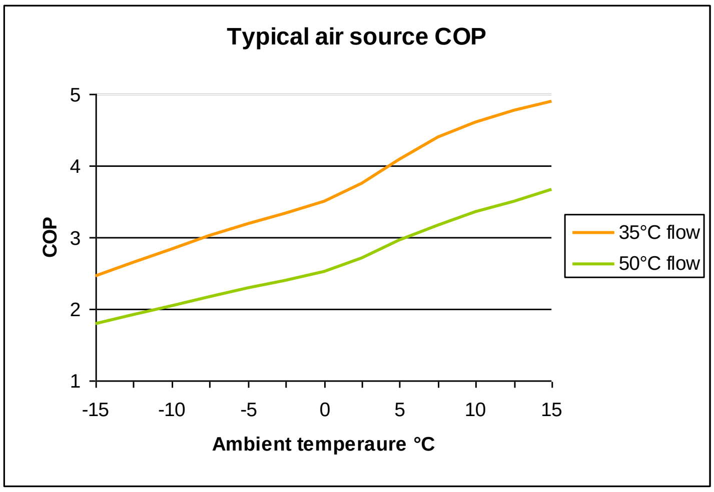

Figure C: Heat Pump efficiency as a function of outside temperatures and flow temperatures
(source: several manufacturers' data)

As can be seen, the COP is greatly affected by the temperatures of both the 'cold' and the 'hot' sides of the heat pump. We'll look at outside temperatures in a moment, but staying indoors, a general rule-of-thumb for heat pumps states that there is about 2.5% system efficiency loss for every 1 degree rise in heated water temperature.

As an example, an ASHP tends to use about 35% more power to supply the same amount of heat (in kWh) at 50 degrees C, compared to when it is running at 35 degrees (which incidentally is often the operating flow temperature chosen for the impressive-looking COPs quoted on the data sheets).

There are numerous elements in the system which can and do impact on the running temperature and therefore the system performance. My observations in the field are that there are a few main reasons for installations not achieving their potential efficiency.

- Emitter circuits not designed to operate at relatively low temperatures.
- Poorly insulated homes that simply cannot be kept warm by relatively low temperature emitters, in cold weather.
- Controls not set up to allow the heat pump to function towards its most efficient operating temperatures.

It should already be clear that simply regarding an ASPH as a replacement boiler, and bolting it into a standard house, with a conventional radiator circuits designed for water temperatures of up to 70°C, is going to be asking for trouble. To get good efficiencies with a heat pump, the working temperature needs to be much lower. This simple fact almost certainly lies behind some of the disappointing results with heat pump installations, particularly in retrofits in the UK.

To make it more complicated, you cannot run a domestic hot water system (DHW) at 35°-40°. So using a heat pump to provide hot water obliges it to work outside its 'comfort zone' (not forgetting that an electric immersion would be much worse, and has an equivalent COP of 1).

Numerous other factors impact on the temperatures that the heat pump experiences – including the number of hours that it is ‘enabled’ per day, the control settings, and heating controls (as determined by both system designer and householder expectations) . We discuss practical ways these can be addressed below.

ASHP’s and cold weather

Just as a heat pump works more efficiently if it is supplying heat at a low temperature, it works more efficiently if it is collecting that heat from outside at a relatively high temperature – it’s all about the temperature difference between the source and the ‘sink’.

The ground source concept relies on the fact that the ground retains heat over the winter. This holds true if the collectors are large and deep. With such collectors, the trench may only drop in temperature slowly as the winter progresses. When the cold weather bites at the start of winter, the GS can run on, collecting from a relatively warm trench, unaffected by the cold above. This system works well, and offers a good COP right in the middle of winter and a reasonable COP at the end of winter. (If the trench is not big enough, the COP can deteriorate considerably as the winter progresses - small trenches can approach ‘exhaustion’ by around February).

By contrast, there is no getting around the fact that an air source unit will operate at its lowest COP during the time when we need most heat – when the air is coldest. An ASHP might lose around one third of its efficiency when the temperature drops from 10^{o} to zero.

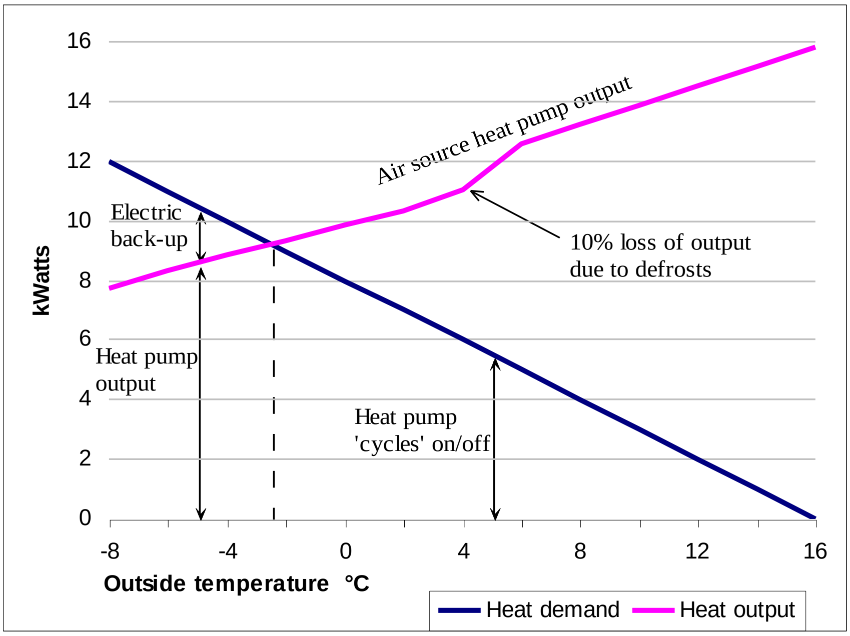

Figure D: Heat pump output and heat demand at different outside temperatures

The graph above shows a typical air source heat pump heat-output performance (magenta line) relative to air temperature.

Web: www.aecb.net

The lower the outside temperature (or the greater the 'uplift') the less heat is produced for the power drawn – in other words, the efficiency drops. Thus while the COP of a heat pump is fixed in known conditions in the lab, the actual performance in real life depends on the weather- which can't be controlled by the manufacturer.

The heat demand of the building (blue) has an opposite slope – the colder it gets, the more heat the building needs.

At the point where the two cross, the heat pump would just provide sufficient heat. Any colder than this point and extra back-up heat is required. In milder temperatures the heat pump will either 'cycle' on and off, or slow down if it is a variable-capacity inverter type. In our example the cross-over or 'balance' point happens to be around -2^{o}C. If we choose a larger heat pump, the pink line (pump heat output) would shift upwards, and the triangle representing the 'back-up' heater (often direct electric) would get smaller. (And of course if the fabric of the house was improved, the blue demand line would shift down, and again, the backup triangle gets smaller). The number of hours per year below, say -2°C is relatively few, so the percentage of energy supplied by the electric heater should be relatively small. However, if the heat pump is too small in relation to the owner's individual comfort demands, then the quantity of heat supplied by the electric heater could be significant.

This graph, whilst illustrating the principles, is an oversimplification of a dynamic process. There are delays in the rise and fall in space heating demand from the building following changes in outside air temperature; the time lag depends on the mass, airtightness and insulation of the building, which may 'buffer' a building over a cold night between two milder days. It also ignores solar gain.

Note also that most of the modern Japanese-design units are variable-capacity 'inverter' types. These tend to give a fixed output independent of conditions, down to very low outside temperatures, at which point the output may drop by around 20%.

Defrosting

As air passes through an ASHP, and heat is extracted, moisture will condense on the fine fins of the heat exchanger. This improves the energy efficiency slightly for much of the time by adding the latent heat of condensation to the heat collected. However, when the air is around 6°C and below, this moisture can freeze and block the air passage, thus greatly impairing heat transfer, so a method of defrosting the heat exchanger must be used. Some defrost mechanisms inject 'hot gas' refrigerant to warm up the outside heat exchanger, but most are the 'reverse cycle' method, since this is more reliable in all conditions. Effectively, the whole system is thrown into reverse for a few minutes to melt the ice with heat from indoors.

There is a lot of uncertainty about the energy penalty incurred due to defrosting, so I recorded the way my own ASHP performed in very cold weather. As defrost starts, the fan stops. The defrost duration is variable, and controlled by temperature/pressure sensors. My observations show that on average the defrost sessions last around 4 minutes. It seems that the 'negative' heat recorded (cooling the house) on the heat meter was made up again after about 6 minutes total duration ie 6 minutes running period with zero net heat. Defrosts seem to occur on demand no more than once per hour – and the compressor power does go down a little during defrost.

In this instance, the average reduction in heat output was around 10% (at worst times - this being humid air around 3°C to 5°C). As the temperatures drop, the actual water content (kg/kg) drops, so defrosting will become less frequent. All in all, according to manufacturers' data defrosts seem to account for something like 5% of the total. That said, defrost methods on cheaper units may be quite crude, and average losses could greatly exceed 10%.

I have always been an advocate of large heat exchangers since they generally give better COPs, and may not require a defrost at all above say 4-5°C. However, it must be said that current heat pumps, using small lightweight heat exchangers, do make for quicker and more efficient defrosts. There are some inflated concerns over defrosting, but most COP v temperature curves now include defrost losses.

However, more independent, published research is needed to establish unequivocally how efficiently each model deals with frosting. A standardised comparison of the defrost energy penalty, perhaps summarised in a "defrost efficiency rating" might help informed, fair comparisons to be made.

Whilst the COP may only drop modestly on better machines in cold weather, the defrost down-time is another issue, and not ideal at a time when full capacity might be needed. Since the total heat output drops significantly as the outside air temperature drops, this, coupled with the reverse-defrost, shows why air source heat pumps are more likely to require some form of back-up from an alternative conventional heat source. This is often provided by a conventional electric heater.

Sizing for the cold

Heat pumps are often given a nominal output rating, and one can see from the graph above (figure D), the output of this particular heat pump can vary from 8 to 16kW. The nominal rating is often quoted at 7°C. In this case, it might be stated at 13kW. Whilst variable-capacity 'inverter' types will give a mostly constant output, standard models will not; at -7°C their output drops significantly (to 8kW in our example). The output of all types will reduce at -10 or -15°C. It is therefore vitally important to ensure that the rating relates to your expected conditions. The graph ignores the supply of domestic hot water, which can also affect the heat output available for space heating, and must also be taken into account when sizing (although it should be noted that for most homes, the average kW demand for hot water over the day is relatively small).

The danger of incorrectly assessing the heat pump's output relative to heat demand is that there could be insufficient heat, and this may result in significant use of back-up heating. If (as is usual in the UK) the backup is electric, this may lead to higher than anticipated electricity bills, and worse carbon performance than hoped for.

Concern about the extra impact of direct heating has been taken up by MCS (the industry certification scheme), and it seems likely that future heat pump standards will specify the need to cover the design heat load without reliance on direct acting electric heaters for all but the coldest 1% of hours in the year. (More info on proposed standard available at time of writing from http://www.microgenerationcertification.org/consultations

A heat pump sized like this should be able to cover all but the most exceptional cold without backup in a building with a reasonable fabric though, particularly for non-inverter types, power demand could still rise significantly when it's very cold – and for all types of course the power demand goes up because the house needs more heating.

There is an issue here for national energy strategy. The COP of most ASHPs drops considerably during a cold snap, and of course approaches 1.0 when integral direct-acting electric heaters (if fitted) are engaged. These issues raise questions about the likely impact on the grid, at times of extreme cold and peak demand on the grid, of encouraging a technology that draws a high load just at those times.

This may not really be of concern to the individual (so long as we have a secure power supply), but it may become a concern for the supply utilities – and if the demand cannot be met, will indeed become a concern to individual consumers as well. For a closer look at the questions raised, see the box 'Questions Arising' on page 23.

Air-source versus ground-source

As we saw earlier, recent real-life studies in Germany on 'typical' air and ground source systems indicate that the SPFs of air source fall behind ground source by about 20% - and the greater impact of cold weather on the performance of ASHPs is probably the major reason for this difference.

If we consider the 'source' of both air and ground, there is little to go wrong with an air source installation – so long as the air supply is not restricted or the unit hemmed in. However, it is likely that some of ground source systems studied still fall short of their potential, due to poor design of the ground loop (for example, insufficient collector size for given ground conditions, or design that demands more pumping power than necessary). So with ground-source systems there may be opportunities for improved performance on both 'sides' and therefore more scope for increased SPFs than with air-source. However, as with the heating system design, there is always the danger that cost pressure will 'trim back' the performance.

Designing a heat-pump friendly system

Going back indoors, we have seen that if an air source system were to be fitted in place of a boiler, without making changes to the system, then the energy efficiency is likely to be low.

Possibly the most common mistake to date has been with emitter circuits operating at too high a temperature. A reminder; the general rule-of-thumb for heat pumps states that there is about 2.5% system efficiency loss for every 1^{o} rise in heated water temperature, so little details can have a significant effect.

To allow the heat pump to supply heat efficiently, ideally at around $35\text{-}40^{o}$, the emitters need to be larger and they need to be 'enabled' for longer than in our old established methods of intermittent high-temperature heating.

Traditionally we have time clocks that enable radiators to operate at up to 70°C (far too hot to touch), then to ‘cycle’ on and off to provide the desired room temperature. Many pre-existing underfloor systems are designed to run up to 50°C, still much higher than the ideal for a heat pump.

So to heat a building using the lower emitter temperatures that suit a heat pump, emitters need to be larger, and running times generally longer (see Controls below).

One often sees rule-of-thumb suggestions that radiators need to be only 1.3 times bigger than 'normal'. This is almost certainly not enough to deliver a reasonable level of heating at the 35-40^o at which heat pumps perform best.

However, if some energy reducing measures have been applied to the building and a more continuous mode of operation adopted, then if there are enough of them, it can still be possible to use radiators successfully at surprisingly low temperatures. In order to approach ‘ideal’ conditions for the heat pump, the radiator area may need be roughly double familiar sizes, and for some situations, the use of more compact fan-convectors might be appropriate; these that have improved greatly in recent years. The important thing is to calculate the load, size the emitters correctly, and set up the controls properly too.

Radiators can of course be added/modified, but new and existing pipework must also be adequate (see below). However in most cases, radiators are generally a poorer fit with a heat pump than underfloor heating.

A point about underfloor heating sometimes missed by specifiers is the floor covering. Tiled surfaces are considerably better than wood at transmitting warmth from buried pipe to room, and may allow a water temperature up to be 5^o cooler, resulting in at least 10% saving. However, a few rugs placed appropriately may not affect the COP significantly.

Heat pump choice, impact of controls
Traditionally we have sized boilers to give us plenty of heat. It's not uncommon to let houses go cold when we are out (or at night), and set the controls and size the boiler system so it can blast in the heat as necessary - it doesn’t cost a great deal more on installation cost to accommodate this extra boiler capacity, and it doesn’t affect the boiler efficiency greatly.

But to heat a house up quickly enough from cold like this using a ‘wet’ heating system, the emitters need to get hot, not just warm. Asking a heat pump to heat up a building quickly from cold in this manner will result in a lower COP. Added to this, there is the risk that supplementary heaters may automatically be engaged more frequently (over the year) if this strategy is adopted. Furthermore, fitting a heat pump with capacity that is greater than the design heat loss, simply to provide the fast heat-up, is expensive.

So it is more economical to fit a relatively small heat pump, and to expect it to be running for most of the time in mid winter, and the heat pump can be sized accordingly.

This then requires a different approach to the heating controls, with householders understanding that heating should be left ‘enabled’ more continuously, and that the familiar on/off time-clocks don’t really fit the bill.   Occupants either need to engage more with the heat pumps integral controls, or the controls need to be better designed so pitfalls are avoided.

The idea is to avoid sudden demands for heat, but to allow the pump to work steadily so the building never requires a fast heat-up. So if the heating has too low a night set-back temperature, (say 16°C), the heat pump may rest for much of the night. In the morning the controller senses that the temperature is too far below the desired morning temperature, which could result in unnecessary switching in of the electric back-up heater. In this instance, having a night set back of maybe only 1.5^{o} below day temperature is likely to be a better strategy, as it will minimize electric heater use – effectively providing more of the day’s heat from the heat pump

Fit good electronic controls, and set them up to ensure the building never gets so cold that the heat pump’s relative sluggishness is an issue. Check that the controls are comprehensible to the user (some seem fiendishly complex) – check they both know how the system should be run for optimum performance, and how to set the controls to get the system to behave that way!

Weather compensation

As we know, the lower the heating supply temperature, the better. It would therefore seem sensible to vary this temperature, dependent on outside conditions, so it is no higher than it needs to be, and this is exactly what weather compensation does for you. To give an example – if at -5°C outside temperature, the emitter circuits require water at 40°C, then at +5°C outside temperature, the water could be reduced to around 33°C, thus saving 17% (given 2.5% improvement in COP per 1° drop in water temperature). Almost all heat pumps include this form of control since the potential savings are so great. It is vitally important to set this control up correctly, and is usually done by trial and error.

This control is fairly straightforward for ground source systems since their performance is not affected by the outside air – only the load is. However, for air source systems, the COP reduces as the air source gets colder, so this control needs setting up a little more carefully. Manufacturers’ guidelines should be followed carefully. Seasonally adjusted emitter temperatures may be one solution.

Pipework & pumps

To maintain the low supply temperature that delivers good efficiency, the water flow rate must be relatively high. If flow rate is low, then the heat emitter system will have a relatively large temperature gradient across it, this leads to an overall drop in energy efficiency. For this reason, the pipework needs to be generally bigger than standard, eg 28mm copper is more typical on heat pump systems where a boiler might use 22mm.

It is, incidentally, a mistake to assume that plastic and copper act the same. Since pipes are measured by their outside diameter, plastic pipes of equivalent dimension have a much smaller internal bore size. This has a surprisingly dramatic effect on the flow rate and pressure drop. I have nothing against plastic, but it must be chosen thoughtfully. A typical oversight is adding a radiator with a long run using 15mm plastic, where 15mm copper would have been far better. If too long, it would need to be 22mm.

Another issue is circulation pumps. Sometimes these are running almost continuously just to allow the temperature sensor to see a meaningful reading. Pumps with long run times should ideally be 'A' energy rated. Typically the Germans like lots of pumps. This is not necessarily a bad thing, but this is where power can be slowly guzzled up, thus reducing the effective COP. The pump's speed adjustment is also important. Occasionally one finds flow-rate adjusters overly 'throttled' to balance an underfloor heating manifold. There should always be at least one adjusted to maximum. If the flow is too high, then the pump speed should be adjusted down

Most existing central heating systems also employ Thermostatic Radiator Valves (TRVs). These are ideal for boiler systems where a) the heat output is considerably greater than the room's heat demand, and b) where the heating device (boiler) can tolerate frequent stopping and starting. For a heat pump, TRV use would need reviewing since too many constantly modulating TRV's are not really what a heat pump likes.

TRV valves operate by automatically opening and closing the flow to a radiator depending on the room temperature. One is likely to be able to operate with lower water temperatures with systems that have a reasonable percentage of radiators allowing full-flow. For that reason, many heat pumps have the facility for a master room thermostat that can be positioned in a 'lead' room. TRVs would then be used more as a temperature-limit for extremity rooms.

Buffer cylinders can minimise the issues with TRVs , however such cylinders are not always practical. For many UK homes, there would not be the space to fit one. Systems with variable-capacity inverter drives (most modern ASHPs) cope much better with variations to flow-rate, and tend to mitigate the need for a buffer vessel.

In summary: Keep the heated water temperature as low as possible. This cannot be stressed too much. This is the best way to maintain a high COP.

Hot Water System

The hot water function (DHW) of most heat pumps was never that good – it has not been the main focus of development for the technology, partly because in the past we have considered DHW a small fraction of the total, and immersion heaters (with COP 1) were not generally scoffed at.

However, as the carbon, as well as the cost implications of direct electric water heating have risen up the agenda, this has become less acceptable. At the same time, building fabric efficiency has improved so much that in a good new build home, the hot water can form a significant proportion of the total domestic heat load. In a Passivhaus, hot water demand will normally exceed the building heating load. (see http://www.aecb.net/PDFs/Clarke_Grant_Hot_Water_System_Design_2010_Paper.pdf)

As with space heating, the heat pump performance depends a lot on the supply temperature. Because hot water has to be a good deal warmer than you need for the space heating emitters, the heat supplied to heat DHW tends to be more energy and carbon intensive. However, also as with space heating, good hot water system design can go a long way to limit the scale of this efficiency drop.

Existing boiler-design DHW cylinders are very rarely suitable for heat pumps. To minimise cylinder size, traditionally for domestic hot water use, we tend to 'dilute' relatively small tank of hot water, So cylinders have been designed on the assumption that water will be stored at 60^{o}C and the boiler can run at 80^{o} (ie a lot hotter still) to heat the tank. But for efficient use of a heat pump the water temperature should be lower and therefore the tank size (volume) needs to be larger. But the real difference is the heat exchanger coil within.

To get the heat into the water effectively at the lower operating temperature, the heat exchanger 'coil' needs to be much bigger – preferably 3 or 4 times the surface area of that in a standard 'boiler-design' cylinder. An exchanger surface of 3 sq m is not uncommon.

Since there is often an upper temperature limit for a specific heat pump, it is usual to install an immersion heater or other alternative heat source so that the cylinder can be pasteurised periodically for legionella protection. This supplementary or back-up heat may also be used the depth of winter when the heat demand exceeds the output capacity of the heat pump. Since the DHW is less efficient than space heating, it is sensible to allow the back-up to heat the water first, when it is needed.

Energy consumption by a well-designed efficient hot water system is likely to be around 2,000-3,000 kWh per year in a typical house. Further losses in a poorly designed system with long, unlagged pipe runs and inadequate tank insulation can add the same load again. In winter some of this might be useful heat, but much is waste, and at all times it is working the heat pump less efficiently.

Thus it is hardly surprising that the EST system efficiency measurements that included hot water system losses, showed such poor overall performance. The answer is not to disregard these losses of course, but to minimise them with better hot water system design.

New kid on the block

A relative newcomer is the CO_2 refrigerant heat pump. This uses the transcritical cycle which differs slightly to the normal refrigeration vapour compression cycle. The main difference between this cycle and the normal cycle is that there is a significant temperature gradient along the 'hot-side' heat-exchanger. This means that it has potential to heat domestic hot water more efficiency. However, it may not necessarily be as efficient for space heating.

So far as we know, none of these units were included in the EST trial. The jury is out on the future for these heat pumps, but they certainly look promising.

Hot water in ultra-low energy homes

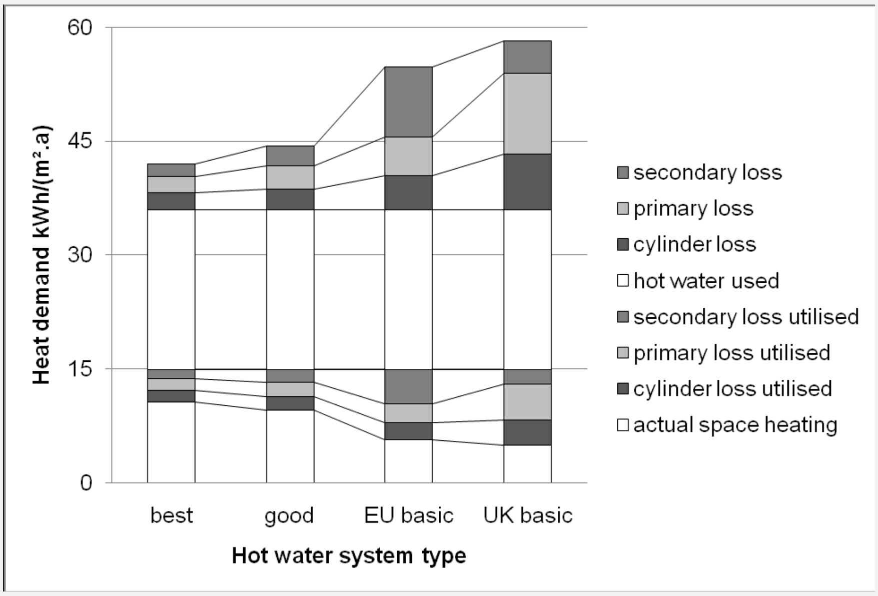

Figure E: Useful heat and wasted heat from hot water systems in a Passivhaus
Graphic from the paper by Clarke and Grant

Graph shows calculated total heat demand in a Passivhaus, where annual space heat demand is 15kWh/m2.

'Useful' losses from the hot water system (grey stripes below the central white section) meet some of the heating load – the Passivhaus "15kWh/m²" is at heart a building fabric efficiency standard, and doesn't take account of whether the heat comes from heating pipes or hot water ones (this is a significant difference from SAP) and in practice a proportion of the 15kWh comes from the hot water system and not the heating system.

Over the whole year, however, you can see that the majority of the losses from the HW system are 'useless' (grey stripes above the white central section). A feature peculiar to heat pumps is that "useful heat" from the hot water system is more expensive, because of lower COP, than actual heating system output.

Even with the best HW design, in a Passivhaus hot water plus losses from hot water add up to around 3 times as much as the actual space heating system output . If the HW design is poor ('UK basic') the HW system may draw an alarming 10 times as much heat as the space heating system.

This means that in a Passivhaus with space and HW both heated via a heat pump, the SPF will be much more influenced by the COP at hot water supply temperature, than at the space heating supply temperature.

For a non-Passivhaus building, you can still see from this graphic that a poorly-designed hot water system will require the heat pump to produce almost twice as much high-temperature, high-cost heat, as a good system does.

Summary checklist:

- Low temperature emitters (preferably below 45 deg) – adequately sized in relation to the heat load
- Correctly sized heat pump
- Correctly sized pipes
- Hot water tank with sufficiently large area coil.
- Controls set so the system is enabled for more continuous operation.

If these conditions are not met, the performance could be disappointing and the competitive advantage in terms of carbon and costs will be lost and – worst of all the customer may even be cold into the bargain.

Has my installer taken all this into account?

Heat pump installers have to take an MCS approved qualification, and would also normally receive training from the company whose heat pumps they install. This training covers the basics and deals with the details of the specific equipment. Many of these training courses are excellent, but It is fair to say that standards do vary, and one does unfortunately come across systems where emitters or pipes are not adequately sized, or a 'standard design' heat pump has been installed inappropriately.

A good installer is crucial to a successful installation. A good installer will take a proper look at the setting and help decide whether an ASHP is in fact the wisest choice – and a good one will be ready to tell you when an ASHP is unlikely to work.

What are air source heat pumps like to live with?

Customers, who are happy, tend to be very happy, feeling they are warm, their bills are lower, and they have no hassles with maintenance or with ordering fuel. Unhappy customers complain of cold, of high bills, and of breakdowns which are expensive or impossible to get repaired. There are also occasional issues with noise (for user and/or their neighbours). The warm/cold and cheap/expensive issues are what the bulk of this article is addressing. Reliability and noise are more a function of which individual pump is selected – the wise specifier will evaluate the reputation of a particular model before making any recommendation.

Are ASHPs cost effective?

While installation costs are high (EST quotes around £6,000 - £10,000 for a 'detached home') these are not always paid for, at least in full, by the householder. Local and national grants have helped with the capital costs of many (some may still be available for example through manufacturer deals with energy supply companies, and a national programme of one-off payments is opening in August 2011 under the Renewable Heat Incentive). ASHPs in particular are also of interest to social landlords looking both to be greener, and to save heating costs for tenants.

The issue of whether the installation will pay for itself in absolute terms depends on the capital cost, energy prices, the building's energy demand, and also on the expected life of the appliance (which is considered later in the article).

However, in most cases, the expectation that running costs will be low is an important part of the equation. So how cheap are ASHPs to run?

The figure below (Figure F) is based on a snapshot of prices (early 2011) and suggests that with a heat pump with an SPF of 3 the user would currently enjoy running cost savings not only over direct electric heating, but also over oil and LPG.

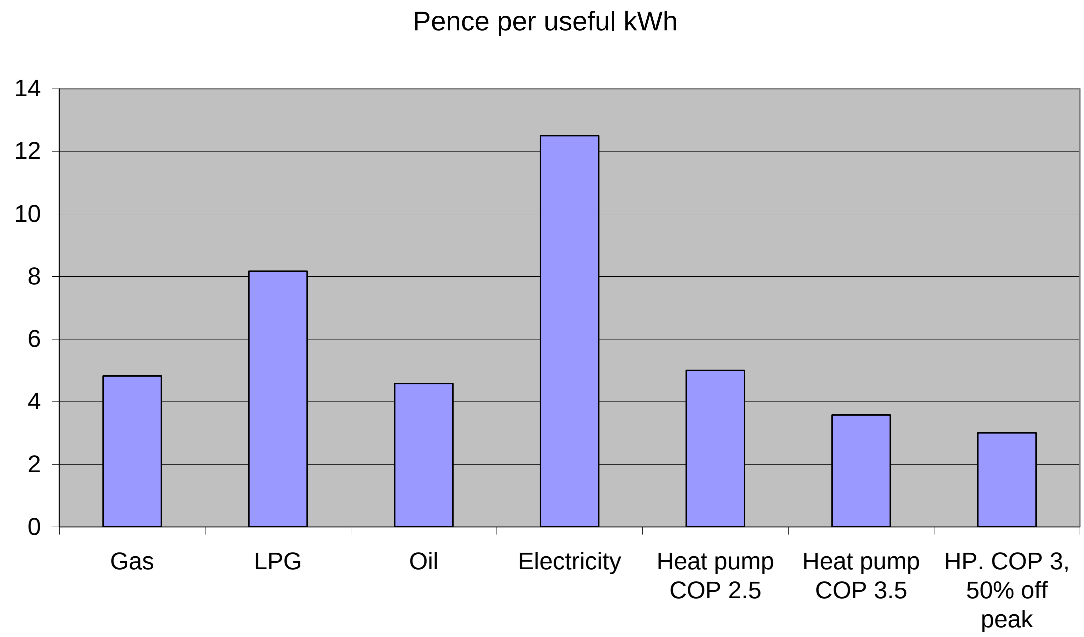

Figure F Cost of heat from various fuels/systems, prices as at early 2011
(Note this graph does not include off peak storage heating, because owing to the considerable penalty from heat at the wrong time, the data cannot readily be compared with other heat sources. The heat pump running on 50% off peak is assumed to be set for 24-hour running.)

Most ASHP installations tend to be in off-gas areas since the high competing cost of oil, LPG or direct electricity (even off-peak) make a heat pump more cost effective. That said, gas has been creeping up in price, and the breakeven SPF could (at the time of writing) be around 2.6. However given the generally higher associated costs, to have a worthwhile cost advantage over gas one needs an SPF significantly higher than this.

The fuel price comparison is additionally complicated by the possibility of running cost subsidy from the RHI. As no revenue cost incentive for ASHPs has been agreed at the time of writing, we do not address this here.

Durability of ASHPs
Air source units, being outside, are generally more exposed to the weather than snug and dry GS units housed inside the building. This can give rise to some degradation of

components. The heat exchanger fins can corrode in time (especially if near the sea) however, polyester or vinyl coatings are available to almost eliminate this. The actual internal workings of the heat pump are similar to a fridge, and could go on working for 20 years without problem. They are sealed clinically-clean when manufactured, so hardly wear out, and never need an oil change.

There are however a few failure risks as with any mechanical equipment and a worry is the availability of dedicated spares. Whilst compressors, heat exchangers and most components are generic, the electronic controllers are not. Spares could become obsolete for some of the more sophisticated models. In some ways, this favours the 'replace the whole unit' strategy if components become obsolete. Some argue that this is not a bad thing since a new unit will probably be more energy efficient than an old one – though this will inevitably be expensive. It can also be hard to get extensive repairs carried out on site to the same standard as new unit from the factory.

In very general terms, a good air source should last 10-15 years (ie similar to a boiler), a GSHP should last 20 years, or possibly more, and the buried ground pipes may last almost indefinitely. The expression 'you only get what you pay for' may be relevant here.

How quickly might a heat pump pay for itself and can it do so within its expected lifetime?
Well of course the answer to this depends on the (absolute or marginal) cost of the installation, the overall seasonal performance, the amount and cost of the energy required, and the likely movements in energy prices over the period in question.

Grants and incentives do muddy the water here; clearly if the capital costs are lowered through grant assistance , and/or the running cost savings are increased because they attract a subsidy (as potentially available under the RHI after 2012), the payback time will be shorter, and more likely to be realised within the expected lifetime of the appliance.

Some indicative annual running cost savings figures are given on the EST website (http://www.energysavingtrust.org.uk/Generate-your-own-energy/Types-of-renewables/Air-source-heat-pumps) and reproduced here (figures given by EST at June 2011)

Using typical system efficiencies from the EST field trial, and energy prices being quoted by EST in July 2011, EST has modelled the following savings for replacing an existing heating system in a notional 3 bed semi detached home with an air source heat pump.

		Savings from typical performing system 220% *	Savings from good performing system 300%*
GAS	**£/yr**	**-£130**	**£70**
	kgCO2/yr	*-105*	*750*
ELECTRIC	**£/yr**	**£330**	**£530**
	kgCO2/yr	*4,600*	*5,455*
OIL	**£/yr**	**-£40**	**£160**
	kgCO2/yr	*700*	*1560*
SOLID FUEL	**£/yr**	**£175**	**£370**
	kgCO2/yr	*4,475*	*5,330*

While these figures clearly highlight the benefit of replacing both direct electric and solid fuel heating with a better-performing system, they cannot be used to predict the running costs of an ASHP and its nearest rivals (oil, gas and LPG) for a particular setting, or the likelihood of any system paying for itself. To do that one has to have to hand the modelled heat loads for the building in question, the actual installation costs (including changes to heating, hot water and controls) and local fuel prices.

Remember too, that if a combination of energy-saving measures is being considered (for example, cavity wall insulation plus a heat pump), the savings can't simply be added to each other, but must be considered as a whole.

Therefore when selecting possible measures, look at the energy and cost savings and likely longevity of each measure individually, to select the most cost-effective candidates, but model the combination to predict the final running costs and savings.

Of course, the prospect of continually-rising energy prices tends to make investment in all forms of energy-saving more cost-effective.

Are they 'green'?

The graph (Figure H) shows the carbon content of mains gas and oil, and compares it to electric heat pumps with SPF up to 4 1 (Note; an electric heater has a COP of 1).

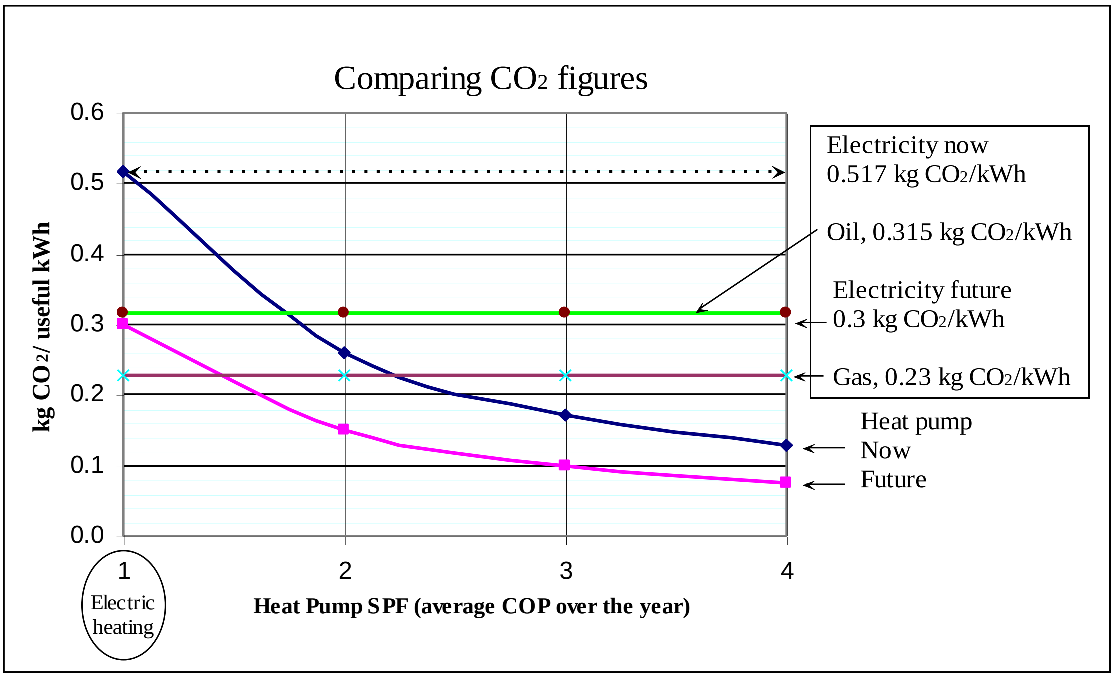

Figure H Carbon intensity of heat from various heat sources (CO2-equivalent figures from DECC)

We can see by the blue line that we would currently need an SPF of 1.7 to achieve break-even CO_2 emission compared to oil, and an SPF of about 2.2 to achieve comparability to gas.

However, for the 'green' claims to hold true, break-even is not enough. To achieve a worthwhile benefit the COP must be considerably better than the break-even figures. For example, if we can achieve an SPF of 3.3, we would reduce CO_2 emissions by 33% compared to mains gas, and almost 50% compared to oil. This level should be achievable for some properties if systems are better installed and operated better.

Sadly, the performance levels reported in the field trials suggest that some installations in some situations are not currently offering much of a green advantage.

The pink line indicates our possible future CO_2 figure for electricity when the mains grid has been partly de-carbonised. This leads to difficulties in assessing the merit of a system – should one consider the current CO_2 figures for electricity, or should one allow for possible de-carbonisation? Should one meet half way? And of course one needs to know the likely life expectancy of the installation.

These estimations are made on the basis of the standard DECC carbon factors for electricity generation in the UK. There is however an argument that we should really be looking at the seasonally adjusted carbon factor, since heat pump systems require the greater part of their electricity in the winter months. The spike in power demand from heat pumps during cold snaps raises additional questions about peak loads on the grid. These are looked at in more detail in the box 'Questions Arising'.

It should of course be borne in mind that if the main motivation for the installation is to cut CO_2. The CO_2 savings from an ASHP installation should be compared with the CO_2 savings from investing a similar sum in a cheaper heating system plus fabric improvements that cut the heat load.

Should we worry about the refrigerants?

One topic that has swayed environmentalists away from heat pump technology has been the working fluid within it. A refrigerant is used to enable the heat transfer, and in the early days the refrigerants used were CFCs or HCFCs, both being ozone depleters. Given that early equipment sometimes used gasketed and mechanical joints that could leak; some early units will have caused more harm than good.

Things have moved on considerably. Heat pumps are generally hermetically sealed (all-welded), and ozone-depleting refrigerants are no longer manufactured. However the common substitute refrigerants still have a high global warming potential. So if the refrigerant is released to the atmosphere, it can negate the very reason for adopting the technology in the first place.

Without going into much detail on this in this article, we can say that the CO_2 numbers due to reduced energy consumption over many years are considerably greater than the equivalent damage that the expected occasional leak of refrigerant may cause. Whilst Global Warming Potentials (GWP) of several thousand times that of CO_2 might sound alarming, one should be aware that there is generally only ½ litre of refrigerant in a heat pump, and the days of leaky equipment have passed, and it is a legal requirement to recover refrigerant from old equipment (See end section - http://www.heatpumps.co.uk/ecology.htm)

Alternative refrigerants have been considered for some time. Hydrocarbon refrigerants like propane are relatively benign, and give excellent performance, but being flammable, there are safety issues. This has unfortunately lead to a reduction in their use. Hydrocarbons are common in domestic fridges, and used in just a few heat pumps. One might expect them to be more appropriate for air source systems where all the equipment is located outside the building.

CO_2 refrigerant is a new contender, and shows promise for the future. It has incredibly high pressures so it too has some safety issues. However, since there is such a small amount, it is environmentally benign.

Customer priorities - is a heat pump right for this customer?

The final choice between a heat pump or an alternative strategy depends on all the variables above – the building, the system, the household and its lifestyle, and the fuel choices available at that location -- but of course must also be seen in the light of the customer’s own priorities. So we can’t answer this until we have asked the customer - Why are you considering an air source heat pump?

Possible priorities might include:

- Lower bills
- Cash in on a grant/save capital
- Save money overall (capital +running)
- Minimise disruption caused by installation
- Lower carbon emissions
- Low maintenance
- No gas main, Oil/LPG/Coal not wanted for variety or reasons (eg dirty, no space, security worries, difficulties with deliveries or with paying for fuel in advance)

The answer might be one or several of the reasons above – or indeed another reason altogether. Even in a given building, depending on the customer's priorities (and also, the prevailing grant regime), then a heat pump might be either a poor or a good solution for an individual customer. The important thing is to ensure all the factors above have been taken into account, and all the relevant calculations are done properly, so a realistic picture of likely performance in that particular setting can inform the final decision.

Questions Arising

The introduction in August 2011 of the Renewable Heat Premium payable towards capital costs for both air-and ground-source heat pumps, expected to be followed by revenue payments at least for GSHPs, indicate that increasing the number of heat pumps is official policy. Figures from BERR from 2008 suggest at that point the government were anticipating perhaps 150,000 new ASHP installations by 2030, and 425,000 by 2050 (cited by National Energy Action in their paper 'ASHPs – assessing the impact for the electrical distribution system'). The capital and revenue subsidies under the Renewable Heat Incentive are to be drawn from general taxation.

The current 'direction of travel' for UK energy policy thinking appears to favour ambitious grid decarbonisation, coupled with widespread introduction of electric heating methods such as heat pumps. This implies support for considerably wider-scale adoption of ASHPs than the figures quoted above.

Implications of a large national programme to increasingly electrify UK heating using heat pumps begs the question of what level of additional drain on the grid would such a programme impose – particularly during cold snaps such as we have experienced over the past two winters. Is such an additional load likely to be acceptable given that the UK may have serious problems keeping the lights on and supplying electricity for other essential purposes as things stand at the moment? The new generating and transmitting infrastructure is paid for in the main via increases in consumers' electricity bills – a burden arguably falling disproportionately on lower-income households. How much will it cost us to beef up the electricity infrastructure to ensure it can cope and to provide the investment to develop the extra electricity generation capacity required, whilst existing 'firm' electricity generation capacity is falling? And what is, and will be, the carbon-intensity of electricity generated in cold periods – the electricity preferentially used by ASHPs?

These and other critical questions are being addressed in the forthcoming AECB report, *"LESS IS MORE: Energy Security After Oil" (LIM) by David Olivier and Andy Simmonds* - to be published on www.aecb.net during August – look out for the announcement.

Introduction to "LESS IS MORE":

"LESS IS MORE: Energy Security After Oil" (LIM) owes a good deal to a series of three earlier reports which appeared after the 1970s first and second oil crises. These studies were in part government-funded:

- *An Alternative Energy Scenario for the UK* [i]
- *A Low Energy Strategy for the UK* [ii] and
- *Energy-Efficient Futures: Opening the Solar Option*. [iii]

Moving on 30 years, energy is again at the centre of UK attention. This time, the concern centres on climate change. But issues which were topical then, such as energy security and the serious burden of energy costs on the UK economy, have not gone away. They continue to be acutely pressing.

LIM tries to address the problem as a whole. It identifies ways forward which might help to resolve all the above concerns, not just address one of them at the expense of others. It is written in the context of other recent studies of the UK's energy future, which include:

- *Zero Carbon Britain 2030* [iv]
- *Sustainable Energy Without the Hot Air* [v] and
- *Scenarios for 2050 - A Key Scene Setting Report*. [vi]

The title *LESS IS MORE* signifies a view that the UK's energy security and economic well-being after oil depends on much more extensive investment in energy efficiency, in all its forms. It is the only future bulk energy option which appears to compete with fossil fuels.

The sub-title *Energy Security after Oil* reflects the fact that the UK's energy system is noticeably insecure, for instance in its low level of natural gas storage, its high coal imports, its growing natural gas imports, its high dependence on unpredictable regimes for oil and the concern about "keeping the lights on" as old coal, nuclear and oil power stations are closed. The position is deteriorating steadily as indigenous fuel production declines. Under present policy, we fear that it would not improve.

---

i Todd, R, et al, *An Alternative Energy Scenario for the UK*. CAT, Machynlleth (1977).

ii Leach, G, et al, *A Low Energy Strategy for the UK*. ISBN 0-905927-20-6. IIED, London (1979).

iii Olivier, D, et al, *Energy-Efficient Futures: Opening the Solar Option*. ISBN 0-946281-02-5. Earth Resources Research Ltd., London (1983).

iv Kemp, M, ed., *Zero Carbon Britain 2030*. ISBN 978-1-902175-61-4. CAT, Machynlleth (2010).

v Mackay, D, *Sustainable Energy Without the Hot Air*. ISBN 0-954-45293-3. UIT Cambridge Ltd. (2009).

vi *Scenarios for 2050 - A Key Scene Setting Report*. UKERC Energy 2050 Project. http://www.ukerc.ac.uk/support/tiki-index.php?page=Energy+2050+Overview