STATE OF THE ART IN GAS DRIVEN HEAT PUMPS

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SUMMARY

All of the products currently on the market or known to be under development are being developed by European companies. The market leader is Robur, with ammonia-water absorption heat pumps available in air, water and ground source versions with nominal heat output around 40kW. GUEs in the different versions are higher than competitors. Water at up to 70°C can be produced but the GUE under these conditions is generally not available. A half-size version is under development. The present machines are single outdoor packages.

Vaillant and Viessmann have water-zeolite adsorption machines on and near-market respectively. They are single indoor units, large in size, and when in heat pumping mode cannot produce water hotter than 55°C. They use solar heated water (Vaillant) or ground source heat, air source being unfeasible with water as a refrigerant.

Viessmann are developing a much more compact absorption machine, thought to use methanol as a refrigerant and capable of operating with air as a heat source.

Other adsorption developments are in progress but further away from market. Improvements are needed in size and capital cost to achieve sales, but the efficiencies achieved by Robur are probably sufficient at least in the short term.

1. INTRODUCTION

1.1 Scope

In the past there have been many approaches to the provision of gas driven heat pumps that have reached varying stages of development. Most, but not all, have not gone beyond RD&D to commercial launch. Systems can be categorised as engine-driven or sorption.

Engine driven systems can range from conventional gas fuelled engines driving conventional vapour compression heat pumps to novel engine types, sometimes combined with novel heat pump cycles. In the past, extensive research went into Stirling-Stirling, Rankine-Rankine and other concepts. Whilst some of the more adventurous ideas may still have some potential, the only ones to survive today as commercial systems are conventional engine types (spark ignition or diesel) driving conventional heat pump cycles via open compressors and recovering engine waste heat as useful output. The vast majority of these systems are sized for larger buildings (30kW +) where a strict maintenance schedule can be enforced and economies of scale work well. The major manufacturers are Sanyo, Aisin (Toyota group), Mitsubishi Heavy Industries and Yanma. European sales are estimated at around 10,000 in total [1]. Sales in Japan are an order of magnitude higher. This size range is less suited to the complexity and maintenance of engine driven systems, although in Japan there have been domestic products down to 14kW capacity (Aisin).

Within the EU there is consensus that the way forward for domestic units is through sorption systems and IEA Heat Pump Annex 43 is restricted to this area. The focus of this work (as in Annex 34) is on domestic applications perhaps extending to light commercial.

The Annex scope [2] is:

> … the use of fuel driven sorption heat pumps in domestic and small commercial or industrial buildings or applications. If applicable the additional possibility of supplying cold will also be considered.
>
> Fuel driven heat pumps within the scope of this Annex will be
>
> - Adsorption heat pumps
> - Absorption heat pumps
>
> Gas engine heat pumps are not within the scope of this Annex.
>
> Possible scenarios for the implementation of small fuel driven heat pumps will be:
>
> - New-built houses with low energy consumption.
> - Retrofit of existing buildings
> - Small scale commercial and industrial applications

1.2 Definitions of Energy Efficiency

There are a range of measures of efficiency. Based on a review of current normative documents for heat pumps, Annex 34 [3] proposed three different levels of performance figures, according to system boundaries:

1. Coefficient of Performance (COP) represent the heating capacity of the thermally driven heat pump only under steady operating conditions, divided by the supplied driving power to the unit, without auxiliary electricity or heat but including some corrections;
   Seasonal COP (SCOP) represents the calculated efficiencies of the unit for the same boundary as for the COP, however for defined, time dependent climatic (operating) conditions and user behaviour patterns (e.g. oscillating source temperature, changing supply temperature etc.) for a certain period of time, usually a year.
   All figures are obtained from laboratory measurements under well-defined operating conditions.
2. Seasonal Performance Factor (SPF) is the ratio of the delivered useful energy to the user divided by the consumed driving energy on the system level. Different systems and sub-systems can be defined. Annex 34 proposed five main system boundaries:

   i. Overall system performance including energy distribution system;
   ii. Overall system performance excluding energy distribution system;
   iii. Performance of the system without the influence of storage;
   iv. Performance of each energy conversion unit including all subsystems needed for its proper functioning (heat sources and/or heat dissipation units);
   v. Performance of each energy conversion unit itself, without the influence of "parasitic" energy (energy sources etc.).

A detailed explanation for the choice of boundaries and there applicability can be found in the Annex 34 technical report [5].

3. Primary Energy Ratio (PER) is the ratio of the useful heating and/or cooling energy in relation to the primary energy demand. Preferably, the whole system without energy distribution should be used.

Since gas fired systems generally require both thermal and electrical energy for the operation which are not equivalent in terms of exergy content, price, emissions etc., a clear distinction between a thermal performance factor and an electrical performance factor should be made, except for the PER where all energy sources are valued by their primary energy content. For the calculation of the SCOP, an adaption of the temperature bin method used in a number of standards for electrically driven heat pumps (e.g. Ref 4) was discussed within the Annex.

These distinctions are important and it is hoped that methods of calculating seasonal and system performance will be agreed, but at present the only international standard relating to gas fired heat pumps that allows comparison between different products is EN 12309 Part 2 [6].

The standard defines an equivalent to COP termed the gas utilisation efficiency:

$$\eta_h = \frac{Q_h}{Q_T}$$

Where:

η_h is the gas utilisation efficiency (abbreviated to GUE in manufacturers' literature)
Q_h is the heat output power in kW (may be adjusted to take account of defrost cycles etc as appropriate)
Q_T is the net calorific value of the gas input in kW)
It is important to note:

1. The UK is one of the few countries to use Gross Calorific Value (GCV) of gas, rather than Net Calorific Value (NCV). The GCV is 1.1 x NCV and includes the heat energy that can be obtained if the water vapour produced in burning gas is condensed to a liquid thereby contributing its latent heat to the useful output. Thus, using NCV it would be possible to consider a condensing boiler as having an efficiency of more than 100%. A new version of EN 12309 Part 2 that allows reporting of GUE with either gross or net calorific values should be approved this year. It will also include tests for part load performance and a simplified means of calculating an SCOP (annual GUE based on a temperature bin method).

2. The existing definition of GUE takes no account of electricity use which could be significant. Academic discussion of the most appropriate way of combining gas and electricity use into one number can be lengthy and complex; no one method makes sense in all countries or for all purposes. However, it is expected that the revised EN 12309 Part 2 will use the simplifying assumption that 1 Joule of electricity used is equivalent to 2.5 Joules of gas.

The standard gives a number of set operating points for the different types of heat pump source and sink, as shown in Table 1:

Test conditions		T1	T2	T3	T4
Outdoor air/water	With defrost control	A7(6)/W50	A2(1.5)/W35	A15(12)/W50	A-7(-8)/W50
	Without defrost control	A7(6)/W50	A15(12)/W50	A7(6)/W35	A7(6)/W50
Exhaust air/water		A20(12)/W50	A20(12)/W35		
Water/water		W10/W50	W10/W35	W15/W50	
Brine/water		B0/W50	B0/W35	B-5/W50	

Table 1: Standard operating conditions from EN12309 [6]

The temperatures in Celsius are of air (A), water (W) or brine (B) for air, water and ground source machines and in all cases the output is of hot water. The numbers in brackets are wet bulb temperatures. Thus A7(6)/W50 refers to an air source heat pump with outside air at 7°C (dry bulb), 6°C (wet bulb) producing water at 50°C.

Outlet temperatures of 50°C are assumed typical of radiator systems and 35°C of underfloor heating.

2. TECHNOLOGIES

2.1 Absorption, adsorption cycles

What all sorption systems have in common is that they use the ability of a liquid or solid sorbent to ab/adsorb large amounts of refrigerant to be used in a 'thermal compressor', analogous to the mechanical compressor in an electric heat pump. The refrigerant is ab/adsorbed at a low pressure and temperature, then the sorbent is heated (in our case by burning gas) and the refrigerant is then driven out (desorbed) at high pressure. The fundamental thermodynamics are the same whether the refrigerant gas is being absorbed into a liquid or adsorbed into a solid.

The major practical difference is that liquid absorption machines operate continuously. The absorbent is pumped to different components at different pressures where it can be heated to desorb, cooled to absorb etc and in principle it operates in a steady state. By contrast, since solid adsorbents cannot be pumped from one place to another, adsorption machines all use batch processes; a 'bed' of adsorbent is heated for some time (perhaps a minute) to desorb refrigerant, then later cooled to adsorb. The absorption machines require a solution pump that consumes electricity and in the past has been a problematic component but the system has a steady output. The adsorption machine needs no solution pump but is subject to losses incurred by the thermal mass of its components being cyclically heated and cooled. Adsorbents can be 'engineered' to have specific properties whilst the choice of liquid absorbents is more limited.

<u>Thus there are engineering advantages and disadvantages in using solids or liquids but neither is inherently 'better' and the choice of one or the other in a particular application will depend on the way they are implemented and the resulting efficiency, cost, size, etc.</u>

The history of both technologies [7,8] actually goes back to before conventional vapour compression cycles were developed but largely disappeared from the early 1900s. The exception was the use of Lithium Bromide – water and ammonia – water absorption machines, mainly for air conditioning but also for gas domestic refrigerators.

Absorption/adsorption heat pumps have had a revival from the late 1970s onwards as their potential for reduced primary energy and emissions has been recognised. The basic operating principles are explained in Chapter 2 of the Annex 34 Handbook [9].

2.2 Refrigerants

The refrigerants used by either absorption or adsorption cycles need the same characteristics (high latent heat being the major one) and the three main refrigerants considered for both are the same: water, methanol and ammonia. Water has the highest latent heat by far and so for the same complexity and cost of machine gives higher GUEs. This varies with both the ambient temperature and the delivery temperature but a seasonal average can be calculated for a specific climate and heat delivery system, e.g. underfloor heating, radiators. Given enough clever design and extra heat exchangers etc the performance of the other refrigerants can be as good but this is at the disadvantage of higher capital cost. Water also has the benefits of low cost, being non-toxic, environmentally friendly etc but has one major disadvantage; its very low operating pressure. From a practical point of view it is not possible to boil water in the evaporator of a heat pump at less that about 5°C, when the pressure is less than one thousandth of atmospheric pressure. In the case of an air source heat pump this would restrict the ambient temperature at which any heat pumping could be carried out to more than 10°C which is clearly not sensible. Manufacturers currently working with water as a refrigerant [see below] either have to use the ground (which is warmer) as a heat source or even use solar energy. Both of these result in much higher capital costs and whilst they may have a niche market are not seen as having a large impact in the UK. Where water absorption comes into its own is gas fired air conditioning, where evaporating temperatures are higher and it is generally the system of choice.

Ammonia has much lower latent heat, but none of the other disadvantages of water. It is the refrigerant of choice in large industrial systems, is not a global warming or ozone depleting gas and can be used at ambient temperatures below -20°C. Its higher pressure allows smaller pipe sizes thereby reducing cost. Its disadvantages are that it is chemically incompatible with copper or brass and that it is toxic, however neither of these problems is insurmountable and existing regulations govern the design of refrigerators or heat pumps that use ammonia refrigerant.

Methanol is (in pressure terms) between ammonia and water and although methanol based systems are well below atmospheric pressure is should be possible to use it to extract heat from ambient air at around 0°C. It is environmentally friendly but has the disadvantage that it decomposes at temperatures beyond about 120°C which could be problematic. High efficiency systems tend to need heat input from the burning fuel at higher than 120°.

2.3 Evolution of sorption technologies

In order to understand the state of the art it is useful to know something about the history of development. When refrigeration compressors became reliable and low cost in the beginning of the 1900s sorption systems disappeared apart from absorption ones used for air conditioning, generally heated by steam but also directly fired. LiBr-water air conditioners in large sizes (up to many MW of cooling power) remain a successful commercial sector and there are manufacturers in Europe, the USA, Japan and China. Scaling down to domestic sizes is problematic, partly because of the difficulties of purging air from the low pressure water vapour. MW units have purging devices and maintenance schedules that keep them operating at design efficiency but a domestic system needs to be both completely hermetically sealed and to avoid volatile gases being evolved internally. However a number of companies have produced small (c 10kW) LiBr-water air conditioners, including Yazaki (Japan), EAW (Germany) and Sonnenklima (Germany, no longer in business). All of these chillers were intended for use as air conditioners, predominantly powered by solar thermal energy. The first successful <u>ad</u>sorption chillers used for air conditioning in modern times were water-silica gel units made by Nishyodo in 1986, and then Mayekawa (Mycom) in Japan. They produced large (>70kW) chillers whose key advantage was that they could be driven by heat at lower temperatures than LiBr absorption chillers. This made them competitive in either solar or waste heat driven systems. Encouraged by the Japanese success, in the 1990s and later, two German companies, Sortech and Invensor developed small (10kW) adsorption machines for solar cooling applications, the former using silica gel adsorbent and the latter a zeolite. None of the above companies ever considered heat pump applications.

By contrast, absorption using ammonia-water has always been considered for both heat pumping and air conditioning. Ammonia-water air conditioners never went out of favour completely and were produced by Arkla-Servel in the USA. They tended to be used in niche applications, for example in hospitals where the noise of a compressor driven system would be unacceptable. In the 1980s when there was a resurgence of interest in low energy heating the Phillips Engineering Co. in the USA worked on a GAX (Generator Absorber heat eXchanger) ammonia-water heat pump with a COP of 1.5 [10]. In Germany, ammonia-water heat pumps for domestic use were marketed for a few years but did not become established. In the 1990s and 2000s ammonia-water machines were developed by Pink (Austria) and AGO (Germany), and used mainly in solar cooling applications [11].

Moving into the present, the market leader with ammonia-water absorption machines is the Italian company Robur, who bought Arkla-Servel and its ammonia-water technology from the USA. Thus its products, described in the section 2, are based on a long history and experience.

There have been fewer companies working in adsorption for heat pumping but there has been notable success. The American Gas Research Institute (GRI) funded what were regarded as risky but high potential and longer term solid adsorption projects in the 1980s. GRI and others in the USA funded Wave Air (carbon-ammonia), Zeopower (zeolite – water) and Rocky Research (ammonia – salts). The Wave Air product, a gas fired 3-ton air conditioner/heat pump based on Shelton's thermal wave cycle using ammonia and carbon adsorbent [12] came nearest to commercial success but was finally rendered uneconomic by the de-regulation of gas prices in the USA – a victim of low energy prices. A prototype built in 1993 delivered 12 kW cooling with seasonal gross COP of 1.0 or 24kW heating with a gross COP of 1.3. [13].The study showed that a payback of 5 years could be achieved if capital cost could be reduced by 14%. Field trials and productionising were promising but the development ended when US natural gas prices were de-regulated. It is entirely possible that the thermal wave technology developed in the 80's and 90's was simply too soon in terms of market conditions and that, were it re-launched, it could be viable today. Research in ammonia-carbon adsorption continues today at the University of Warwick and its spin-out company, Sorption Energy, as reported below in Section 2.

The German interest in adsorption cycles using water as refrigerant also led to product development. The Vaillant product below came out of research it funded at Aachen University in the 1990s as did the competing Viessmann product.

In summary, sorption cycles have a long history and have been in and out of favour. There is much that can be learnt from past successes and failures. The products on the market or under development now essentially are the successors to three different strands of past development:

1. Ammonia-water absorption based on water chiller technology evolved over more than 50 years.
2. Adsorption cycles using water and inspired by the success of larger air conditioning machines developed in Japan in the 1980s.
3. Ammonia-carbon adsorption pioneered by Shelton in the 1980s.

There are other sorbents and refrigerants available but thermodynamics does not allow a 'magic sorbent-refrigerant pair' that will give dramatically improved performance without the need for more complexity or heat exchange area, both of which mean increased capital cost. New materials can help to improve cycle efficiency, heat transfer etc., but delivering a viable gas heat pump to the market depends more on innovative engineering than fundamental science.

3. EXISTING AND NEAR MARKET PRODUCTS

There are at present two products on the market with a third close to market and two others at an earlier stage of development. All are being developed or sold by European companies. For availability see Table 2.

3.1 Vaillant [Information from Ref. 14, given with download link]

The Vaillant system uses water as the refrigerant, together with a zeolite adsorbent and consists of the heat pump itself, a solar collector which acts as the low temperature heat source and a water storage tank. In summer the solar collectors can provide domestic hot water. It is only intended for use with underfloor heating systems with maximum output temperature of 40°C and under these conditions has a claimed reduction of annual energy use of 18% when compared with a condensing boiler. In principle it could also be used with fan convectors with a flow temperature of 40°C but perhaps requiring twice or more the wall area occupied by heat emitters compared with conventional radiators supplied by a gas boiler. The initial system sale price was around €16,000.

Heat pump Water storage Solar collector

Figure 1: Vaillant zeoTHERM VAS 106/4 subsystems [14]

Laboratory test results are presented in [15] based on the German 'Initiative Gaswärmepumpe' (IGWP): [Gas heat pump initiative]. The system has a contribution from solar energy and efficiencies based on net calorific value are presented both with and without the solar input. To convert to a seasonal based on gross calorific value GUE for the German climate chosen the GUE should be divided by 1.1. Additional information in Chapter 4 [9] gives results of field trials implying seasonal GUEs of around 1.3 (net) when delivering water at 35°C to underfloor heating.

Technical data of zeoTHERM VAS 106/4

Rated heat output range Heating 1,5-10 kW
Rated heat output range d.h.w. 4,2-12,5 kW
Adjustable flow temperature 20-75 °C
Recommended max. flow temperature HC < 40 °C
El. power consumption max. 100 W
Appliance width 772 mm
Appliance height incl. flue outlet 1.700 mm
Appliance depth 718 mm
Transport weight (without casing) 160 kg
Operating weight 175 kg
Integrated controller
zeolite module > no moving parts / no maintenance

Figure 2: zeoTHERM VAS 106/4 specification [14]

The unit has also been assessed according to VDI 4650-2 [16] that allows calculation of estimated seasonal performance based on part load GUEs and assumed ambient temperatures, using a bin method.

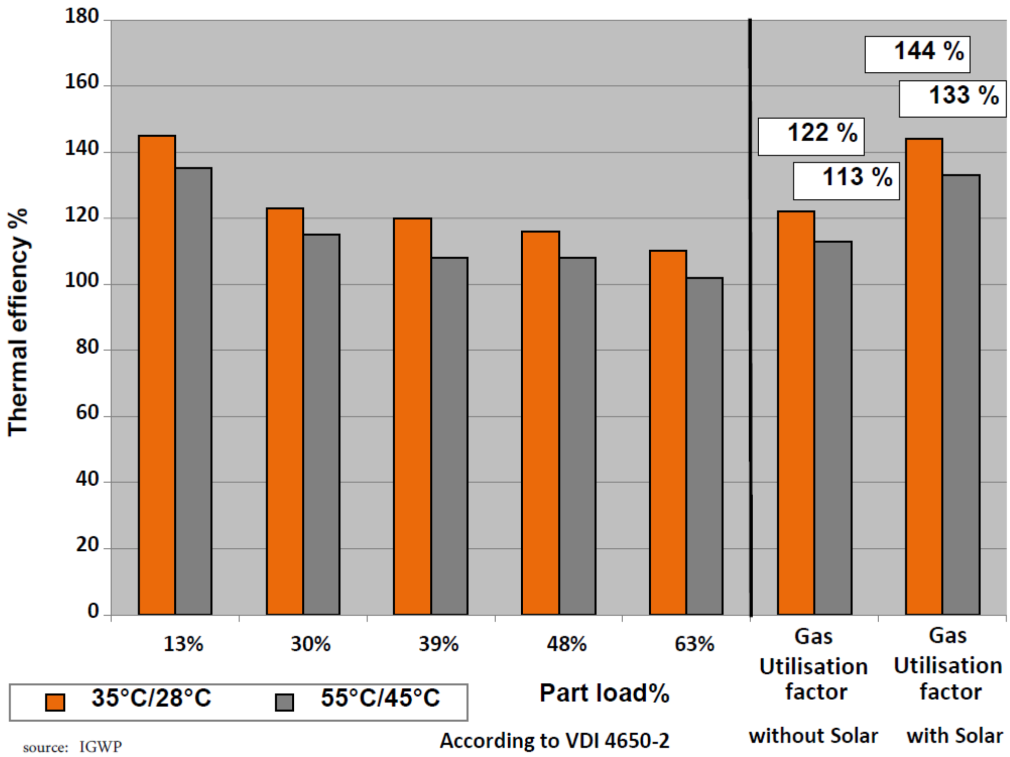


Figure 3: VAS 106/4 annual GUE [15]

The predicted average net GUE (or SCOP) for an underfloor heating system is 1.22 and for a radiator system is 1.13, compared with 0.95 for a condensing boiler [14] if using laboratory test data or 0.83-0.85 based on field trials. The calculated GUE and field trial data, plotted against design heat load are shown in Figure 4 [9] for underfloor systems. This implies reasonable agreement although predicted performance is around 10% higher than actual.

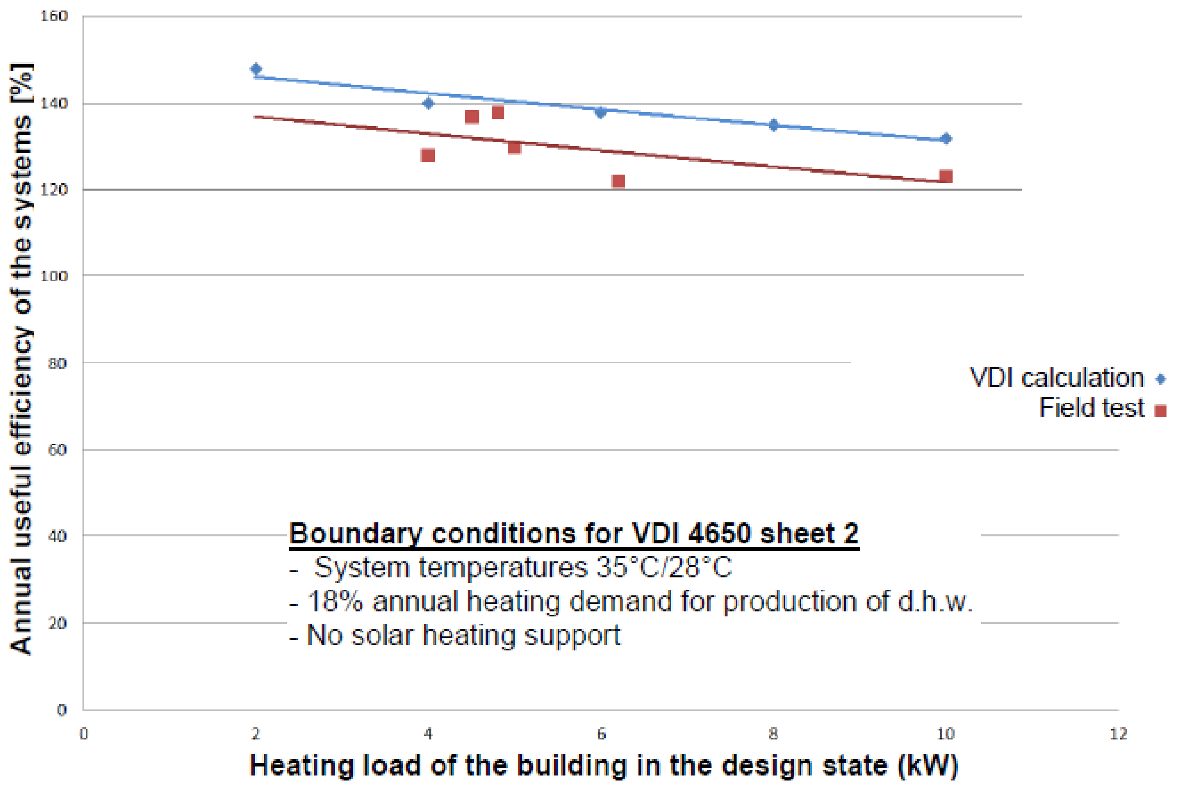


Figure 4: VDI calculated and actual annual efficiency (net) v. building load [8]

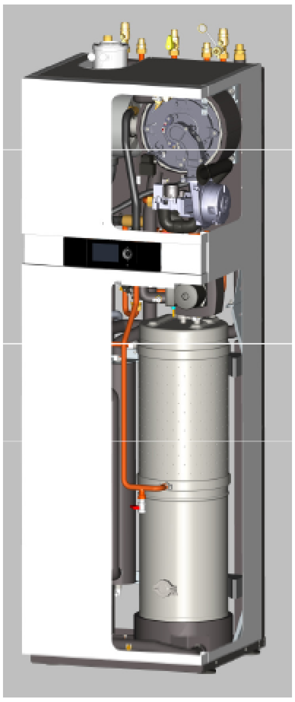
3.2 Viessmann

a) Viessmann have a water-zeolite system intended for ground heat source and underfloor heating only and is very similar in concept to the Vaillant product. It is currently undergoing extensive field trials. The details below are from [16 with download link given].

Fuel savings are claimed to be 20-25% compared to a condensing boiler and details are in Figure 5 below.

b) Viessmann also have an absorption heat pump (Vitosorp 300, shown in Figure 6) at a much earlier stage of development, but few details are available. It again uses a ground source but has improved performance and is physically much smaller. It probably uses methanol as the refrigerant and Viessmann hope to be able to produce an air source machine at a later data.

Viessmann Gas-Fired Zeolite Compact Heating Appliance
Features at a glance



- Hybrid Heating Appliance:
  Heating Power Modulation: 1,6 to 10 kW (1 to 7)
  Booster capacity for DHW: 15 kW
- SGUE Heating (VDI 4650-2): 135 % (Hi 35/28 °C)

  SGUE Heating (VDI 4650-2): 125 % (Hi 55/45 °C)
- Ambient Heat Source: 2013 GHS

  From 2014 also Solar
- Working pair completely environment friendly
- Installation, maintenance and service analog to condensing boiler compact units
- Gas-Fired Adsorption Heat Pump in the dimensions of Viessmann compact heating appliances
- Dimensions: BxHxT: 600x595x1875 mm
- Weight : <170 kg (separable in two parts)

Figure 5: Viessmann Adsorption Gas Heat Pump [17]

Viessmann Gas-Fired Absorption Heat Pump
Features at a glance

- Wall mounted hybrid appliance:

  Gas-fired absorption heat pump and a condensing boiler
- Seasonal heating GUE > 1.4 (55/45 °C)
- Seasonal heating GUE > 1.3 (65/50 °C)
- High modulation range (1.6 to 14 kW)
- Dimensions: BxHxT: 600x595x900 mm
- Weight : <90 kg
- Low noise
- Installation & Maintenance comparable to condensing boilers

Figure 6: Viessmann Absorption Gas Heat Pump [17]

3.3 Robur [Technical data from Robur literature [18 given with download link]

The Robur product is an ammonia water absorption heat pump (i.e. ammonia refrigerant, water absorbent) which offers air, water and ground source options. It is a development of technology previously used for air conditioning and thus is comparatively mature. The present air source machine can deliver domestic hot water at 65°C (gross GUE 1.24) and will supply 38 kW to radiators (supply temperature 50°C) with a GUE of 1.52 (gross), 1.38 (net). This represents a saving of about 40% in gas consumption compared to a condensing boiler. The unit is a single module intended to be positioned outside the heated building and 854(w) x 1256(d) x 1281(h). An 18kW unit, more suited to typical UK dwellings is under development. The product is 'badged' by a range of manufacturers including BDR Thermea and Bosch Buderus and the cost of the 38kW unit is c. £12,000.

Figure 7: Robur Gas Air Source Heat Pump GAHP-A [18]

3.4 Comparative performance data of products on or near market

It is difficult to give a completely meaningful table to compare products since the manufacturers do not necessarily give data at the same test conditions, some give calculated seasonal averages etc. The Robur air source data is given below since that is probably of main interest but [18] also gives the ground source option with net GUEs of 1.69 (B0/W35) and 1.49 (B0/W50).

	Robur		Vaillant	Viessmann Adsorption	Viessmann Absorption
Heat source	Air		Solar heated water	Ground	Ground / Air
Depth (mm)	848		718	600	
Width (mm)	1258		772	595	
Height (mm)	1537		1700	1975	
Mass (kg)	390		175	170	
Sound power (EN ISO 9614)	82.1 dB(A)*				
Output power (kW), GUE(net)	HT, A7/W50 1.52 38.3	LT, A7/W35 1.65 41.7	Water 35/28, SGUE 1.22 Water 55/45 SGUE 1.13 1.5 to 10 kW heating 4.2 to 12.5 kW to DHW	Water 35/28, SGUE 1.35 Water 55/45 SGUE 1.25 1.6 to 10 kW heating up to 15 kW DHW	Water 35/28, SGUE > 1.4 Water 55/45 SGUE >1.3 1.6 to 14 kW heating up to 15 kW DHW
Max water temperature (°C)	65 (Heating) 70 (DHW)	55 (Heating) 70 (DHW)	75 with direct gas firing		
Electricity use (kW)	0.9				
Availability	Available badged as BDR or Bosch		Available as an import – none yet in operation in UK	Launch in Germany 2014	R&D only

* - The sound power level is unnecessarily excessive and associated with the original technology's use as a light commercial air conditioner. Gas heat pumps have smaller evaporators than electric heat pumps and produce less fan noise provided a suitable fan and air flow system is used.

Table 2

4 Products under development

4.1 Sorption Energy

The company (of which the author is a director) is a university spin-out developing an ammonia-active carbon adsorption heat pump. The concept is based on research carried out at the University of Warwick [19]. The product envisaged would consist of an indoor unit of comparable size to a condensing boiler and an external air source evaporator. Emphasis is being placed on the need for compactness, low capital cost, low maintenance and installation by non-specialist personnel. Targets include >30% savings on annual gas consumption (gross GUE 1.3 , net GUE 1.4 at A7/W50 condition) and a better than 3 year payback.

Figure 8: Sorption Energy conce

4.2 A spin-out company (Cooll Sustainable Energy Solutions B.V., www.cooll.eu) from the University of Twente in the Netherlands is developing a carbon ammonia thermal wave heat pump but there are no details available.

4.3 Behr GmbH is an automotive heating, air conditioning and engine cooling company based in both Germany and the USA. It has patents [e.g. 20] on a complex but highly regenerative multi-bed adsorption concept that might use either a zeolite water or methanol-carbon pair.

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