Booster Heat Pumps for Space Heating, Hot Water Heating and Process Heating from Geothermal Energy

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ABSTRACT

This paper addresses the use of shallow to deep geothermal energy in Northern Ireland for space heating, process heating and power generation. It considers the temperatures of potential sources of heat and the technical, social, economic and institutional barriers that must be overcome in order to deploy this significant heat resource in Northern Ireland. The role of advanced heat pumps, the development of heat networks and the potential efficiency and environment gains are noted through using elevated temperatures as a heat source for heat pumps. For space heating, R410a alternatives e.g. mixtures using R160 are assessed for ground source heat pumps. For industrial processes such as Northern Ireland’s Dairy industry, the performance of booster heat pumps is presented that utilise new working fluids, such as R1233zd(E). A similar working fluid is utilised for lower temperature Organic Rankine Cycles and the performance of such a machine is noted. A summary of likely heat network techno-economic challenges is given alongside the benefits of higher efficiency and reduced carbon emissions that the use of geothermal heat can give.

Keywords: Refrigeration, Carbon Dioxide, Compressors, COP, Energy Efficiency.

1. INTRODUCTION

This work considers the use of Geothermal Energy in the space, hot water and process heating as part of the CO_2 reduction pathway to 2050. Northern Ireland has a significant geothermal resource (e.g. Kelly et al, 2005) and space, hot water and process heating capabilities will be presented for a range of geothermal temperatures approximately corresponding to shallow geothermal depths of 10’s of meters to 1000’s of meters. There is also consideration given to role of heat distribution networks to utilise such heat with or without upgrading based on recommendations from Rutz et al (2019). Where temperature upgrading is required, the role of heat pumps is discussed, and their challenges presented. Where enough temperature is available, the potential of binary cycles to generate power is also addressed. Finally the Committee on Climate Change (2019) has noted that an 82% reduction in CO2 emission is sufficient for Northern Ireland’s contribution to the greenhouse gas reduction agenda, given the strong reliance on agriculture.

2. BOOSTER HEAT PUMPS FOR SPACE HEATING, HOT WATER HEATING AND PROCESS HEATING FROM GEOTHERMAL ENERGY

The primary focus of this work is the consideration of booster heat pumps to upgrade available heat sources to a temperature that is required by space heating, hot water heating and process heating.

2.1. Geothermal Resources

In Northern Ireland Kelly et al, (2005), combined borehole tests and geothermal/geological modelling to assess the geothermal resource. The shallow resource (up to 10’s of meters) would be primarily focussed on the space heating (individual homes, commercial properties etc.) and hot water heating i.e. vertical boreholes for ground source heat pumps. There is also the possibility to store excess heat from summer cooling/onsite solar energy in such shallow systems. Spring and ground water temperature in Northern Ireland is typically 10°C, although any extraction requires careful consideration due to the role that such springs and ground water play in potable water supplies. At 100m, geothermal resource temperatures at 33°C can be extended up to over 90°C at 2500m (Figure 1). At 5000m, temperatures are calculated at temperatures approaching 180°C. The oil industry has drilled to 5000m and has seen temperatures over 170°C while Hoang et al (2021) are investigating deep well casings for geothermal energy at temperatures up to 450°C, so making use of such temperatures is being used.

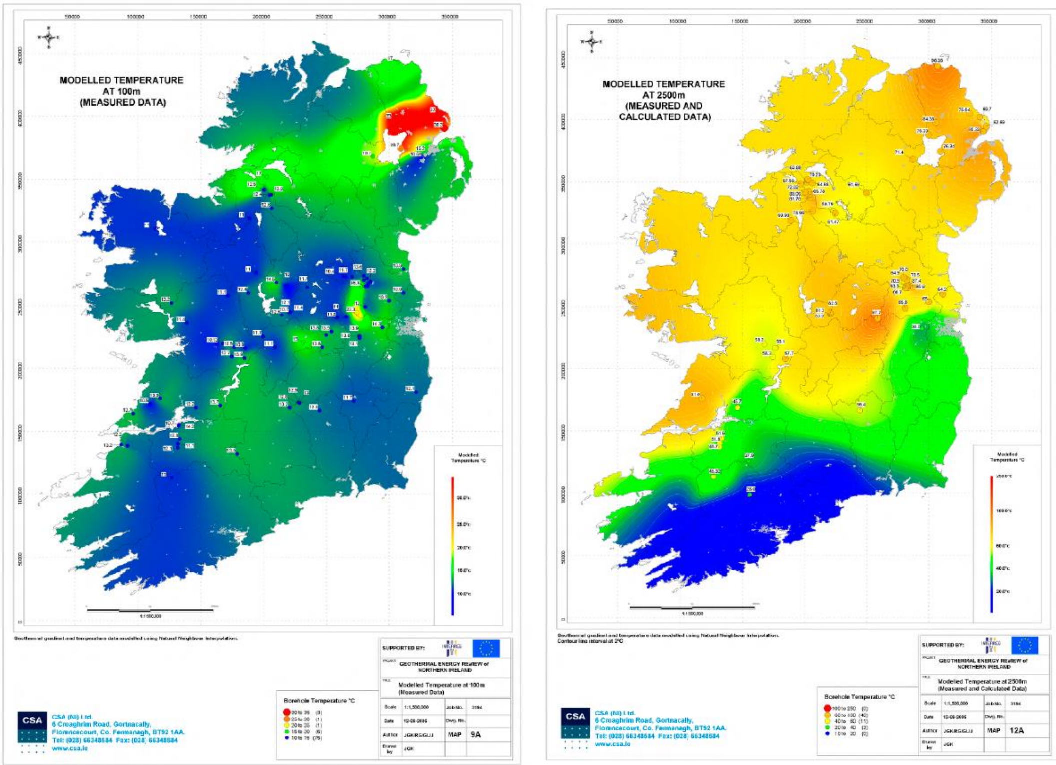

Figure 1: Modelled Temperature at 100m and 2500m based on Measured Data (Kelly et al, 2005)

2.2. Heat Pumps

Using vapour compression heat pumps to upgrade geothermal energy to higher temperatures may utilise technologies delivered under the auspices of the UKRI EPSRC LoT-NET research programme (EP/R045496/) and UKRI EPSRC DELTA PHI (EP/T022981/1) where a series of advanced heat pumps are being developed for applications ranging from low temperature lift, high coefficient of performance (COP) systems to high temperature lift applications for industrial/commercial purposes.

2.2.1. Low Temperature Space Heating and Domestic Hot Water Applications

The focus for this research has been on the replacement of R410a. F-Gas regulations have seen a tightening of regulations in favour of low Global Warming Potential fluids with a GWP < 150. An evaluation of mixtures with a GWP less than 150 as a substitute R410a may include up to five refrigerants and include fluids that allowed only “mild” flammability. Four mixtures have almost the same vapour pressure to that of R410a making drop-in a possibility. Mixtures of three components included a new fluid R1123 and a non-refrigerant fluid R13I1 alongside R32, R1234ze(E), CO_2, R1234yf, R41, R1270, R161 etc. REFPROP was used to illustrate the performance of mixtures with a GWP < 150, a similar COP and volumetric capacity to that of R410A for both cooling and heating applications. For example, vapour pressure of four mixtures that had almost the same pressure to that of R410a, they were R32/R1123/R161/R13I1 (20/40/10/30), R1123/R161/R13I1 (65/5/30), R1123/R152a/R13I1 (65/5/30) and R1123/R1234ze(E)/R13I1 (65/5/30) by mass. Typically, there is a 4-6% drop in COP when using these replacements when compared to R410a (Wu et al, 2021).

The exploitation of new variable speed drive compressors to optimise heat supply when operating with, for example weather compensated control for space heating from lower temperature heat sources has seen a range of performances for a range of compressor speeds as noted in Figure 2. A test facility was constructed using R410a variable speed compressor and the heat exchangers and controls were constructed around this compressor provided by Emerson. Two aspects were considered, namely the impact of compressor capacity regulation on performance and the ability to deliver space heating and domestic sanitary hot water on demand. Wide ranging capacity tests were carried out with results demonstrating a reduction in performance at speeds other than 50-60 Hz. One of the biggest challenges has been to develop a non-flammable low-GWP R410A substitute. This was impossible with H, C and F-based molecules until the introduction of ionide. R466A is a refrigerant designed for R410 drop-in, with a GWP of 730, and it's composed by R32, R125, and CF3I. The CF3I molecule containing iodine is known as a flammability suppressor, but it also has an ODP value yet not accounted for in the Montreal Protocol. Material compatibility, development, and testing of components is mostly ongoing. However, it has a GWP of 733 and its COP was about 5% greater than R410a.

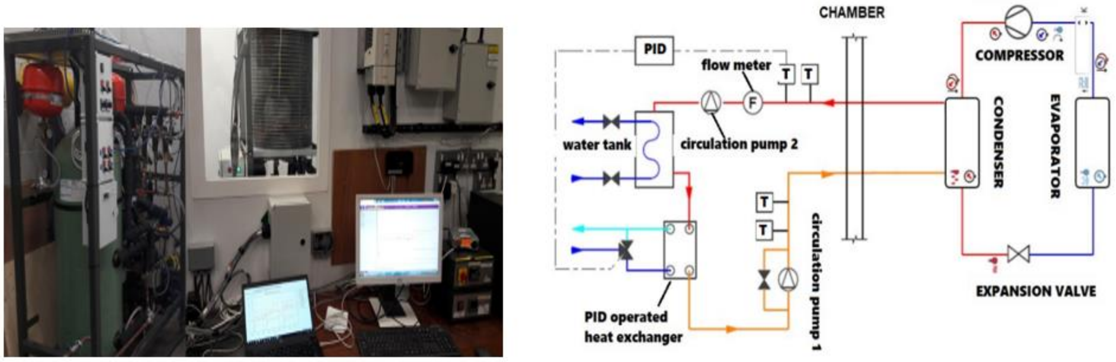

Figure 2: Heat Pump Test Facility

2.2.2. Process Heat Applications

A test facility was developed that addresses the upgrading of lower temperature heat sources to temperatures required by process heating. Cooper et al (2019) identified the dairy industry and the food and drink sector are likely beneficiaries of new efficiency improvements and carbon dioxide reductions that geothermal energy and heat pumps can bring. In Northern Ireland, the dairy industry is worth £925m per annum with processes such as Pasteurization where Low Temperature, Long Time is 63°C for 30 minutes, High Temperature, Short Time is 72-75°C for 15-25s and Ultra-High Temperature is up to 138°C for 2-4 seconds.

The system performance was evaluated thermodynamically at various evaporation temperature and condensing temperature as described earlier for R12333zd(E) and R245f. Figure 3 shows comparative analysis of system performance for R245fa and R1233zd(E). Performance analysis is presented in terms of condensing capacity, compressor power and COP with varying condensing and evaporating temperature condition. It is evident that for same temperature lift condition, heat output for R245fa is higher compared to R1233zd(E) but compressor power consumption is also higher which ultimately results in negligible reduction in COP compared to R1233zd(E). This is mainly due to density/pressure difference at those conditions temperature condition which results in higher enthalpy difference for R245fa. It is evident that R1233zd(E) gives higher COP in a range of 1 to 9% but lower heat output in range of 8 to 15%. This may result in increased heat exchanger size and volumetric area in a case on R1233zd(E) if used as a direct replacement of R245fa.

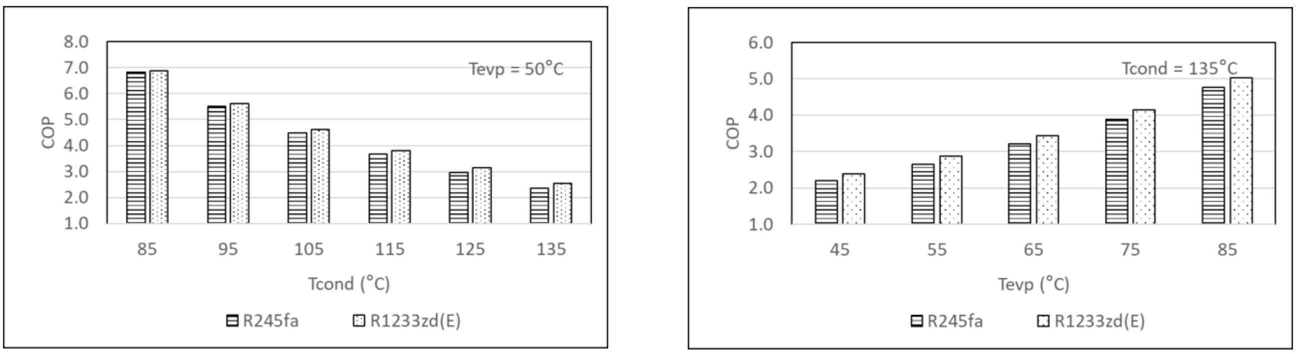

Figure 3. Comparative analysis for R245fa & R1233zd(E): Left: variation in Tcond, Right: variation in Tevap

Underpinning this work, was an analysis of suitable compressor lubricants for higher temperature operations. Figure 4 illustrates the experimental setup. Tests were completed to validate the operation of the equipment.

These tests were conducted between 50°C and 100°C with refrigerant introduced at 10°C lower temperature. Tests were conducted with pure oil and repeated with oil that had refrigerant recovery completed. These ramp-up test results show viscosity reducing with increasing temperature to 6 cTs at 100°C which is still appropriate for compressor lubrication. Results indicate that POE320 lubricant used in conjunction with R1233zd(E) will provide increased lubricity at higher operational parameters up to 10% concentration and up to 30% concertation with adequate cooling. However, viscosity rating is determined by compressor manufacturer and further testing of lubricant oils with higher viscosity index is required to comprehensively assess suitability in achieving operational conditions for the High Temperature Heat Pump. Lubricant plays a crucial role in safe and efficient compressor operation, especially for high temperature applications. Lubricant and refrigerant mixture viscosity analysis and behaviour during heat pump operation requires careful investigation.

Figure 4: Oil Solubility and Miscibility Analysis

2.2.3. Binary Cycle Operations

Organic Rankine Cycles may be the basis of power generation from higher temperature geothermal resources in Northern Ireland. Commercially available systems typically use R245fa, but its use is now questionable due to its GWP. R1233zd(E) has then been considered for use in such cycle and its performance has been modelled. The schematic diagram of the semi empirical model for scroll expander is shown in Figure 5. While this is not suitable for large scale applications, its use illustrates the performance differences of R1233zd(E) in this application.

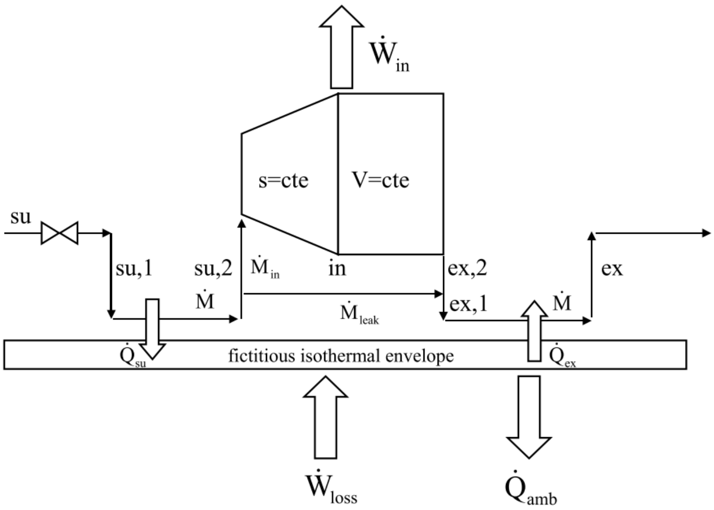

Figure 5: Semi empirical scroll expander model (adapted from Lemort et al, 2009)

The performance of R1233zd(E) when substituted in place of R245fa is very similar to that exhibited by R245fa. However, the expander supply temperature of R1233zd(E) is around 10 K higher than that of R245fa for the same degree of superheat indicating R1233zd(E) requires higher heat source temperature than that of R245fa for that same operating pressures. The Irish Government's 2019 Climate Action Plan predicts that data centres will account for as much as 31% of Ireland's electricity needs by 2027 (EirGrid & SONI, 2019). With current Irish data centres and other large industrial users ranging in size from 3MW to 140MW electricity capacities, the potential decarbonisation benefits are huge, particularly if the need for diesel- and gas-fired co-located generation for uninterruptable power supplies (UPS) can be eliminated. For each MW of capacity that can be replaced by geothermal, the benefits range from 2600 to 6000 tonnes CO_{2e} per annum per MW. By 2028, data centres and other large users will consume 29% of Ireland's electricity, according to EirGrid, Ireland's state-owned transmission system operator. Worldwide data centres consume about 2% of electricity, a figure set to reach 8% by 2030. Few countries, if any, will match Ireland's level of data centre development and this will have consequences on the operation of the All-Ireland Electricity Market. A report by the Irish Academy of Engineering (IAE) has estimated data centre expansion will require almost €9bn in new energy infrastructure and add at least 1.5m tonnes to Ireland's carbon emissions by 2030 – up 13% spike on current electricity sector emissions. Given the All-Ireland electricity market, Ireland's data centre growth will impact on the availability and price of off-peak electricity. However, provision of onsite generation through geothermal energy are projects that are highly site sensitive. Typical costs for geothermal power plants range from £1350 to £3700 per kilowatt(kW), noting that binary plants are normally more expensive than direct dry steam and flash plants. The levelized cost of electricity (LCOE) of a conventional (high temperature resource) geothermal power plant ranges from £0.03 to £0.11 per kilowatt-hour (kWh), assuming maintenance costs of £80 per kW per year and a 25-year economic life. This compares with a levelized cost of electricity (LCOE) in Europe for combined cycle gas turbine of £0.05/kWh, onshore wind (£0.04/kWh), offshore wind (£0.09/kWh), solar PV (£0.047/kWh) and onshore wind/battery (£0.11/kWh). Thus, if proven to be able to progress through a declining LCOE learning curve similar to solar and wind in the last decade or so, the mid-temperature geothermal energy system to be assessed in this project looks highly attractive for a net-zero emission data centre in terms of running costs. NI has several attractive locations and industrial users that would form potential sites for prototype systems, and successful prototyping in NI would lead not only to further industrial decarbonization in NI but enable massive growth of application elsewhere.

2.2.4. High Temperature Heat Pump Development

Arpagaus et al (2018) identified a number of commercial products available in the market where maximum temperature of 165°C is achievable with source temperature in a range of 35 to 70°C. For HTHP, the following types of compressors are used in commercial products: Screw (single or twin), Piston (single and parallel), Turbo (single/two-stage). Figure 6 shows commercially available compressors used in HTHP with their capacity range and maximum achievable sink temperature.

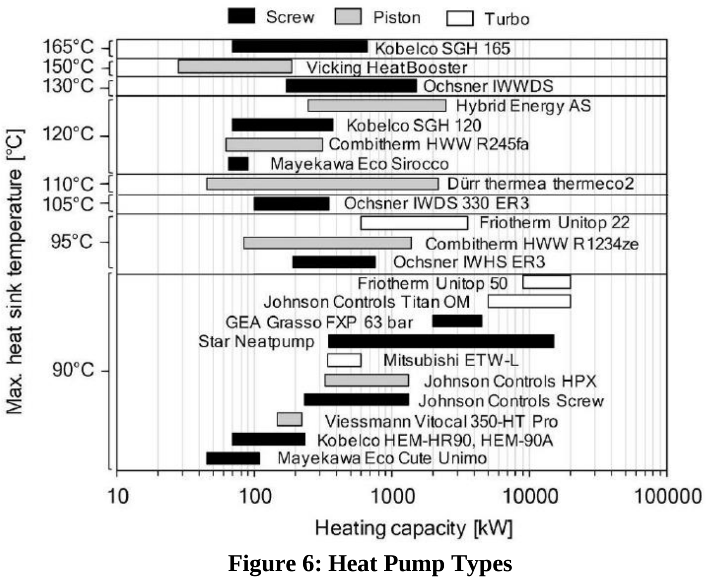

Figure 6: Heat Pump Types

Typically, piston compressors (reciprocating) are constructed in V and W-shaped Monoblock for strength, rigidity and ease of layout. They are direct flow with false cylinder covers to protect from water-hammer effect. They are either water cooled, or air cooled with fins etc based on temperature and refrigerant. However, they have complex access to bearing, lubricant system and other details, located in the block-crankcase. In order to move beyond these temperatures, a cascade system will be developed using as its basis a high temperature heat pump (HTHP) utilising R1233zd(E). Its operation will be extended up to 150˚C based on existing equipment. Ulster will then develop a very high temperature heat pump (VHTHP) based on a new transcritical cycle to move beyond 200˚C. Sarkar et al (2007) indicated that n-butane was a possibility, but new fluids have emerged since this publication including:

- HFCs: R365mfc, R245ca, R245fa (issues: Global Warming Potential above 150)
- HFOs: R1336mzz(Z), R1234ze(Z) (Promising, although A2L for R1234ze(Z))
- HCFOs: R1233zd(E), R1224yd(Z) (Promising)
- HCs: R601, R600, (promising but SG: A3 - Flammable)
- CF6: Novec649 (recent development, lack of information)
- Natural: R718, R717 (R718 promising, R717 SG: B2L)

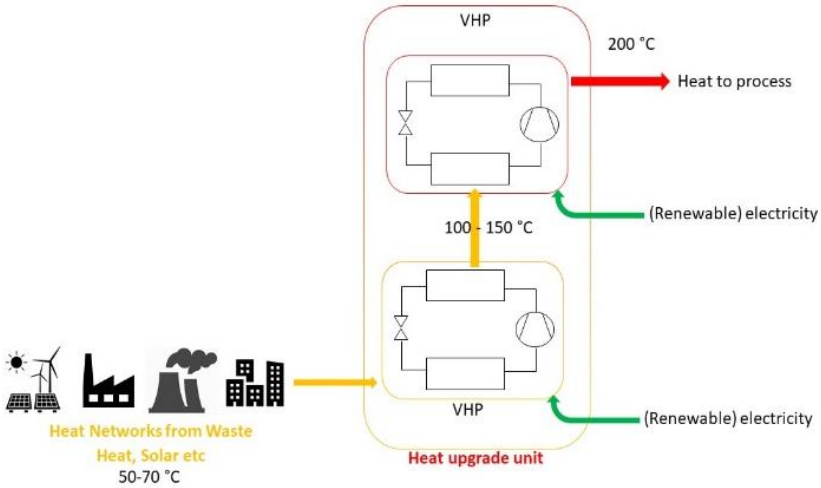

Figure 7: System Concept

A number of these fluids have been modelled in REFPROP where data is available and considered for transcritical cycle operation. It is intended to use commercially available components and Gas Coolers associated with Cardon Dioxide (CO_2) which can operate at 100 Bar A and temperatures over 200˚C. The use of CO_2 equipment facilitates tests at high pressures as commercial equipment is rates at 120 Bar A.

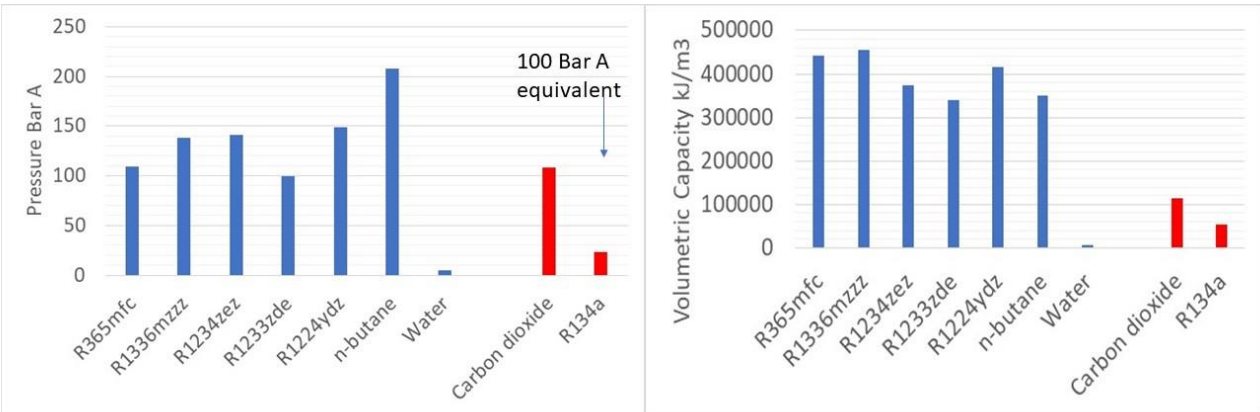

Figure 8: Pressure at 230 deg. C and Volumetric Capacity for Gas Cooler Sizing

The initial models reveal R1233zd(E) as a potential starting point although the Gas Cooler would need to be three times oversized when compared to CO_2 operation and the compressor would need to be 20% oversized for comparable operation. Compressor lubrication for current compressors must be maintained typically at 20 centistokes and through Ulster's Flucon Laboratory Viscosimeter QVis 01/L, the dynamic viscosity of the lubricant – refrigerant compositions with a precision of +/- 2% will ensure successful lubricant selection for very high temperature operations. R1233zd(E) has been used in higher temperature Organic Rankine Cycle (ORC) operations. Most papers refer regarding ORC and/or VHTHP were based on mathematical model/simulation/theoretical analysis. Bobbo et al (2018) addressed the properties of R1233zd(E) and other low GWP refrigerants but Arpagaus et al (2018) identified that none of the current industrial HTHP use R1233zd(E). Potential benefits of R1233zd(E) in terms reduced compressor size etc. and COP for HTHP applications have been discussed by Frate et al. (2019) and Bamigbetan et al. (2018). Thus, the use of

R1233zd(E) for HTHP and ensuring lubrication compatibility and the development of a VHTHP (based on CO_2 equipment to accommodate pressure) using a Transcritical approach will be developed.

2.2.5. Heat Networks

Geothermal heat utilisation will require heat network implementation. The argument is whether to upgrade the heat centrally and delivery through higher temperature heat networks to clustered industries or utilise Generation IV and above heat networks (temperatures <50°C) to deliver lower temperature, which is then upgraded at point of use. Thermodynamically, there are less losses with the latter (e.g. Rutz et al, 2019) but in either case, the economics of heat networks require examination. Revesz et al (2020) noted the CAPEX breakdown of costs for the proposed GreenSCIES scheme, the network infrastructure in a dense urban area was found to be the highest proportion of funding. With average costs of £1000/m (BEIS, 2015), clustering of businesses will be important. Clustering of Data Centres and the Dairy industry may prove a local solution.

3. CONCLUSIONS

Geothermal energy in Northern Ireland may ultimately provide electricity and/or space and process heating. It will need to present a strong case to gain a foothold in the race to decarbonise Northern Ireland by 2050, given the regional importance being placed on hydrogen. A range of heat pump performances have been presented that show promisingly high performances when supplied with geothermal heat but there would need to be a case by case analysis to avoid excessive expenditure.

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