River Source Heat Pumps for Residential and Commercial Heat Networks – A Case Study

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ABSTRACT

The decarbonisation of our use of energy in all its forms requires a radical re-think of the way in which we provide heating to our homes and commercial buildings. River source heat pumps provide one part of the solution and are particularly suited to the geography and climate of the United Kingdom. This paper presents one such project, the development at Queens Quay in Clydebank, Scotland, as a case study of current technology in this sector. The paper describes the technical challenges in engineering a river source system, outlines the solution adopted and gives an overview of actual performance since commissioning. The paper concludes with a review of obstacles to the widespread adoption of this technology which need to be addressed if the targets of the UK government commitments are to be achieved.

Keywords: Heat Pump, District Heating, Energy, Performance.

1. INTRODUCTION

The response to climate change requires a wide range of strategies and technologies over a broad scope of applications. It needs an overview of the challenge as being about all forms of energy use, not just electricity, and success will depend on deployment of many solutions in parallel. One such approach is the use of large scale heat pumps in district-wide networks to transfer the demand for heat in homes and commercial buildings from fossil fuels to electric heat. Substitution of electricity for gas, coal or oil could be done with direct electric heating, but there a substantial heat advantage to be gained by using a heat pump in order to deliver three or four times the amount of heat as would be supplied by the direct method. This has major implications for the affordability of heat as well as the burden that such a move would place on the electricity supply network, so the use of heat pumps is strategically very important. This case study describes one method of using heat pumps to supply domestic and commercial buildings but it is not held up as the only way to do this. Individual ground-source or air-source heat pumps are also part of the solution, as are low temperature networks; the so-called 4th and 5th generation district heating systems. The system described in this paper uses river water as the source and is supplying a 3rd generation network, although the design temperatures are almost low enough to qualify as 4th gen.

2. BACKGROUND

In the late nineteenth century, centralised neighbourhood heating systems were developed in the USA serving college campuses or neighbourhoods with high pressure steam for building heating. In the 1930s the 2nd generation of heating systems started to replace the original steam systems on grounds of safety, reliability and efficiency. The 2nd gen systems circulated pressurised water at temperatures above 100 °C and were supplied by central boiler houses burning fossil fuels. In the 1970s the 3rd generation, also known as the Scandinavian system, was developed. The supply temperature was lowered to between 70 °C and 100 °C making prefabricated construction and operation simpler, but the network was still often supplied by coal and gas burning boilers. The 3rd gen systems however introduced the possibility of industrial sized heat pumps as an auxiliary or even as the main source of heat for the network. The largest district heating heat pump system is in Stockholm, installed from 1984 onwards and with a capacity of 180MW. This plant originally used R-22 and was retrofitted to R-134a, starting in 2003. It indicates that district heating heat pumps can be scaled up to substantial capacities and are generally not limited by the heat source if it is a large river or open sea.

4th generation district heating systems deliver water at lower temperatures than 3rd gen; typically between 40 °C and 70 °C and are associated with modern buildings incorporating low temperature systems, such as underfloor heating for which high temperatures are in any case prohibited. In general 4th gen systems are not compatible with older buildings or specialist applications such as hospital heating or domestic hot water. These require some auxiliary form of heating (perhaps direct electric) if connected to a 4th gen network. The 5th generation circulates water at what is effectively ambient temperature providing a source of heat for localised water source heat pumps, a sink for heat rejected from cooling systems and a source of direct cooling for some high temperature process loads.

During the first introduction of heat pumps to 3rd gen systems the majority of plant used CFC, HCFC or HFC as the refrigerant, but starting around 2005 natural refrigerants were introduced, with some particular advantages. In particular ammonia offers the possibility of higher heat advantages than can be achieved with HFCs, primarily due to the higher critical temperature. One such system was installed in Drammen, Norway, by Star Refrigeration in 2010 supplying around 13MW of heat to a 90 °C network serving the commercial buildings in the centre of the town. With a heat advantage in excess of 3.0 when delivering heat at 90 °C this was considered to be around 15% - 20% more efficient than could be achieved with HFCs in similar sized systems.

3rd gen systems are now 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.

Ten years after the installation in Drammen the first river source ammonia heat pump of this type in the UK was installed by Star Refrigeration in Clydebank. The project was led by West Dunbartonshire Council with funding from the Scottish Government through the Low Carbon Infrastructure Transformation Programme (LCITP). It is part of an urban regeneration scheme led by Ryden and Dawn Developments, with the district heating system devised and constructed by Vital Energi.

3. THE QUEENS QUAY SYSTEM

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 centre of Glasgow. Despite strong support from the Holyrood government and the City Council, the challenge of ensuring heat sales in a complex commercial environment of disparate individual existing buildings 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 new homes, the college, a medical centre, a sports centre and the town hall. West Dunbartonshire Council (WDC), with their main contractor, Vital Energi, led 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 2,650 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.

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.

Figure 1 – QE2 under construction at John Brown's Shipyard in Clydebank in 1967

Figure 2 shows one of the river water cooling packages being delivered. All that is now left of the yard shown in Figure 1 is the famous Titan crane, which can be seen reflected in the windows of the Energy Centre in Figure 2.

Figure 2 – A river source heat pump (2,650 kW heating capacity) delivered to Queens Quay, Clydebank

Figure 3 – The two heat pump systems (each 2,650 kW heating capacity) in the energy centre

4. SYSTEM DESIGN DETAILS

Each module of the system comprises a spray chiller evaporator, a twin screw compressor and a series of heat recovery heat exchangers on the district heating loop; a subcooler, a condenser, an oil cooler and a desuperheater. The heating water is pumped through the heat exchangers in that order, ensuring that maximum temperature can be achieved by passing through the oil cooler and desuperheater after the condenser. On the river water side the evaporators are of the shell and tube spray chiller style. This maximises the cleanability of the evaporators while keeping the ammonia charge as low as possible. The tubes are titanium as the river water is brackish and each evaporator is fitted with a brush cleaning system which scours the tubes periodically to keep the chiller in good condition. Many operating scenarios were modelled during the design phase and a summary of the results is shown in Figure 4.

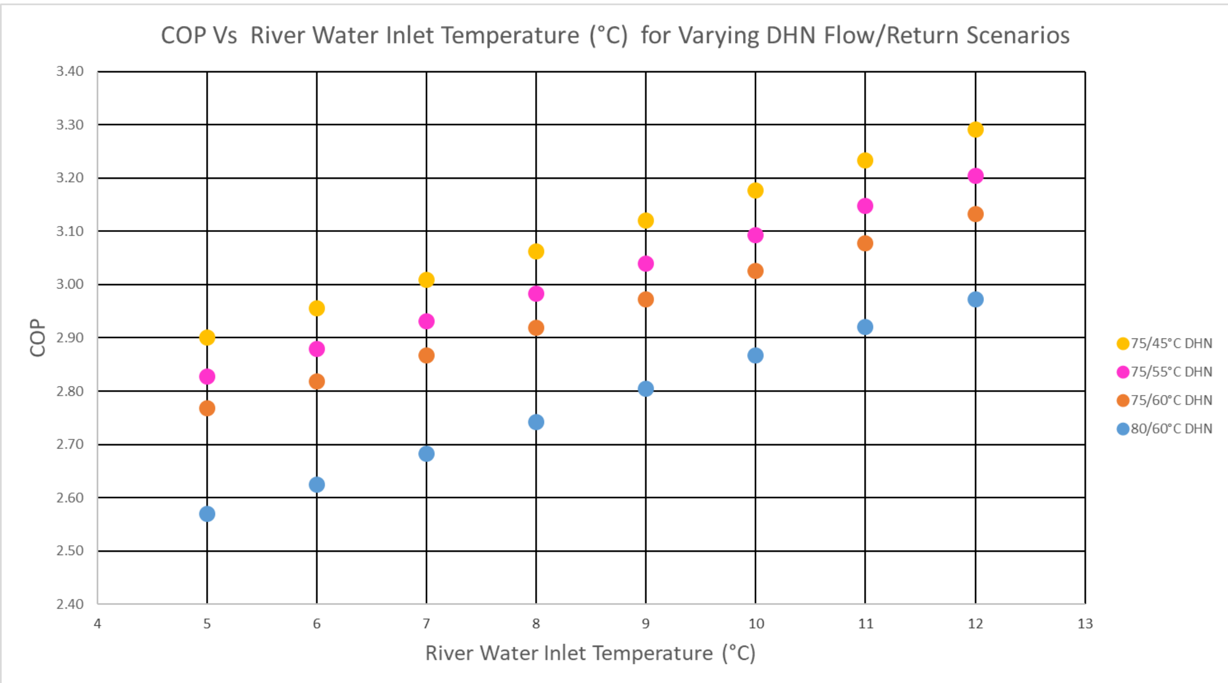

Figure 4 – Calculated COP for the district loop under different conditions

The compressors are twin screws with a design rating of 52 bar and a swept volume of 1,746 m^3h^{-1}. This provides a nominal heating capacity of 2,653 kW when the heating loop is supplied at 75 °C. Under these conditions the CoP varies from a minimum of 2.9 (including losses of 6% across the motors and variable speed drives and allowing for the spray chiller pump power) up to 3.3 as the river warms.

The matrix of operating conditions in Figure 4 showed that for every degree rise in river temperature the CoP rises by 1.9%. However it also clearly illustrated three other effects.

- If the heating water inlet temperature is fixed the CoP will increase by between 1.1% and 1.6% for every degree that the supply temperature on the heating water is reduced.
- If the temperature difference across the heating loop is maintained at a constant differential the CoP will increase by between 1.5% and 2% for every degree that the supply temperature on the heating water is reduced.
- If the temperature difference across the heating loop is widened beyond 20 K with a fixed supply temperature the CoP will increase by a further 0.2% to 0.4% for each degree that the difference is increased.

It therefore follows that the optimal strategy for operation of the heating network is to supply heat at as low a temperature as possible but also to widen the temperature drop across the heat consumers by as much as possible. Combining the three effects with a river water temperature of 8 °C shows an increase in CoP from 2.74 to 3.06; an increase of 11.7%.

To qualify for the Renewable Heat Incentive (RHI) the plant has to meet minimum performance standards. These are set with a flow temperature of 65 °C but with a low temperature drop in the loop of only 10K and for a river inlet temperature of 10 °C. Under these conditions the nett CoP of the installed system at Queens Quay (including motor and VSD losses and ancillary loads) is 3.4 – well above the qualifying threshold of 2.9 for RHI.

To provide additional operating experience for future system design one of the two units was equipped with a break heat exchanger on the river water side. This adds a further 2K temperature difference on the evaporator side reducing the CoP and limiting the operation of the unit in colder weather. The break heat exchanger can be bypassed if it is deemed unnecessary in future based on operational experience.

The system was set to work in November 2020 and commissioning logs with a dry air cooler connected to the heat loop to create a false heat demand showed that the plant met the RHI threshold under all operating conditions. On full load with river water at 8 °C and with the break heat exchanger in circuit Unit 1 delivered a CoP of 3.18 on full load and even achieved the RHI threshold when operating on reduced capacity (66% of full load). Unit 2, without a break heat exchanger, delivered a heating CoP of 3.34 on full load and 3.07 at 66% capacity.

Since commissioning the system has remained in operation but is only ticking over at the moment as the heat demand is very low because the site is still under development so very few buildings are connected to the network at present. The demand will gradually increase over the next two years as the development becomes more fully populated.

5. PROSPECTS FOR WIDER USE OF THIS TECHNOLOGY

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 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.

[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
[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

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.

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.

[5] https://www.the-scientist.com/features/air-pollution-may-damage-peoples-brains-66473

6. CONCLUSIONS

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. One of the key questions to be addressed is why the tax on electricity is 75 times that on natural gas per kg of carbon emitted. This is not encouraging the desired behaviour and needs to change. Another hurdle is that while legislation looks likely to require new developments to subscribe to heat networks there are currently no plans to do the same for existing infrastructure. Without the financial incentive of expensive gas and cheap electricity some other motivation is required for existing buildings.

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. It offers significantly higher efficiencies than a plethora of much smaller heat pumps operating on a 5th gen network and has the advantage of using a zero-GWP refrigerant. This is a combustion-free solution, giving the benefit of 4th generation heat sources but elevated to 3rd generation temperatures in order to serve the great number of legacy heating requirements around the country. It reduces the load on the electrical grid compared to smaller heat pumps or direct electric heating and it enables the use of thermal storage to further balance supply and demand across the heat network. In comparison, as the grid gets cleaner other previously popular technologies such as gas-fired CHP effectively get dirtier. Hydrogen for combustion doesn't offer a good alternative because the electricity to heat conversion ratio for manufacturing, distributing and burning hydrogen is about 60% compared to over 300% for a river source heat pump system such as Queens Quay.

The performance of this system has been confirmed to be well in excess of the RHI threshold under controlled commissioning conditions. Valuable lessons have been learned in terms of operation of heat network systems and now that this technology has been proven to be efficient and effective in the UK it is hoped that many more systems will follow when there is a need for renewable heat in 3rd and 4th generation heat networks.

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REFERENCES

Muschamp, H., 2014, Energy Heat Mapping, Scottish Renewables – Harnessing the Heat from Rivers, seminar hosted on 10 September 2014 by University of Glasgow