Scotland's role in the development of heat pumps: 1850 – 2050
Presidential Address – Institution of Engineers and Shipbuilders in Scotland

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ABSTRACT

This paper follows the development of the heat pump and considers the role played by Scotland in that process over the last one hundred and seventy years. The University of Glasgow played a key role in the development of the science of thermodynamics in the mid-nineteenth century. This included, in 1852, the publication by Professor William Thomson of a paper on the heating and cooling of buildings by currents of air – the first recorded description of a heat pump in academic literature. Several other significant milestones in the development of heat pumps in Scotland followed and some of these are identified and explained in this paper. The paper finishes with a look forward to the prospects and expectations for heat pump technology in the next thirty years. The challenges ahead are not only technical, requiring a multi-disciplinary approach, but are also commercial and predominantly political.

Keywords: Heat Pump, Industrial History, Energy, Performance, Scotland.

1. INTRODUCTION TO HEAT PUMPS

A heat pump is a type of heat engine in which work input is used to deliver heat to a point of use (sometimes called a "heat sink") by extracting the heat from a lower temperature point of supply (sometimes called a "heat source"). The work is added to the heat in order to raise its temperature to a suitable level for transfer to the point of use. The cycle most often used to achieve this outcome is the same as the vapour compression refrigeration cycle, patented by Jacob Perkins in 1834, with the caveat that the focus is on the warm end rather than the cold end of the machine. The term "heat pump" is often doubly misunderstood – firstly because the concept of heat is not well understood by the general public but also because the machine is not really a "pump", although it may use pumps to transfer water or other liquids in order to move the heat from one place to another. It would be more useful to adopt the analogy of an "elevator" in which the heat is raised from an initial level to a higher level where it is of more use. We use this metaphor all the time when we talk about temperature being higher or lower – not in terms of altitude, but in terms of energy content. The purpose of a heat elevator is to take energy from a lower temperature level and raise it up to a higher temperature level where it can provide warmth for personal comfort or some manufacturing or chemical process. The advantage of using a type of heat engine for this purpose is that the amount of energy delivered at the higher temperature may be several times higher than the amount of energy expended in doing work to raise the temperature. This makes it a very economical way of delivering heat under the right circumstances.

In the vapour compression cycle, which is the focus of this paper, the elevation is achieved by working a fluid in a closed loop between lower pressure and higher pressure in order to adjust the boiling point of the fluid. All liquids have a clearly defined relationship between the pressure applied to them and the temperature at which they boil. The temperature at which a fluid will boil from liquid to gas and condense from gas to liquid varies according to the pressure applied to it. High pressure inhibits boiling, so that each molecule requires more energy to break free from the body of the liquid and conversely low pressure enables molecules to break free with less added energy. By careful manipulation of the fluid's pressure, it can be made to boil at a temperature colder than the heat source, causing heat energy to transfer from the source to the fluid. Likewise when the fluid is pressurised the condensing temperature will rise. When the condensing temperature is higher than the temperature of the heat sink, heat energy will transfer from the fluid to the sink. It is beneficial to use a fluid that turns from liquid to gas as heat is added at the lower temperature and then turns back from gas to liquid as heat is removed at the higher

temperature because the fluid can carry more heat for a given mass flow. The same effect can be achieved with substances that remain in the same state (gas all the time or liquid all the time) throughout the cycle, albeit less efficiently.

For a heat pump, the ratio of the total amount of heat delivered to the sink divided by the total amount of work input is called the "heating coefficient of performance", sometimes abbreviated as CoP_h. At various points in this paper, in accordance with the sources referenced, the same parameter is also called the "heating efficiency" or the "heat advantage". The terms are interchangeable.

2. BACKGROUND – THE SCIENCE OF HEAT AND WORK

The science of heat was transformed in the decade from 1845 to 1855, largely through the work of Professor William Thomson of Glasgow University, Professor Rudolph Clausius of the University of Berlin (and latterly Zurich) and two amateur scientists, Mr James Joule, a brewery manager from Salford and Mr William Rankine, a civil engineering consultant based in Glasgow. The foundation of this joint effort was laid in France by three engineers; Sadi Carnot, Emile Clapeyron and Victor Regnault. Carnot published a short book on the analysis of steam engines and other prime movers in 1824 ("*Reflections On The Motive-Power Of Fire, And On Machines Fitted To Develop That Power*") which took the unusual step of analysing the performance of the engines in terms of an idealised cycle and led to several novel insights into the theory of heat. Carnot died at the age of 36, eight years after the publication of his treatise without having developed the idea much further, but his concept was championed by Clapeyron, a railway engineer working on the development of the rail network around Paris, including the design of the locomotives. Clapeyron studied Carnot's ideas and in 1834, two years after Carnot's death, published his version of Carnot's theory using a graphical presentation to simplify the concept. Clapeyron's "*Memoir on the Motive Power of Heat*" was much more widely circulated than Carnot's original work and attracted the attention of both Joule and Rankine who started musing on the nature of heat as a diversion from their routine employment. The scientific establishment in Great Britain, like the rest of Europe at that time, was not particularly interested in heat. Much more exciting and innovative discoveries in electricity and magnetism were capturing the imagination so when Joule and Rankine met at the British Association meeting in Cork in 1843 they were viewed as outsiders. Joule's paper "*On the Calorific Effects of Magneto-Electricity, and on the Mechanical Value of Heat*" was allocated space in the Chemistry Section of the Proceedings rather than being included in the Mathematics and Physics section. Rankine was also directed to the Chemistry section to read a paper on the generation of electricity by the flow of high-pressure steam. The reception for Joule's paper was not impressive – there was virtually no reaction to it and the press reported of the whole meeting that "*We cannot point out one remarkable scientific fact which is entirely novel*." (Cardwell, 1989). Joule was 24 and Rankine was 23 at the time.

William Thomson at this point was an undergraduate at Cambridge and just 19 years old. He had been intrigued by the essay by French mathematician Joseph Fourier on the Analytic Theory of Heat shortly before going up to Cambridge and had submitted a defence of Fourier's mathematical system to The Cambridge Mathematical Journal under a pseudonym in 1841. When he graduated in 1845, Thomson went to Paris to study under Victor Regnault, Professor of Physics at the Collège de France in Paris. Regnault was conducting a series of precise measurements on the physical properties of steam and other fluids on behalf of the French Government in order to analyse the steam engine and his results, when published in 1847, provided a level of accuracy previously unknown. Thomson returned to Glasgow in 1846 when he was appointed Professor of Natural Philosophy at the age of 22, following the death of Professor William Meikleham who had held the chair since 1803. Thomson's range of interests was phenomenally wide and included the mathematical analysis of Clapeyron's model according to the methods of Fourier, possibly sparked by his short study time in Paris.

Rankine had developed a theory of heat from about 1842 onwards, perhaps encouraged by Joule's presentation in Cork in 1843. When Regnault's data on the properties of steam was published in 1847 Rankine returned to his thoughts on heat and prepared a detailed analysis that was presented to the Edinburgh Royal Philosophical Society in October 1849 and published by the society in February 1850.

Joule also continued with his investigation of the mechanical equivalent of heat and presented updates to the British Association in Oxford in 1847. His paper was squeezed into the end of a long session and might have passed with as little reaction as the 1843 offering except for the attention of William Thomson, the young Glasgow professor who had been sitting at the back of the room and led a spirited discussion of Joule's ideas after the paper was delivered. Thomson was not convinced at this stage but started a lengthy correspondence with Joule that spanned the next eight years and was of undoubted benefit to both men. One of the first fruits of this cooperation was Thomson's paper of 1849 "*An Account of Carnot's Theory of the Motive Power of Heat; with Numerical Results deduced from Regnault's Experiments on Steam*". This was published over several months in the London, Edinburgh and Dublin Philosophical Magazine and Journal of Science.

Meanwhile in Halle, Germany a young physicist Rudolph Clausius, graduated with a PhD in atmospheric optics in 1848 and started studying the Clapeyron paper. He also received a copy of Thomson's 1849 paper and developed the concept further, publishing his findings in Poggendorff's Annalen Der Physik und Chemie in German in 1850, translated into English for the London, Edinburgh and Dublin Philosophical Magazine in 1851. This triggered a lively, friendly and sometimes slightly competitive correspondence between Clausius, Rankine, Joule and Thomson conducted over many months through the pages of the Philosophical Magazine. They had a healthy respect for each other: in 1859, Clausius, Joule and Thomson were made honorary members of the Institution of Engineers in Scotland at the end of the term of the Institution's first President, William Rankine.

These major publications and the subsequent discussion marked the beginning of a more reputable position for the science of heat and work and many more publications followed.

3. THOMSON'S HEAT PUMP PROPOSAL

In the midst of his analysis of various forms of heat, William Thomson received news from Belfast of a scheme to distribute fresh, heated air to the Queen's College buildings using a ducted air system. When combined with his detailed study of heat this concept prompted a novel thought in his mind. He did some quick calculations and presented a short (5-page) paper to the Glasgow Philosophical Society in December 1852 "*On the economy of the heating or cooling of buildings by means of currents of air*". He observed that if an expander were also used in tandem with the compressor, and sufficient time were allowed for the temperature of the air after the first stage of processing to equilibrate with the outdoor air then the temperature of the delivered air might be regulated to any desired temperature within 30°F above or below the ambient temperature. More specifically, if heating were required then the ambient air would first be expanded to a pressure of 82% of atmospheric pressure, then stored in a receiver until it had warmed back up to ambient temperature, counteracting the cooling effect of the expansion. To deliver air from the sub-atmospheric receiver to the conditioned space it would need to be compressed back to atmospheric pressure, which of course would heat it up above the ambient temperature, thereby delivering warmed air to the space. The figure of 82% for the receiver pressure was selected by Thomson to provide "*thirty degrees*" of heating – this is understood in the context to be on the Fahrenheit scale.

Conversely, if cooling were required then atmospheric air would be compressed into the receiver and allowed to cool, then expanded into the conditioned space resulting in a flow of air at a temperature below ambient. He goes on to observe that if the device is required to provide both heating and cooling, depending on the season, then "*undoubtedly the best*" method of doing so would be to add an auxiliary cylinder arranged so that it can be used either with the ingress or egress cylinder. If the two main cylinders were of equal size and driven by a common crankshaft then the auxiliary cylinder would have $^1/_{17}$ of the volume of each main cylinder in order to deliver a thirty-degree change in temperature, or slightly less than one quarter of the diameter, for the same stroke. Diagrams of this arrangement are shown in Figures 1a (heating) and 1b (cooling). The valve arrangement required to switch from cooling to heating is omitted from the diagrams. (Pearson, 2016).

Thomson goes on to suggest that the air compressor need not be driven by steam (produced by burning coal) but could be powered by water or windmills. He also suggests that the same effect could be achieved with a machine "*like a steam engine, founded on the evaporation and re-condensation of a liquid (perhaps some liquid of which the boiling point is lower than that of water)*" rather than with an air engine.

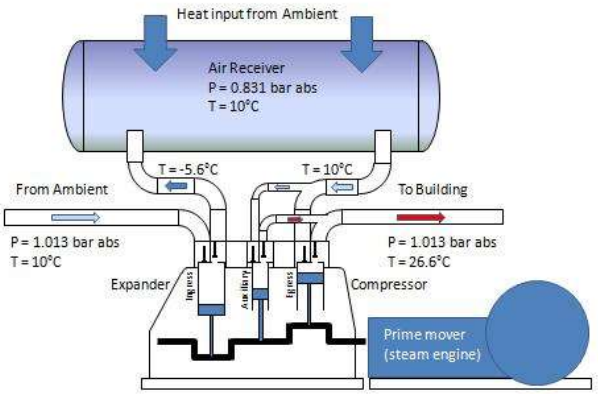

Fig 1a – Air machine in heating mode

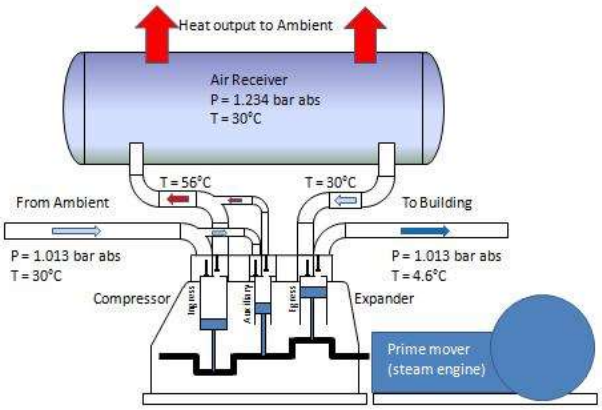

Fig 1b – Air machine in cooling mode

Using the steam-powered air engine as his model he suggests that the power input would be "*not more than about $^{1}/_{35}$ of energy of the heat thus communicated*" and goes on to state that "*a very good steam engine converts about $^{1}/_{10}$ of the heat generated in its furnace into mechanical effect; and consequently if employed to work a machine of the kind described, might raise a substance thirty degrees above the atmospheric temperature by the expenditure of only $^{10}/_{35}$, or $^{2}/_{7}$, that is, less than one-third of the coal that would be required to produce the same elevation of temperature with perfect economy in a direct process*." He is, in effect, claiming a heating Coefficient of Performance of 35. (Thomson, 1852).

Thomson's scheme was ill conceived and deeply flawed. As far as is known, the air-cycle scheme in the form he proposed was never implemented and would have been a serious disappointment if it had been. A more detailed analysis of the inherent problems was presented at a conference in Edinburgh a few years ago (Pearson, 2016) – in summary the performance claims were overstated in two ways; the ideal heating CoP would have been about 18, not 35, but allowing an isentropic efficiency of 70% in the compressor and the expander would reduce this to 1.865. This is still a reasonable proposition, delivering almost twice as much heat as the work input to the heat engine, but it is not sufficiently attractive to justify the additional complexity and expense. In addition, the proposed method of exchanging heat with the ambient through the surface of a receiver was impractical. For a modestly sized heat pump of 10 kW heating capacity the vessel would need to be 8 m diameter and 36 m long. Even a fin-fan heat exchanger with extended surface would be unfeasibly large and would introduce additional problems. The condition of air delivered to a space includes the humidity as well as the temperature but Thomson's machine would have delivered very dry air, which could lead to discomfort even when the temperature was satisfactory. Finally the solution did not actually address the more subtle aspect of the problem – that the requirements for fresh air and heating or cooling are not coincident and so there may need to be a high airflow when no heating or cooling is required, or conversely heating may be necessary in the early morning before the building is occupied.

Despite these flaws, the paper did not pass into complete obscurity. It became well known in engineering circles that the heat pump was invented by the famous Lord Kelvin (as Thomson became when he was ennobled 40 years after the presentation of his modest and flawed heat pump paper). The idea did not catch on in Great Britain but a similar scheme was deployed a few years later in the Austrian

salt mines. An Austrian mine manager, Peter von Rittinger, developed a similar system in 1856 for the drying of brine slurry in salt marshes. Von Rittinger's system is not well documented but it appears to have been what we now call a mechanical vapour recompression system – essentially using the steam evolved from the brine as the compressor intake with the compressor discharge, at higher temperature and pressure, fed through a heat exchanger in the brine to promote evaporation. In this way, the heat input to the salt baths is greatly reduced making the salt purification much more economical. This appears to be the first practical implementation of the heat pump as an industrial device.

4. HALDANE'S DOMESTIC HEATPUMP, 1930

It took about 75 years for the concept outlined by Thomson to be applied in a domestic setting. This was also in Scotland, at the home of the Haldane family at Foswell, near Auchterarder. Graeme Haldane was an electrical engineer, employed by consulting engineers Merz and McLellan in 1925 to work on the development of the National Grid following the 1926 Electricity Supply Act. He worked with Leuig Chew of L Sterne and Company, Glasgow, to design and construct a small ammonia system in the boiler room at Foswell, using river water from a nearby stream as the heat source and transferring the heat into a water loop that served the radiators in the house.

Figure 2 – Foswell House, Auchterarder, home of the world's first domestic heat pump

Leuig Chew was an English engineer, born in Stroud in Gloucestershire in 1871. He worked for HJ West & Co in London from the early 1890s until the early 1920s, at which point HJ West granted a licence to L Sterne & Co of Glasgow for the manufacture of the West "*high speed*" compressor designed by Chew. Sir Samuel Beale, Chairman and Managing Director of Sterne's, noted in his 1949 book marking the firm's 75th anniversary that in 1924 "*Mr L Chew, who had been associated with the Company for some years in a consultative capacity, was elected to the board.*" He went on to add 25 years later "*We cannot express too strongly all that we owe to Chew for his ingenuity in design, as well as for the persistence with which he pursued many large contracts, many of which through his great technical knowledge he secured for us.*" Chew's "*high speed*" compressors ran at speeds of up to 350 revolutions per minute – fast indeed in comparison with the industry standard at that time of about 80 revolutions per minute.

The Foswell heat pump was described by Haldane in papers he presented to the Institution of Electrical Engineers in December 1929 in London and thereafter at several Institution branch meetings (Haldane, 1930). It was also mentioned in a paper to the British Association of Refrigeration, now the Institute of Refrigeration, in 1930, co-authored by Chew and Haldane. In the discussions that followed both of these papers, the audience seemed to struggle with the concept of "*efficiency*" as used by Haldane to describe the heating Coefficient of Performance of the heat pump. This coefficient of performance is the heat

delivered to the heat sink divided by the work input required to raise the temperature from source to sink. The same term is used in almost the same way to describe the effectiveness of refrigeration systems with the subtle difference that the heat quantity used for the refrigeration CoP is the amount of heat extracted from the source. The problem for the audience, as electrical engineers, was that Haldane's efficiency was significantly greater than 100%. Haldane defended this position robustly on two counts. Firstly, he said, the term coefficient of performance is widely used in the slightly different form in refrigeration and so would cause confusion. He was right – that confusion persists to the present day. Secondly, and more significantly, he also pointed out that when the effectiveness of combustion of a fuel is calculated it is based on the heat delivered divided by the total calorific content of the fuel, and it is well understood that this cannot exceed 100%. However if the calorific value of the fuel is considered to be the energy input to the combustion system it is easy to see that, for consistency and to enable valid comparisons to be made, the same logic should apply to the heat pump. Hence the metric of heat output divided by work input is a very suitable method of assessing the performance of a heat pump and since it is called "heating efficiency" in the context of combustion it is appropriate to retain that term in order to facilitate comparison with both fossil fuel combustion and electric heating. Fifteen years later the eminent consulting engineer Oscar Faber addressed the same issue in a paper delivered to the Institution of Mechanical Engineers in London in April 1945 (Faber, 1946). Faber proposed that the ratio of heat delivered to work input should be termed the "*advantage*", perhaps drawing an analogy with the term "mechanical advantage" as applied to a system of gears, pulleys or levers. The term "heat advantage" has not yet caught on, but the need for better understanding is as great as it was in 1945.

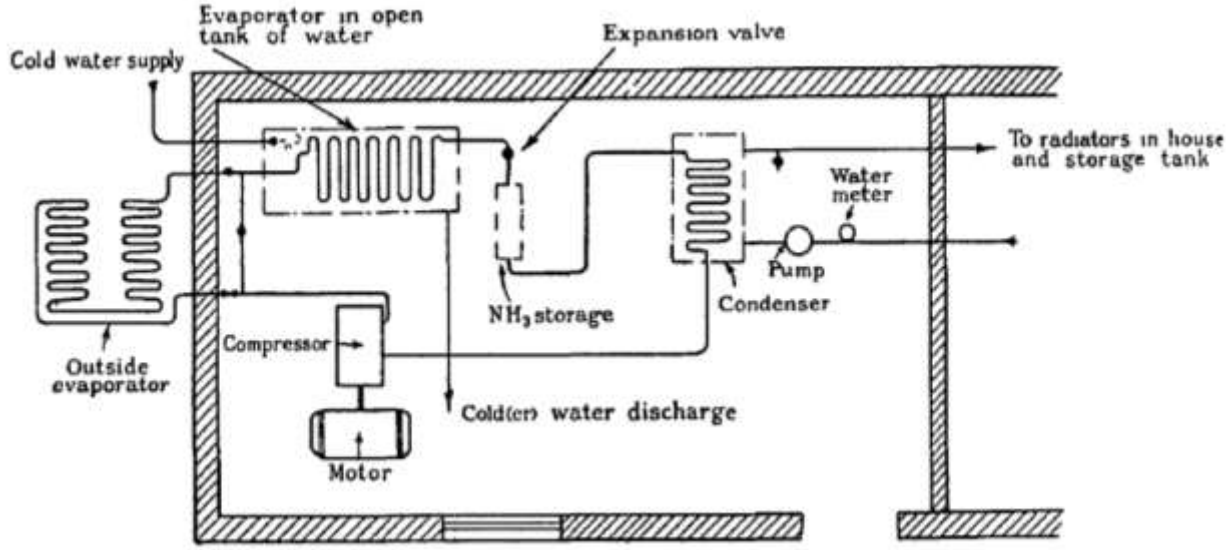

Figure 3 – Haldane's schematic of the Foswell Heat Pump (Haldane, 1930)

Haldane's system used ammonia as the refrigerant and heated water for the central heating system to 100 °F (37.8 °C) with a further boost of 30 deg F (16.7 K) provided by electric immersion heaters. A further feature of the system, only mentioned in passing by Haldane, is that the house was supplied with all its electrical needs by a small hydroelectric installation that served the cooking and lighting needs of Foswell and two neighbouring farmhouses. The limit on heat sink temperature was set by the pressure rating of the compressor and the need to limit the power demand due to the electrical supply constraint but Haldane noted that this was a benefit in terms of the system efficiency. However he also observed that the compressor efficiency, because it was a very small model, was low in comparison to larger industrial machines and therefore the overall performance of the system should not be taken as typical of what could be achieved on a larger scale. Of course, the domestic hot water temperature that Haldane used is not high enough to satisfy modern requirements on the control of bacteria in water systems.

Chew was assisted in his work at Foswell by a young graduate engineer, Peter Brown, who was the nephew of Sir Samuel Beale and who had joined L Sterne & Co in 1925, aged 23.

5. THE STATE OF THE ART, 1950

In 1950 Peter Brown presented a paper to the Institute of Refrigeration entitled "Some Considerations on The Heat Pump" in which he noted that, as far as he was aware, no papers on this topic had been read to the Institute in the twenty years since Chew and Haldane's offering. This sentiment was consistent with an article by American Engineer Bill Holladay in Engineering and Science Monthly, October 1948 that said "*for most of the 96 years since Kelvin's article there have been more papers on the subject than there were heat pumps in operation*". It was also echoed by an article in The Spectator in September 1948 that stated "*Today we have only one heat pump operating in Britain*." This was in reference to an installation built for Norwich City Council Electrical Department in 1945 by John Sumner, the City Electrical Engineer for the Corporation of Norwich. Sumner was one of the contributors to the discussion after Faber's 1945 paper when he bemoaned the lack of interest in the heating and ventilating trades, who had universally declined to submit proposals for his scheme. He consequently had constructed a system using his own workshop staff in the Electrical Department and used sulphur dioxide as the refrigerant as he was unable to get hold of R-12 due to wartime restrictions. He subsequently presented his results to the Institution of Mechanical Engineers in March 1947 during which several interesting comments were made. Sumner paid tribute to Haldane's pioneering work and noted that his 1930 paper had been widely read not only in Great Britain but also particularly in Switzerland and the United States of America where it had "*led to several commercial installations being made in those countries*". Haldane was present for the reading of Sumner's paper and contributed to the subsequent discussion, pointing out that the motivation for interest in Switzerland was a lack of indigenous fossil fuel coupled with an abundance of hydroelectric power whereas in the United States the prime motivation had been the possibility of combining winter heating with summer cooling in a climate that was more severe in both cases than Britain's. These different motivators had led to a divergence in application. The United States was vigorously pursuing the development of high performance domestic units whereas in Switzerland engineers were cautious about the use of heat pumps for space heating but enthusiastic about application to industrial processes. Haldane observed that the efficiencies being specified for domestic units in the United States were ambitious, noting that "*the performance called for from these units exceeded anything yet achieved by the manufacturers*". However, he called on the refrigeration engineer, the electrical engineer and the heating engineer to be brought together "*with a view to designing complete and standard equipments suited to the needs of the public*." Another contributor to the discussion, Mr S.B. Jackson of London, noted that he was one of only three people in Great Britain to have experience of owning and operating a heat pump. The other two, he said, were also in the room, namely Haldane and Sumner. He had, he explained "*designed and erected a small installation in 1938 which had operated until its disappearance in 1941 due to enemy action*." Haldane's Foswell plant had a 5kW drive motor and Jackson's was even smaller, with a 4hp (3kW) drive, so Sumner's system, at the time of publication of his paper in 1947 was certainly the largest system in Great Britain at that time, as it had a 110hp (85kW) motor and was designed to deliver a peak of 8 therms per hour (234kW) at a temperature of 49°C. The Norwich system's connection with Scotland is somewhat tenuous but in his concluding remarks Sumner acknowledged the "encouragement and assistance given by Mr L Chew of L Sterne & Co and by Mr T.G. Haldane". He also acknowledged the support of Peter Brotherhood of Peterborough who supplied a two-stage compressor free of charge in 1946 to replace the original 25-year-old second hand Brotherhood machine originally installed by Sumner.

Brown's paper of 1950 presents a much more pessimistic note than Faber and Sumner, noting that the cost of finance to fund the higher capital cost of the system, the load factor applied to the plant (the period of the year during which the heat pump is in operation), the cost of maintenance and the low cost of fuel all tend to weigh against the financial arguments for deploying a heat pump. He notes that with a load factor of 0.5 a CoPh of at least 5 is required to make the heat pump economic in comparison with a coal-fired or oil-fired boiler when coal cost £4 per ton and heating oil was 9¼d per gallon. If the load factor were 0.25, the CoPh would need to be over 7.5 to make the system financially viable. His focus was therefore on three possible applications – the use of heat pumps for swimming baths where the load was year-round, for industrial processes with a high heat source temperature and high load factor and as an adjunct to refrigerating systems on cold stores and ice plants where fuel economy could be

achieved by boosting the heat rejection temperature of the refrigeration plant. This may have been no more than Scottish pessimism at its worst but the continued enthusiasm for heat pumps in academic circles and lack of practical application by mechanical engineers in the field suggests that he had a point.

Despite Brown's scepticism, L Sterne & Co delivered a heat pump in 1950 to the Anglo-Iranian Oil Company (renamed British Petroleum Company in 1954). Several photographs were taken of this system under construction in Sterne's factory at North Woodside Road, Glasgow, for example Figure 4. It served the AIOC offices in West Braim, Abadan and comprised five units, each with a 480hp (355kW) motor. The Shatt-al-Arab River was the source of low grade heat, with the plant heating the offices in winter and cooling them in summer. In 1950 the AIOC refinery at Abadan was the largest in the world, but in 1951 the company withdrew following the Mossadeq nationalist uprising. The fate of the five heat pump units is not known.

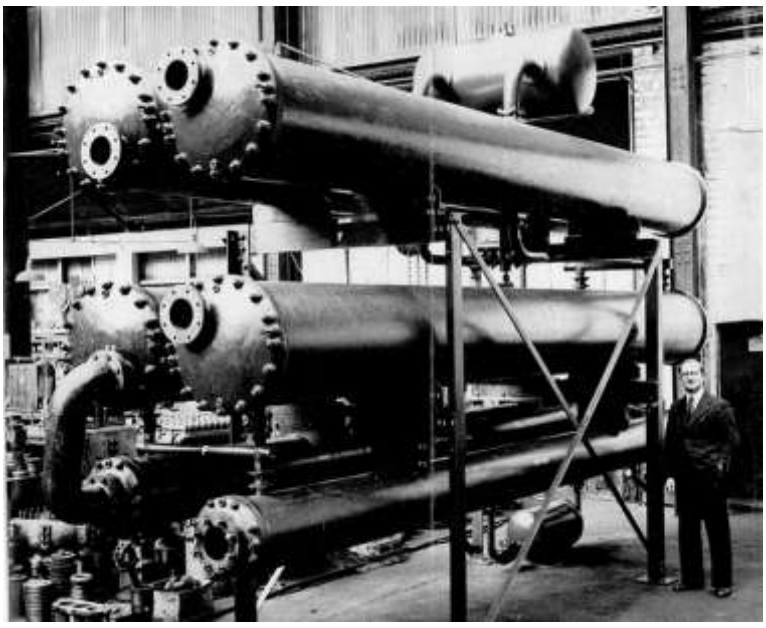

Figure 4 – A river source heat pump evaporator in L Sterne & Co's factory, 1950

6. GLASGOW'S FIRST DOMESTIC HEATPUMP

The firm of Macfarlane Engineering was established in Cathcart in 1912 as manufacturer of electrical machines. It was set up by a father and son, both inventive engineers, with wider family involvement. James Wright Macfarlane worked for many years as a mechanical engineer for Watson, Laidlaw & Co, a firm of centrifuge manufacturers based in Tradeston, Glasgow. His son, James C Macfarlane, born in 1877, was an electrical engineer employed for about six years by Crompton & Co in Chelmsford, Essex at the beginning of the 20th century. During that time, he submitted a large number of patent applications for electrical control devices including several related to electrically powered vehicles. JC Macfarlane had been an apprentice with G&J Weir of Cathcart and received a Whitworth scholarship to study at the Royal College of Science in South Kensington (now part of Imperial College), which led to his employment by Crompton.

While living in Chelmsford, JC Macfarlane married and had two sons. The elder son, also called James Wright Macfarlane, was born in 1908 and his brother, William, in 1911. At that point, the Macfarlane family relocated to Glasgow and the family business was formed.

JW Macfarlane Snr moved in 1912 into a small mansion house on Netherlee Rd called Cartbank that had been built in 1770 and had extensive grounds adjacent to the Snuffmill Bridge, which in 1770 was on the main Glasgow to Ayr road. JC Macfarlane moved to a neighbouring house, Braehead, and the company workshop was established in the grounds of Cartbank. In the late 1920s JW Macfarlane Jnr

also received a Whitworth scholarship and completed his doctorate in the early 1930s at which point he moved into Cartbank and took over from his father as Managing Director of Macfarlane Engineering.

At the end of the Second World War Dr Macfarlane spent some time in Germany where he was intrigued to learn that German U-boats had used a device called a heat pump. He was inspired to look at the possibility of heating Cartbank using the River Cart as the heat source but the technical difficulty of pumping the river water 30 m vertically was off-putting so instead he arranged to lay about 400 feet (120 m) of copper piping in shallow trenches under the lawn in the garden and installed a compressor running on R-12 in the basement of the house. The refrigerant was passed through the underground piping, which acted as a direct expansion evaporator, and the condenser was a finned air-cooled heat exchanger. Ductwork was installed from the condenser to the dining room and Macfarlane noted that it was possible to maintain the room at 75 °F (23.9 °C) when the outdoor air temperature was 30 °F (-1.1 °C). The soil temperature was estimated to be 48 °F (8.9 °C) all year round. As this was more heat than was required for the dining room alone, additional ductwork was added to heat the hall and a passageway. With adjustment of the airflow, the temperatures were maintained at 63 °F (17.2 °C) in the dining room and 58 °F (14.4 °C) in the hall. Macfarlane noted that "for two years this method worked splendidly". In the winter of 1951 a further 600 feet (180 m) of piping were added to the evaporator during additional builderswork. This was initially connected in series with the original piping and it was found that there was sufficient heat with a 3 hp (2.2 kW) motor on the compressor to hold the house at 62 °F (16.7 °C) but this was deemed to be unsatisfactorily cold. It was noted that the pressure drop in this arrangement of the evaporator was about 15 psi (1 bar) resulting in a drop of evaporating temperature of about 20 °F (11 K). The evaporator was rearranged into two parallel circuits and it was found that, with a larger 5 hp (3.7 kW) motor running the compressor faster, the whole house could be maintained at 72 °F (22.2 °C) with an outside temperature of 38 °F (3.3 °C) and 62 °F (16.7 °C) when the outside air was at 12 °F (-11.1 °C).

Dr Macfarlane subsequently added a small air source water-heating heat pump to his system. With a power input of 600 W, it ran on average 5 hours and 30 minutes per day to maintain the hot water storage tank at 120 °F (48.9 °C). When substituted with a 2 kW heater operated under identical conditions the heater ran for 4 hours and 52 minutes per day. The daily consumption of the water-heating heat pump was 3.3 kWh compared to 9.75 kWh for the immersion heater.

Figure 5 – Dr JW Macfarlane and his heat pump in the basement of Cartbank

Dr Macfarlane presented his experience in the Chairman's address to the South-West Scotland Sub-Centre of the Institution of Electrical Engineers in Glasgow in October 1956. Throughout the

development of the heat pump Dr Macfarlane kept meticulous logbooks which included over two years of daily readings on the ground source temperature versus the ambient air temperature (from 1 January 1949 to mid-February 1951) and a year of readings on the hot water heat pump (from 14 February 1954 to 14 February 1955). The ground source temperature was taken from a sump in the basement that contained a varying level of fresh ground water and was taken to be indicative of the soil temperature in the garden. The supposition was that the sump contained water that was draining from the high ground of Braehead to the River Cart. Dr Macfarlane's readings are shown in Figure 6.

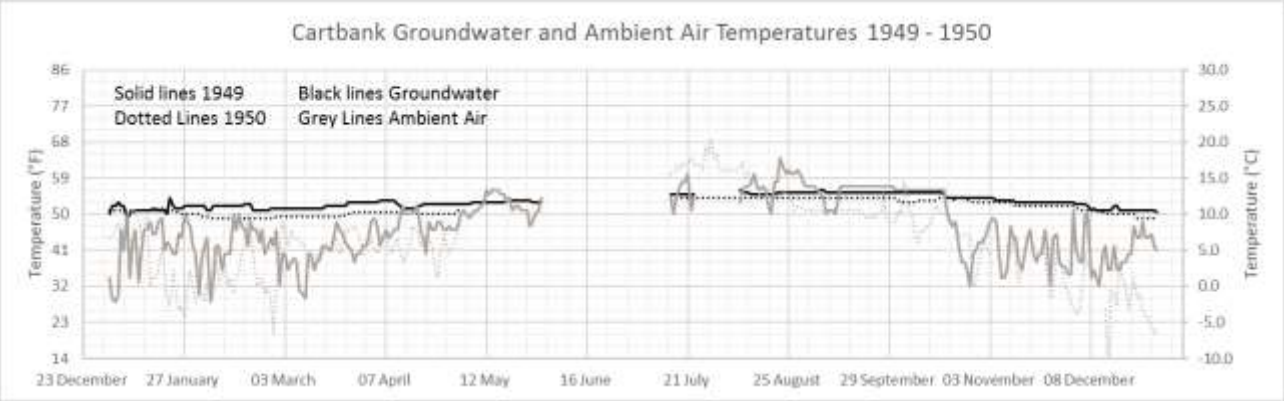

Figure 6 – Readings of ground and air temperatures

Note that the ground temperature readings could not be taken when the sump was completely dry so there are gaps in the data for parts of the summer.

With the extended evaporator and when the system was correctly charged and running well it was able to raise the air temperature across the condenser by 30 deg F (16.7 K) – coincidently the temperature span that William Thomson had used in designing his original concept heat pump. This warm air, at about 85-90 °F (29.4-32.2 °C) was fed by air ducts to the rooms in the house above and the return air was enabled to filter back to the basement at about 55-60 °F (12.8-15.6 °C) where it was recirculated. Dr Macfarlane's logbooks for the heat pump were passed to the present owner of Cartbank, Mr John Irvine, and were made available for analysis for this study. They comprise mainly daily readings of air temperatures and refrigerant pressures. There are not many power readings in the early logs but this became more frequent as the system progressed. The logbooks for the ground-source heat pump cover the period from November 1952 to April 1955, with daily readings for most of the heating season each year.

According to the logbooks, the evaporator was further extended in July 1953. The occasional power readings before this indicate that the compressor was drawing about 3.5kW. After the reconfiguration, this was typically 1.9kW although the house could be maintained at slightly higher temperatures in somewhat colder ambient temperatures ie the heat pump was delivering more heat for less power consumed.

A system model was created using the Reference Properties software tool Refprop 7, developed by the National Institute of Standards and Technology in Boulder, Colorado. Refprop enables the refrigerant properties (enthalpy, entropy, saturation temperature and so on) to be calculated at various points around the heat pump circuit. Based on the sketchy information in Dr Macfarlane's logbooks it is not possible to calculate the heat pump performance precisely but by making some assumptions about compressor performance within reasonable limits the heat advantage of the system can be estimated.

The logs for January 1955 were studied in more detail. This is a particularly interesting period because the weather was unusually cold. The Met Office weather forecast for Wednesday 12 January 1955 for example said "*Very cold generally with keen or hard frost morning and night and also all day over much of Scotland. Snow or hail showers over Scotland, Northern Ireland, Northern England and North Wales. Showers heavy and prolonged at times especially in North and West Scotland with drifting.*" The outlook

for the following 24 hours was "*Very cold and frosty weather continuing with further snow in places, especially in the north*." According to Dr Macfarlane's log the ambient temperature was 20 °F (-6.7 °C) on the morning of the 11th and did not rise above freezing until more than a week later. This extreme cold is not reflected in the official Met Office readings, but they were taken from the weather station at Abbotsinch and so could be expected to be a few degrees warmer. A summary of Dr Macfarlane's readings is given in Table 1 and the analysis of the information is presented in Table 2.

Table 1 – Dr Macfarlane's readings for w/c Monday 10 January 1955

Date	Motor kW	Dining Room °F	Air on condenser °F	Air off condenser °F	Compressor Suction psig	Compressor Discharge psig	Ambient Air °F
10/01/1955	2	66	58	93	9.5	129	26
11/01/1955	2	65	56	92	8.5	123	22
12/01/1955	1.9	63	56.5	92	8	124	23
13/01/1955	1.9	64	55	91	8	120	22
14/01/1955	1.9	64	55	91	7	120	19
15/01/1955	1.9	66	57	91	8	121	25
16/01/1955	1.9	62	55	90	7	120	20

Table 2 – Analysis of Dr Macfarlane's readings for w/c Monday 10 January 1955

Date	Motor kW	Condenser Air Temp Rise K	Condenser LMTD* K	Room-Ambient Diff K	Estimated Heating Duty kW	Estimated Heat Advantage	Ambient Air °C
10/01/1955	2	19.4	14.2	22.2	5.24	2.62	-3.3
11/01/1955	2	20.0	12.8	23.9	5.31	2.66	-5.6
12/01/1955	1.9	19.7	13.1	22.2	4.95	2.61	-5.0
13/01/1955	1.9	20.0	12.3	23.3	5.08	2.67	-5.6
14/01/1955	1.9	20.0	12.3	25.0	4.96	2.61	-7.2
15/01/1955	1.9	18.9	12.3	22.8	5.04	2.65	-3.9
16/01/1955	1.9	19.4	12.8	23.3	4.96	2.61	-6.7

*The log mean temperature difference for the condenser neglects the compressor superheat.

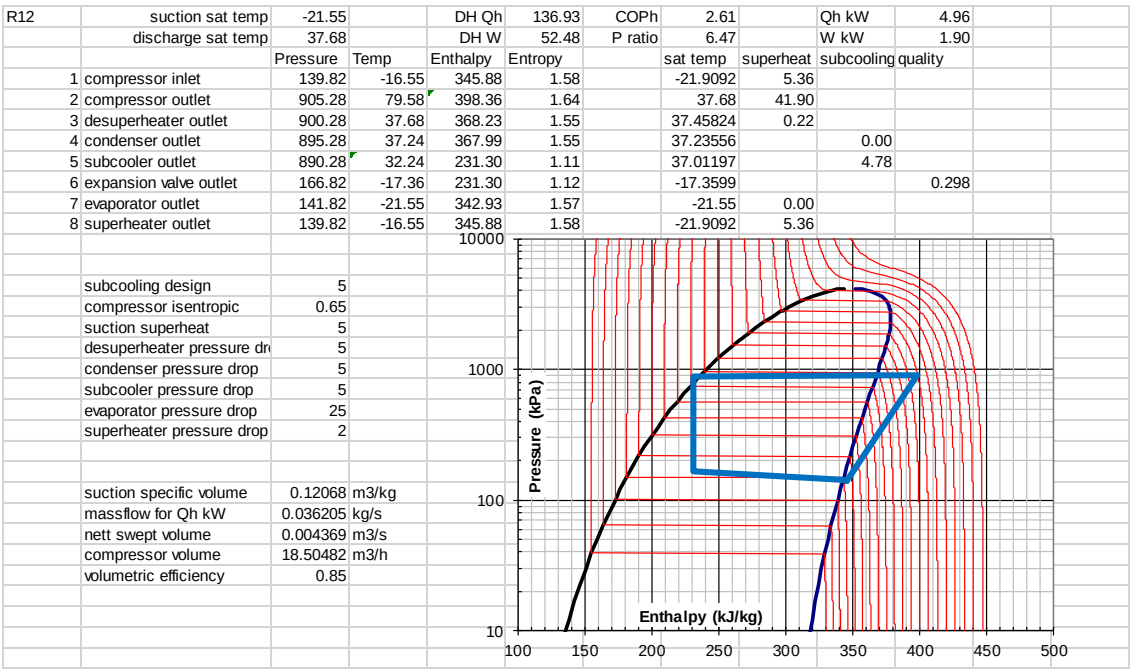

Figure 7 – Refprop model of Dr Macfarlane's Heat Pump

Given the number of guesses inherent in this analysis, it would be a mistake to suggest that the output is accurate but it is striking how consistent the figures are – and not just over the week presented here. Given that the ground temperature was shown in Figure 6 to be very stable through the winter at about 10 °C it is apparent from the saturated suction temperature of about -20 °C that the evaporator did not perform well. The model was set with an evaporator pressure drop of 25 kPa, which equates to a temperature drop of about 4 K. This does not affect the model capacity estimate because the model is based on the compressor suction gauge reading, but if the evaporator had been performing better then the suction gauge would have been higher. If the heat could have been extracted with the compressor running at -10 °C saturated suction temperature then the heating capacity would have been 50% higher with a heat advantage of 3.4 compared with the actual estimated value of 2.6. The fallacy that a direct expansion heat exchanger must be better than an indirect system because there is one less stage of heat transfer is not confined to ground source heat pumps. It was commonly found in DX ice rinks too, where a system using glycol or brine frequently have a compressor saturated suction temperature several degrees warmer (ie better) than the supposedly more efficient DX system.

The conclusion of this analysis is that Dr Macfarlane's system was actually pretty good. It was able to maintain the temperature in the 200 year old house about 20 – 25 degrees above ambient, even when it was below -5 °C outside using less than 40% of the electricity that would have been required for direct electric heating. The system would have been even better with a better design of subsoil heat exchanger, or if a much denser refrigerant, such as carbon dioxide had been used, provided of course that the piping system could withstand the higher operating pressure of CO_2.

7. HEATING AFTER THE ENERGY CRISIS

Despite the good examples demonstrated by Graeme Haldane, John Sumner and James Macfarlane heat pumps remained almost unknown through the 1960s and early 1970s. They were generally considered to be too complicated, too expensive and too mysterious and the alternatives, oil-fired, coal-fired or gas-fired boilers were too cheap and too easy. The oil crisis of 1973 had some effect and in 1979, Star Refrigeration of Glasgow supplied a novel heat recovery plant to the Magnum sports centre in Irvine, designed by Dr S Forbes Pearson. The original installation, by Star in 1973, comprised two factory built brine chiller packages to serve the ice rink in the sports centre. Four heat recovery condensers were retrofitted in 1979 to heat the adjacent swimming pools. It was undoubtedly the first such system in Scotland, if not the UK, although a few heat pumps had been installed for swimming pools (without ice rinks) before this, including one constructed for an outdoor pool in Market Drayton by L Sterne & Co in the mid-1960s which used river water as the heat source. By the early 1980s packaged heat pump appliances were being supplied for the recovery of heat from swimming pool extract ventilation (Turbard, 1983) but the combination of pool heating and ice rink refrigeration remained rare although it was eminently sensible and had been shown to be viable by the installation in Irvine. In many cases, even when the pool equipment and the ice rink plant were in the same room, the two were kept completely separate and there was no provision for waste heat recovery.

The Magnum Centre project was particularly tricky because the building designer had placed the air-cooled condensers for the ice rink plant very far from the machinery room and it was difficult to manage the distribution of refrigerant between the air-cooled condensers and the heat recovery condensers on the chiller packages. The heat extracted from the ice rink was more than sufficient to provide the heat for the main pool and the leisure pool, but the hot water for showers was heated conventionally because a higher temperature was required.

In 1983, the industrial estate management company that served Star Refrigeration's factory in Thornliebank Industrial Estate decided to greatly increase their rates for supply of district heating. Star took the opportunity to disconnect from the heat network and install a novel heat pump to serve their workshop space. Five gas boilers provided hot water for the office heating, with a combined output of 625,000 Btu/h (180kW) peak heating capacity. The flue gas from these boilers passed through a finned heat exchanger that acted as the evaporator for an R-22 heat pump. The heat pump condensers were four finned heat exchangers in the workshop area, individually controlled by zone thermostats. The

compressor was a six-cylinder reciprocating machine, which was belt-driven by a 30kW drive motor. A desuperheater on the compressor discharge preheated the boiler feed water so some of the flue gas heat was returned to the hot water circuit as well as heating the workshop space. The system provided ample heat for the workshop (about 1,200 m^2) and had the unusual advantage that the heating efficiency remained constant independent of ambient temperature because the heat source was the boiler flue gas.

Figure 8 – Dr SF Pearson's factory heat pump with 5 gas boilers and R22 compressor on the right

The factory heat pump recovered 51kW from the boiler flue gas and a further 21kW from ambient air. With a work input of 18kW to the compressor this gave factory heating in all weathers with a heat advantage of 5.2:1

8. MASS PRODUCTION COMES TO LIVINGSTON

In 1980, in his Presidential Address to the Institute of Refrigeration, Geoffrey Haselden, Professor of Chemistry at Leeds University, said "*At long last heat pumps seem to be happening*". This reflected in part the frustration of the fifty years since Haldane's paper but also recognised moves in the commercial and domestic markets, which were increasing acceptance of the concept. However further progress was still extremely slow.

In 1993, Mitsubishi Electric opened a production plant at Livingston in West Lothian to serve the needs of the burgeoning market for split air conditioners and quickly expanded their production line to include several domestic heat pump products. The mainstay of production in this respect is now the domestic air-to-water range. Mitsubishi now have six production sites in West Lothian employing over 1,300 staff and producing over 300,000 units per year to serve the UK and European markets. They are the largest manufacturing facility for domestic heat pump systems in the UK and Livingston is also their R&D centre for heat pump technology in Europe. The facilities include two purpose built test houses for the evaluation of different concept designs. The company says "*this helps us continue to design smarter and more efficient heat pumps*."

The market for domestic heat pumps sums up all that is difficult about this industry sector and helps to explain why progress since 1930, since 1950 and even since 1980 has been so slow. When a heat pump is considered as an alternative to direct electric heating the financial case is clear. This also makes sense environmentally and when the system is connected to a locally generated renewable source of electricity, for example a wind turbine, solar array or (as in the case of Foswell) micro-hydro scheme the intermittency of the renewable source can be managed by using a very simple hot water storage system. This allows the heat pump to run when electricity is available and store heat to be used when

required. However, when the comparison is with low cost combustion plant with cheap fossil fuel the financial case is much weaker. With a combination of thermal storage and a suitable time-of-day tariff it is possible to make it pay, but this requires careful planning and close management of the system and the energy supplier to ensure that the financial advantage is maintained.

Figure 9 – The Mitsubishi electric R&D Centre Europe – UK Branch test houses, Livingston

The Government's Renewable Heat Incentive (RHI) scheme for domestic systems has played a large part in developing the market for heat pumps and credit is due to those who initiated the scheme and have maintained it since its introduction in 2014. It provides financial support to the system owner for seven years and helps bridge the gap between the capital cost of the renewable heat installation and the operating cost when compared to fossil fuel. Unfortunately the complaints of previous generations about cheap fuel harming the case for heat pumps have not been answered, although we have shifted from cheap coal and oil to cheap gas. Domestic heat pumps retrofitted to existing houses will play a key part in the reduction of carbon emissions over the next thirty years and unless the anomalously low price of gas is addressed directly (which seems unlikely at the moment) a scheme like the domestic RHI is essential. The end of RHI has been announced several times since 2014 and then postponed several times – when it is scrapped next year it will need to be replaced with something else that is equally effective. The Mitsubishi factory in Livingston will play a key role in achieving the transition from burning fossil fuel to the sustainable use of clean electricity.

9. OPPORTUNITIES IN DISTRICT HEATING

The alternative to individual domestic heat pumps is to provide a central plant for heating a network of homes – a district heating system. This allows for great economies of scale in the efficiency of the heat generation plant and is very common in Scandinavia, Eastern Europe and Russia, but although there are a few networks in the UK, they are relatively unknown. Factors that are in favour of heat pumps for district heating in the United Kingdom include the relatively benign climate with cool summers and mild winters. Compare for example other cities on similar latitude to Glasgow and Edinburgh, such as Moscow, Berlin, Minneapolis and even Beijing. In these inland cities the summertime maximum temperatures are much higher than Scotland, up to +40 °C and the wintertime minima are much lower, often below -20 °C. Our mild, moist winters suit the use of air-source heat pumps but the amount of ambient air cooling that can be provided in a tight location should be limited to about 400 kW to avoid neighbour complaints. Ground source heat pumps of this size are uncommon because of the cost of extracting so much heat from the ground unless a geothermal well can be used. This means that water source heat pumps using an adjacent river, loch or the sea as the heat source are the most attractive proposition for a source of natural heat for a district network. Of course, process water from a power station, wastewater treatment plant, data centre or industrial process is a significantly more attractive arrangement particularly when cooling is required for the process anyway. However, despite the

obvious benefits, the same lack of joined up thinking that stymied the swimming pool/ice rink combination in the 1950s, 60s and 70s seems to be prevalent at the moment. This is not "renewable" heat so, strictly speaking, the RHI cannot be applied but a similar government incentive may be required to get discrete entities to cooperate. Whether this is carrot-shaped or takes the form of a stick remains to be seen.

In 2016, Star Refrigeration proposed to develop a river source heat pump scheme using the Clyde as the heat source. The original intention was to construct the system on the south bank of the Clyde opposite Glasgow Green serving high-rise flats, a business centre and a sports centre in the Gorbals. Despite strong support from the Holyrood government and the City Council, the challenge of ensuring heat sales in a complex commercial environment where the easy option was burning cheap gas proved to be too risky. However, as that opportunity faded, another scheme came to the fore. The redevelopment of the former John Brown shipyard will create a heat network serving 1,400 homes, the college, a medical centre, a sports centre and the town hall. West Dunbartonshire Council (WDC), with their main contractor, Vital Energi, lead the project and it is a testament to their resolve to deliver a low carbon, low NOx alternative to gas based district heating. The initial system comprises two independent packages, each capable of delivering 2,600 kW but the network will be designed for further extension so that more heat customers can be brought online in future and if necessary additional heat pump units can also be added.

Figure 10 shows one of the river water cooling packages being delivered. The development, known as Queens Quay, is where many iconic ocean liners were built by John Brown for Cunard, including in 1967 ship No 736, better known as The Queen Elizabeth 2. All that is left of the yard now is the famous Titan crane, which can be seen reflected in the windows of the Energy Centre in Figure 10.

Figure 10 – A river source heat pump (2,600 kW heating capacity) delivered to Queens Quay, Clydebank

The Scottish Government's Low Carbon Infrastructure Transformation Programme (LCITP) supported both the Glasgow Gorbals and the Clydebank Queens Quay projects. This was not sufficient to enable the Glasgow work to go ahead, but it has been a key part of the Clydebank package. The lessons learned are that the difficulties of transferring schemes like these from paper to reality should not be underestimated and a strong level of government support has been essential in driving these projects forward. As heat pumps will undoubtedly need to form a major part of our carbon reduction strategy over the next fifteen years it is essential that the whole project chain can learn valuable lessons now so that the technology can be delivered in time on a large scale.

It is sometimes thought that river source heat pumps are a niche market because they depend upon open water as a heat source. However, it has been estimated that over 80% of all of Scotland's heat demand is within 1,000m of a suitable open water heat source (Muschamp, 2014) so the concept should not be dismissed too quickly. The ability of a water source heat pump to deliver high heat capacity in a relatively compact package with minimal effect on the environment (unlike ground source or air source systems when scaled up to this size) makes this the first choice solution for heat networks.
The Queens Quay units, like the Foswell heat pump, use ammonia as the working fluid. This gives a high heat advantage at relatively high water temperatures but care is required to ensure that the refrigerant stays inside the system. A much larger system has been in operation in Norway for about 10 years and many other ammonia heat pumps are now in use around Europe so the technology is now well established. The Norwegian system is considered to be "*the most efficient district heating heat pump in Norway*" which is quite an accolade and it was, at the time of installation, the largest natural refrigerant heat pump for district heating in the world. It is still the largest and most efficient to be delivering heat at more than 85 °C.

10. OUTLOOK FOR THE NEXT THIRTY YEARS

In the last ten years, according to data from the Department for Business, Energy and Industrial Strategy, the price of electricity for a medium-sized commercial consumer (using 2,000 to 20,000 MWh per year) rose from 8.54p/kWh to 12.56p/kWh, including the Climate Change Levy. That is an increase of 47%. Over the same period, the price of gas for a medium-sized consumer (using 2,778 to 27,778 MWh per year) rose from 2.321p/kWh to 2.425p/kWh, an increase of 4.4%. The aggregate inflation rate was 35% from 2009 to 2019 - in other words, gas is about 30% cheaper now than it was 10 years ago in real terms but electricity is about 15% more expensive[1].

Looking to the future, BEIS forecast fossil fuel prices forward to 2040[2]. The forecast shows on their central projection that gas prices will rise gradually over the next 15 years at a compound rate of 2% per year and will then plateau, remaining flat for the period from 2035 to 2040. This means that gas will be cheaper in 2040 than it was in 2010 in real terms. However, in the same period, the United Kingdom has committed under the 2019 amendment to the Climate Change Act of 2008[3] to reduce our national carbon emissions by 100% compared to 1990 levels. In other words, by 2050 we intend to be carbon neutral. It is difficult to think of a better example of a failure to join up thinking in terms of energy policy.

The problem is clearly understood – emission of carbon dioxide needs to be reduced very significantly over the next thirty years and the steps taken so far have mainly consisted of switching from one fossil fuel to another one. Further steps in that direction, for example by lacing our gas supplies with a minority proportion of hydrogen to incrementally dilute the carbon emissions will not be sufficient.

The solution is also clearly understood – create zero carbon methods of electricity generation and transition all applications currently using localised combustion onto the electrical grid. The zero carbon methods of generation might be wind, solar PV, micro-hydro or hydrogen combustion, or they might be nuclear of one form or another. They might be centralised or they could be distributed to be close to the point of use, which would help us to make better use of a national grid that is presently configured to transmit power over long distances and is operating close to its maximum capacity.

The main challenges are that these solutions need to be deployed very soon (in fact we ought to have started in earnest many years ago) and they need to be robust and reliable. That is where a heat pump as a method of delivering low grade heat where and when it is required comes into play. If the grid is not robust enough to carry the current required to provide direct electric heating all over the country (and to recharge electric vehicles) then the demand can be substantially reduced by using heat pumps

[1] https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector
[2] https://www.gov.uk/government/publications/fossil-fuel-price-assumptions-2019
[3] https://www.legislation.gov.uk/uksi/2019/1056/contents/made

to deliver a heat advantage of 3 or 4, or even more in the case of sensibly designed heat networks. About one third of fossil fuel combustion is for the delivery of low-grade heat for space heating, principally through domestic and commercial gas boilers. Switching this demand to direct electric heating would place a large additional load on the grid but delivering the heat using a heat pump reduces that additional demand by a factor of four.

The reason that the low price of gas is so damaging to the case for heat pumps is a question of simple arithmetic. In rough terms, the ratio of the price of a kWh purchased as electricity (however you intend to use it) to the price of a kWh purchased as gas for burning - sometimes called the "spark ratio" - needs to be lower than the heat advantage of the heat pump system for the heat pump to be financially attractive. In 2009, as can be seen from the gas and electricity prices given above, the spark ratio was 3.7:1 and in 2019 it had risen to 5.2:1. With very good design it is possible to achieve a heat advantage of 3.7, but reaching 5.2 is much more difficult. Data from the European Commission's report "Energy Prices and costs in Europe, 2018" [4]shows that the UK has the third most expensive electricity and the third cheapest gas of the 27 countries surveyed for the report. However combining these two parameters indicates that the UK has the highest spark ratio of the 27. Contrast our situation with the position in Finland and Sweden where the spark ratio is 1:1 or even lower. Not surprisingly, it is not difficult to sell heat pumps there, where even direct electric heating is cheaper than gas.

Electricity generating markets have been characterised in the last 20 years by a shift from a few central combustion plants to a distributed net including solar photovoltaic and wind turbine generators. These new sources are intermittent (only generating when the sun shines or the wind blows) and this is creating a highly dynamic supply market. Solar PV is of less value to the heat pump market because generation and demand are out of sync. Wind strength (and hence electrical generation from turbines) is, however, generally in phase with heat demand. This means the electrical demand created by heat pumps is a useful load for wind farms at a time of over-capacity in the supply network which could result in favourable pricing. With the market now split into 48 half hourly periods in any given day, heat pumps may be able to gain an advantage over cheap, fixed-price gas. It has been pointed out that wind powered generation suffers from long periods of low output but offshore wind, while more expensive to install than onshore, provides capacity factors (% of maximum output achieved over a year) of as much as 60% compared with 20% onshore.

Linking large scale river source heat pumps to offshore wind could be done with a private wire network to reduce the grid transmission costs and security of supply concerns. The adoption of electrically powered heating is also seen as a significant step in the reduction of harmful particulates, particularly NOx, in urban air quality. In light of growing evidence of the effect of particulates on respiratory function and neuro-degenerative diseases such as Alzheimers, this is a significant change in the regulatory framework, which is expected to bring major changes to the mechanism for planning consent in urban redevelopment[5].

Heat pumps will therefore be an essential part of the transition to carbon neutral over the next 30 years. This is not a matter of opinion; it is a statement of basic necessity. Given the multiple challenges we face in zero-carbon generation with grid capacity, intermittency, ready availability and security of supply, heat pumps will form a key part of the provision of reliable low-grade heat. It seems perverse that we are pouring research and development funding into things that are technically far more risky and difficult and far less likely to succeed when we have a simple concept already available that has been well proven for the last 50 years and was known for more than 100 years before that.

Progress to date towards the 2050 net zero carbon target looks encouraging at first sight. When the 2019 amendment was adopted, a reduction of 42% had already been achieved in comparison with 1990

[4] REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS – Energy Prices and costs in Europe, 9 January 2019, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0001&from=EN
[5] https://www.the-scientist.com/features/air-pollution-may-damage-peoples-brains-66473

emission levels. However, as Figure 11 shows, a large proportion of that improvement was by moving away from coal-fired generation (about 900gCO_2eq/kWh) towards gas-fired generation (about 500gCO_2eq/kWh), reducing the carbon content of the electricity generated in that way by 45%. Widespread use of carbon capture and storage, which is expensive, difficult, inefficient and unproven at full scale, might enable a further 25 %-age point reduction to about 200gCO_2eq/kWh, but it is difficult to see fossil-fired generation doing any better than that.

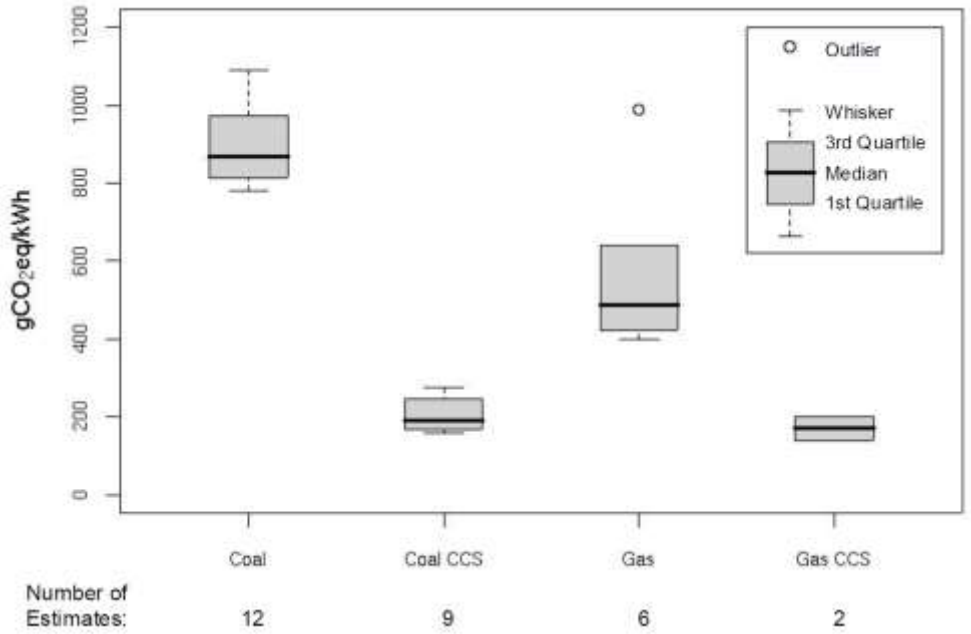

Figure 11 Carbon footprint of coal-fired and gas-fired generation, with and without carbon capture[6]

Meanwhile the domestic renewable heat incentive, which was launched in 2014, is now in the process of winding down and will be closed to new applicants in March 2022. It was a remarkably successful instrument in Great Britain and should not be confused with the Northern Irish "cash for ash" debacle, which gave the whole RHI concept a bad name. In Great Britain over 20,000 non-domestic entities joined the scheme and around 42,000 GWh of heat were generated by them from 2012 to 2019. Over 75,000 domestic properties contributed a further 4,400 GWh of heat in the period from April 2014. However, the Committee on Climate Change wants to have 15,000,000 UK homes with heat pumps or hybrid heat pumps by 2035. We have managed 0.5% of this target in the last 6 years and only have 15 years left to deliver the remaining 99.5%.

The proposed replacement for the domestic RHI is intended to be a grant scheme to assist with the initial capital outlay for the installation of a renewable heat system. This runs the risk of repeating mistakes made elsewhere around Europe. A seminar arranged by the Institute of Refrigeration's International Refrigeration Committee (IRC) in 2011 studied experiences from France, Sweden and Norway; the three countries in Europe that topped the league at that time for domestic heat pump installations. In France the government awarded grants to encourage the uptake of heat pumps and the market was flooded. The scheme was apparently a great success but the installations were not properly designed and implemented and the following year the market slumped because there were so many bad experiences of systems that just didn't work. In Sweden they tried to learn from this experience and announced that a similar grant scheme would be introduced the following year, allowing time for training of contractors and technicians who wanted to participate. However, this had the effect of killing the present market stone dead, resulting in a diminution of skill levels as longstanding experienced businesses went into liquidation through the complete short-term decimation of their market. The path to success lies somewhere between those two well-intentioned failures.

[6] https://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf

11. CONCLUSIONS

An interesting common factor between the three pioneers discussed in detail in the paper, Haldane, Sumner and Macfarlane, is that they were electrical engineers with a clear understanding of the various advantages and disadvantages associated with a national supply network. They installed their heat pumps because they understood the benefit to the nation of the heat advantage and they wanted to satisfy themselves that it was real and demonstrable. Those from a mechanical or civil engineering background seem to have been more often in the naysaying camp, not willing to believe in the apparent "something for nothing" nature of the heat pump and quibbling over terminology.

A recurring theme is that the spark ratio is critical to the widespread adoption of heat pumps and at present it is as unfavourable as it has ever been. This is entirely a political problem: "Fuel poverty is a poverty issue, not an energy-market issue" (Pollitt, 2013). There are three ways for politicians to motivate consumers to adopt heat pumps: support through grants or incentives, prohibition on the use of gas and taxation of gas more heavily than electricity. The RHI was relatively successful, although not to its full potential, but the grant scheme is viewed with suspicion and there is a fear that it will not be supported in the longer term. Prohibition of gas burning in new premises is to be introduced in 2025 and will help to improve urban air quality as well as encouraging the transition to heat pumps, but only 2% of our building stock is renewed each year, so it will take 50 years to complete the switch on that basis. As previously stated, we do not have that long. Prohibition of gas use in existing buildings is much more difficult. There is no statutory or planning mechanism on which to base such a policy. That leaves taxation as the only viable way to improve the spark ratio but so far politicians have been unwilling to raise taxes on domestic fuel for obvious reasons. Unfortunately, this is a bullet that just has to be bitten. There is a precedent. Petrol and diesel are charged 57.95 pence per litre fuel duty and then VAT is charged at 20%. That means that for a litre of fuel at a price of £1.10 the price you pay comprises 18.33p VAT, 57.95p fuel duty and just 33.72p for the actual tax-free price of the fuel. If the same concept were applied to domestic gas at 4.4p/kWh including 5% VAT then the resultant price would be 13.7p/kWh including 20% VAT. Just treating domestic gas the same way as domestic petrol is taxed would completely solve the spark ratio problem.

Another way to improve the spark ratio is to reduce the cost of electricity when it is applied to technologies which align with the long term energy policy. The RHI provided this through financial support of the operating cost of a heat pump, but its replacement, a grant of about 15% - 25% of the cost of installation, will not do this. Using a smart meter to allow low tariff electricity to be used for running a heat pump is already feasible but not yet widely used. This is analogous to the old "white meter" used for storage heaters, so it is not a novel idea. It could also be applied to other technologies which align with long term policy, such as the recharging of electric vehicles overnight. The electricity supplied in this way does not need to be as cheap as gas – a spark ratio of, for example, 1.5:1 would go a long way to encouraging people to switch from gas to electric heating with heat pumps. This could be achieved with a modest tax on gas used to fund the electricity tariff support. It is not going to happen without some form of field levelling like this and the current situation, where domestic gas supply is so much cheaper than electricity, cannot continue for much longer. The Scottish Government has shown a commendable level of support for initiatives to reduce carbon emissions, including their Low Carbon Infrastructure Transition Programme (LCITP), which was instrumental in supporting the Queens Quay development. The government have also been willing to listen and learn as the scheme has gone through several cycles of development. Local government also has a significant role, particularly in linking planning consent to the goals of clean air and low carbon heating. Hopefully there is scope for a Scottish initiative to develop a funding model and legislative framework for the supply of domestic energy that will augment and support the further development of that Scottish invention, the heat pump.

Finally, to echo Haldane's words in the 1947 discussion following Sumner's paper, we need to adopt a multi-disciplinary approach in order to make heat pumps not only a viable solution to the carbon emissions problem, but the preferred solution. Electrical engineers clearly have a role to play, so too do marine engineers designing water abstraction systems and floating energy centres which export heat onshore. Building services engineers designing heating systems, and civil engineers constructing the

buildings that use them and the roads, bridges and tunnels that access them can also make the heat network an affordable, practical reality. Clearly the Institution of Engineers and Shipbuilders in Scotland has a lot to contribute in order to achieve this goal. As Professor Rankine said at the end of his Presidential address in 1857 "*If an institution of engineers is to make good progress anywhere, it ought to be Glasgow. I trust that, in this respect, my most favourable anticipations will be before long fulfilled, and that our Institution will prove of benefit to practice, to science and to the country*."

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