HEATING GLASGOW UNIVERSITY WITH RIVER SOURCED HEAT PUMPS

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ABSTRACT

This paper investigates the feasibility of heating the University of Glasgow's campus using a river water sourced heat pump system. The current heating demand of the university's main campus was estimated by measurements and 3D energy modelling using software, Integrated Environmental Solutions. The river water used in the heat pump system would be sourced from the River Kelvin which flows nearby the campus. The quantity of heat contained within the River Kelvin is also determined through the measurement of flow rate and water temperature data over three months. An ammonia heat pump system is designed to extract and upgrade the heat from the river water to a heating supply at a temperature of 80°C. The financial feasibility and carbon footprint has also been analysed and discussed in detail.

1. INTRODUCTION

The University of Glasgow's estate consists of 14 sites comprising of 300 buildings, Gilmorehill campus is the main site and has the highest heat demand density. Gilmorehill campus contains 172 buildings of which 113 (Brown, 2012) are listed by historic Scotland as being of historical or architectural significance. The main campus utility costs are currently £8.6m (Young, 2013) per year; this consists of £1.9m gas, £5.5m electricity, £1.0m water and £0.19m heating oil. The gas proportion of this represents 47.5 GWh usage (4p/kWh gas price (Department of Energy & Climate Change, 2012)); which over 4000 hours gives an initial capacity estimate of 12MW. At present the Gilmorehill campus relies on gas boilers for over 90% of its space heating and domestic hot water (DHW). This is a considerable amount of energy consumption by burning fossil fuels and will result in carbon dioxide emissions of 9×10^9 $kgCO_2e$ (0.184 $kgCO_2e/kWh$ natural gas (Carbon Trust, 2013)).

These pressing issues of carbon emissions, as well as high utility costs allow for the implementation of alternative low carbon heating technologies. One possibility is a combined heat and power (CHP) system, which is a single process for dual output streams in the forms of heat and electricity. A CHP system has an overall efficiency up to 80% compared to gas and grid electricity separately which is less than 55% efficient. It is attractive due to its high overall energy efficiency when its exhaust heat and electricity can both be utilised. However, it should be noted that heating is usually not required for nearly five months every year, while the CHP has to be turned on with at least 50% of its rated power, hence the exhaust heat has to be dumped into a cooling tower therefore dropping the overall efficiency significantly. Furthermore, CHP still has to rely on the burning of gas. This is not in keeping with the university's plans to reduce its carbon footprint. A more attractive alternative is to employ a large heat pump system to heat the university campus by extracting low grade heat from the River Kelvin which flows nearby the university. Although the exploitation of this heat source would require electrical energy input to run the heat pump system, electricity can be sourced from renewables such as wind or hydro. Therefore this can potentially reduce the university's carbon footprint to zero hence puts the heat pump system at an advantage to alternative heating technologies which would always require the burning of fossil fuels. Two M.E.ng student projects (Poon-King, 2014; McConkey, 2014) have been carried out to study the feasibility of heating Glasgow University's campus with river sourced heat pump system. This paper presents the main findings from these two projects. It firstly investigates heat demand of the university campus, and then focuses on determining the amount of low grade heat contained within the River Kelvin that is available for use in a heat pump system. Finally a heat pump system will be designed to connect the heat demand and source.

2. HEAT DEMAND

An advanced numerical model of heat demand will help implement the most efficient heating system and overcome issues with the "peaky" nature of heat demand. In this paper, the heat demand will be assessed by modelling the campus using Integrated Environmental Solutions® (IES) building energy management software based on the measurement of the parameters of existing heating systems.

2.1 Data Collection

To better comprehend the actual behaviour of the campus buildings, measurements were taken from the existing heating systems. This was to ensure the expected results were correct and there was a correlation between the IES model and real campus. To gain initial parameters for the model a digital temperature probe was used to determine the interior temperatures of buildings. This gave a set point of 20 °C. The probe was also used to measure the domestic hot water temperature.

The university has a building energy management system (TREND) with the principal role of regulating and monitoring heating, ventilation and air conditioning (HVAC Control). This was used to measure flow and return temperatures from the boilers. The results gave a flow temperature range from 40 to 110 °C with the majority of buildings being supplied with 80 °C flow temperature. This temperature is designed around conventional gas boilers that are suited to running at higher flow temperature with a low temperature drop. This does not suit modern systems, as they are designed to better utilize lower temperatures. With the large quantity of poor performing conventional radiators present across the campus and low ambient temperatures it is justifiable to keep flow at 80 °C in winter. However during spring and autumn when ambient temperature is higher it is practical and more efficient to run flow temperatures at 70 °C. Along with TREND manual measurements were taken by data logging temperature probes. Manual temperature measurements were taken in buildings where TREND was not available and allowed logging across a 24 hour period. This prolonged logging gave an indication of the on and off times of boilers.

2.2 Integrated Environmental Solutions (IES) Simulation

Correctly sizing the buildings was essential, therefore as a base for the model a scale map of the Gilmorehill campus was used. The map was imported into the architecture suite of Google SketchUp 8 and set to scale. This allowed accurate floor plans of the buildings to be drawn onto the map. The next procedure was to add height to all the buildings. The University of Glasgow building surveying supplied heights of all the main tower blocks, with the smaller terrace buildings based on a manual measurement of their ground floor. Once all block buildings were modelled closer refinement was completed using pictures taken around the campus for reference.

Figure 1: Google SketchUp Model

To import the model into IES additional parameters were added, foremost being building fabric envelope. This is the composition of the windows, walls, floors and roof. To set the building use type in IES model, the whole campus was categorized into four different types: Office, Classroom, Lab and Gym/Union/Library. This allowed heating mode patterns such as 24 hour (20°C), Night Setback (20/14°C) and Frost Protect (20/5°C) to be added to the model. Heating type was subsequently added with the majority of the buildings using central heating radiators. IES will add internal gains to the buildings compensating for heat added by people and fluorescent lighting. Crucially it has a built in weather database which allowed a weather profile for Glasgow to be integrated, therefore adjusting to seasonal heating variances.

Simulation of the model produced comprehensive results of loads and energies required. University of Glasgow's Energy Conservation Office provided detailed gas consumption data of the campus; therefore the best comparison to validate the model was actual gas consumption versus simulated gas consumption as shown in Figure 2.

From this comparison, gas consumption of the actual campus was 55,566 MWh and the IES model's prediction was 46,015 MWh. The IES had a 17% lower gas consumption prediction; with the majority of the disparity being in the summer months. This was likely due to the IES following a more ideal consumption rate according to previous weather data. In addition the university may be overusing gas during the summer months. A system that combines space heating and domestic hot water cannot be shut off so circulation losses are inevitable as well as artificially high flow temperatures. This latter point will be explored in relation to heat pump efficiency in Section 4.The actual heating required by the campus was determined by the boilers load, which is the output load from the boilers including distribution loss throughout buildings. The boilers load was 37 GWh when distributed across 4000 hours is a capacity of 9.2 MW.

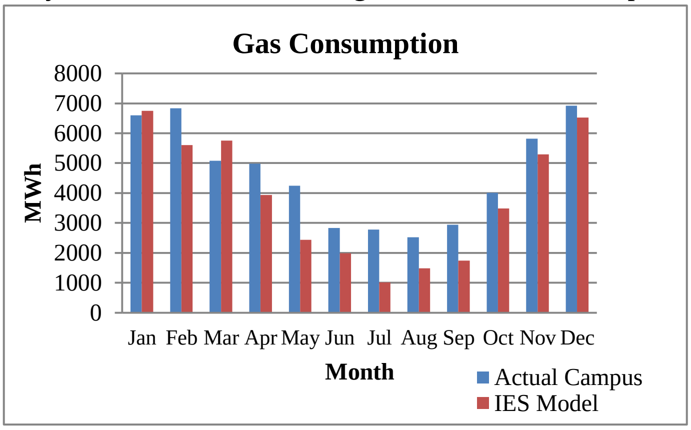

Figure 2: Actual Gas Consumption versus IES model

2.3 Building Selection

With the full campus modelled and appropriate building data collected, sources were combined to enable building selection for a district heating network. To warrant selection, buildings had to meet certain key criteria. Firstly their flow temperatures had to be in the operational range for a heat pump, approximately ≤80°C. They had to have sufficient heating demand to justify the cost incurred when laying pipe network. Geographical location on the map was significant as the heat pump will be located close to the River Kelvin on the Western Infirmary site. This means buildings in proximity to it should be supplied were possible. Finally building efficiency was considered with any abnormally inefficient buildings being omitted in favour of better performing ones. The selected buildings represent 34% of the heat demand for the campus, resulting in boiler loads of 12.6 GWh, which across 4000 hours is a capacity of 3.14 MW with a peak demand of 5.35 MW. This load includes 520 MWh for domestic hot water. Figure 3 shows the instantaneous boiler loads on a 3-D graph. The graph has the months on the X-axis, the system load on the Y-axis and the time on the Z-axis. As expected the graph shows that the peak loads are in the winter months with much lower requirements indicated by the blue section during summer. It should be noted that, the analysis of heat source and the design of heat pump system in the following sections will be based on the peak demand of 5.35 MW for the selected buildings.

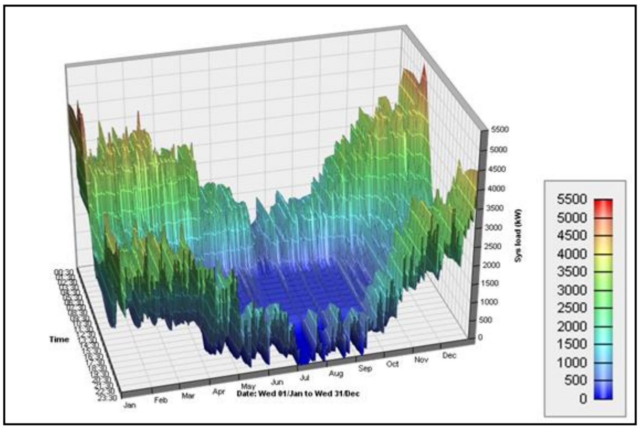

Figure 3: 3-D System Loads

3. HEAT SOURCE

The River Kelvin flows in close proximity to the University of Glasgow's main campus as seen in Figure 4. It was decided that the most suitable location for a large heat pump system would be located somewhere within the area highlighted X in Figure 4. This location was chosen because it is close to both the low grade heat source, and the university's main campus. This will help to reduce any transportation losses that may occur during distribution of the hot water. This location might also allow future "heat sales" to separate institutions, for example the Kelvingrove Museum. The chosen location is also positioned in the Western Infirmary site which is highlighted orange in Figure 4. The Western Infirmary is set to close in 2015. The university has already acquired this site and has plans to redevelop it and then incorporate it into the university's main campus. For these reasons it was assumed that there would also be land space available for the heat pump system. After the location for the heat pump was established, the data collection points were chosen. The main data sets that had to be collected for this project were the river temperature data and the river flow rate data.

3.1 River Temperature Data

The River temperature data had to be collected for two main reasons. Firstly, the river temperature determines the evaporating temperature of the refrigerant in the heat pump system. This in turn affects the Coefficient of Performance (COP) of the heat pump system which is the ratio of heating supplied to the electrical energy consumed. Lower river temperatures generally leads to a lower COP. The second reason for river temperature data collection was to ensure that the river had a suitable water temperature range for operation of a heat pump system. If the river temperature is too low (typically ≤3 °C) there is a risk of freezing in the evaporator section of the heat pump which can damage the system. For these reasons it is important to measure the temperature range of the River Kelvin. The river temperature data were collected using the VWR EC300 Conductivity and Temperature Meter as well as the TG-3100 Tinytag Aquatic 2 Internal Temperature logger.

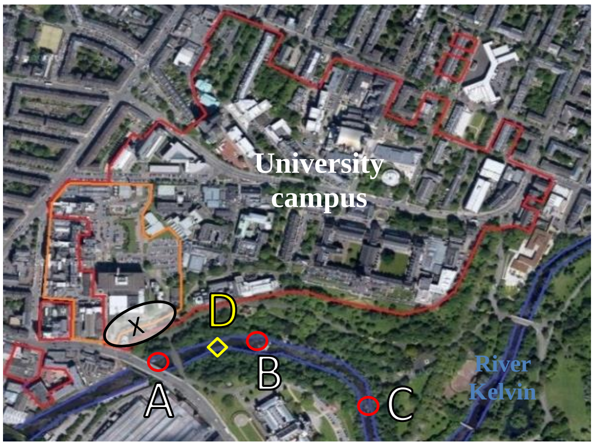

Figure 4: Temperature data collection points

The VWR EC300 Conductivity and Temperature Meter were used at locations A, B and C as seen on Figure 4. River temperature readings were taken two times a day at each location from 01/10/2013 to 17/10/2013. The specifications of the VWR EC300 Conductivity and Temperature Meter are described below (YSI Environmental Inc., 2003). This meter has a reading resolution of 0.1 °C and an accuracy of ±0.2 °C. This degree of accuracy was ample for this study.

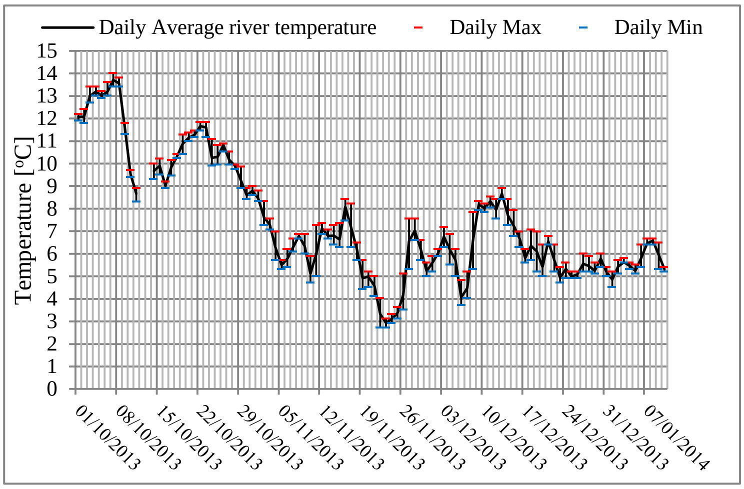

Figure 5: Graph showing river temperature data

TG-3100 Tinytag Aquatic 2 Internal Temperature logger was positioned in the River Kelvin at point D as seen in Figure 4. This logger recorded temperature every hour from the 17/10/2013 the 10/01/2014. The TG-3100 Tinytag Aquatic 2 Internal Temperature logger has an accuracy of ±0.2 °C (Tinytag Aquatic, 2003).

The data collected for the duration of the project was collated and is displayed in Figure 5. It can be seen from this data that the River Kelvin had a temperature range of 2.8 to 14 °C for the recording period 01/10/2013 to the 10/01/2014. It should be noted that there are no technical difficulties collecting the river water temperature data over the whole year. The only reason for presenting data during this period of time in winter is due to the time constraint of these two final year projects. The probe is still currently installed in the river, and more data can be obtained and presented in the future.

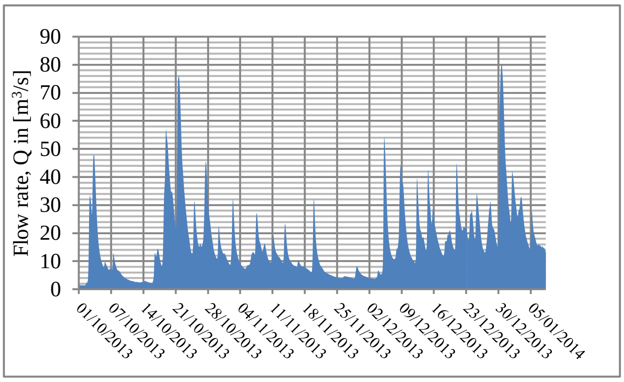

Figure 6: Graph showing flow rate during period of 01/10/2013 to 09/01/2014

3.2 Flow Rate Data

Flow rate data for the River Kelvin was collected by the Scottish Environment Protection Agency (SEPA). SEPA has a river flow gauging station positioned in the River Kelvin located at Killermont. Figure 6 displays the flow rate data of the River Kelvin that was collected during the 1st October 2013 to the 9th January 2014. It can be seen on this figure that the river flow rate fluctuated a lot over this period. It varied in the range from 1.4 to 80.49m^3/s. This data suggests that flow rates can fluctuate between high and low values very quickly over short periods of time.

In order to get a more reliable prediction for flow rate of the River Kelvin, a flow duration curve was constructed using flow data from the past. The Killermont gauging station has been collecting river flow data since 1948. Flow rate data for the period of 1st of October to the 30th of April each year, for the years 1948 to 2012 was used to construct a flow duration curve as seen in Figure 7. The period of 1st of October to the 30st of April was chosen since this would be the main operation period for the heat pump system (during the winter months). SEPA uses this curve to help determine safe amounts of water that can extracted from the river. For example, the flow rate is predicted to be higher than 10 m^3/s in 38% days during this period. This is a predictive model and therefore would have some degree of error. Longer recording periods generally improve the reliability of the curve. The long recording period of 1948 to 2012 makes this model fairly robust.

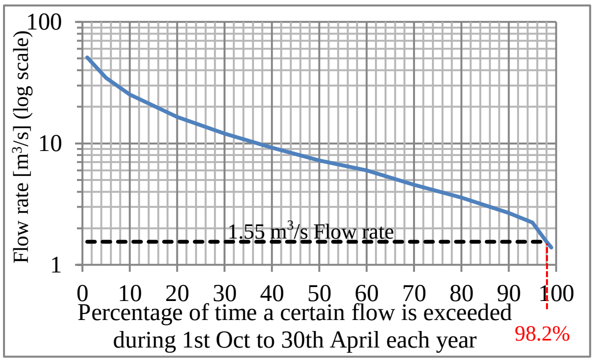

Figure 7: Graph showing flow duration curve for the period 1st October to 30th April each year

4. HEAT PUMP SYSTEM

It was estimated that a heat pump system of 7.43 MW heating capacity would be able to meet the peak 5.35 MW of heating demanded by the targeted campus buildings mentioned in section 2.3. The excess heating capacity could be used to supply either other sections of the campus, or possibly for “heat sales” to external customers. To link the heat source from the river and heat demand of the campus, a heat pump system was designed using the VSC (Vilter/Star Refrigeration/ Cool Partners) software tool. An ammonia heat pump system had been modelled and the operation parameters were calculated. The heat pump system would comprise of two heat pump units (UNIT 1 and UNIT 2 as shown in Figure 8) working together to meet the 7.43 MW of heating demanded by the campus. These two heat pump units have the same configuration. For each unit, the evaporator extracts heat from river water. Ammonia evaporates into vapour and is then compressed by the low pressure compressor which is cooled by the returning water from the heating network. The vapour is then further compressed in the high pressure compressor which is also cooled by the returning water. The vapour is then condensed in three condensers in series where the heat is transferred to the returning water. The liquid ammonia expands in the expansion device, and then cools in the flash intercooler, and finally flows back to the evaporator for the next cycle.

Figures 9 and 10 show the pressure-enthalpy diagrams for the operation of UNIT 1 and UNIT 2 respectively. The state points have been labelled in Figures 8-10. The two Units would have slightly different operation pressures. The VSC software simulations determined this to be the most effective design for the system. The unique feature of this design is that the waste heat from the compressors and the oil coolers can be recovered so the overall COP had been further improved. Tables 1 and 2 also summarise the operating parameters of the different components shown in Figure 8.

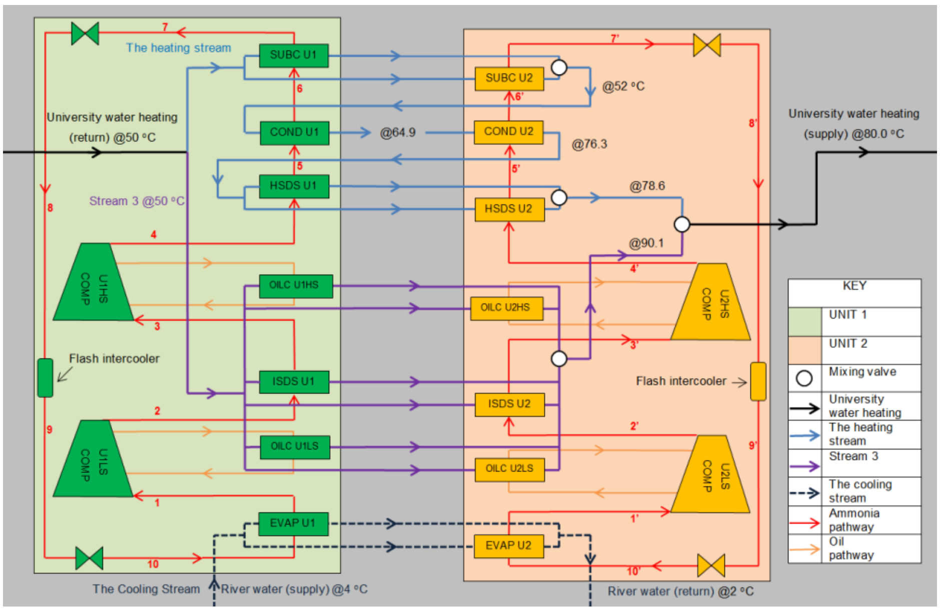

Figure 8: Schematic diagram of the heat pump system

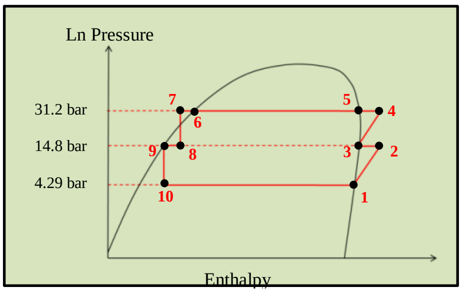

Figure 9: P-h diagram of UNIT 1

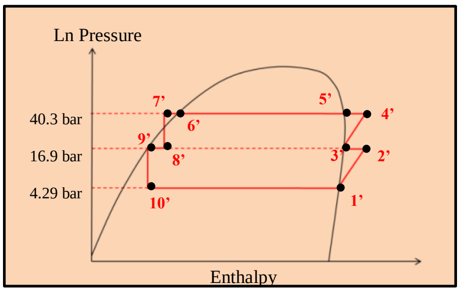

Figure 10: P-h diagram of UNIT 2

Table 1: Components from both units and their respectable heat outputs

	Stream	Symbol	Component	Water temperatures		Water mass flow rate $[kgs^{-1}]$	Heaing capacity [kW]
				In [°C]	Out [°C]		
Water Heating	Heating Stream	SUBC U1	Subcooler, UNIT 1	50.0	52.0	20.12	-164.4
		SUBC U2	Subcooler, UNIT 2	50.0	52.0	31.56	-257.9
		COND U1	Condenser, UNIT 1	52.0	64.9	51.69	-2790.0
		COND U2	Condenser, UNIT 2	64.9	76.3	51.69	-2466.2
		HSDS U1	Highstage desuperheater, UNIT 1	76.3	78.6	21.10	-208.0
		HSDS U2	Highstage desuperheater, UNIT 2	76.3	78.6	30.59	-301.5
	Stream 3	OILC U1HS	Oil cooler, UNIT 1 High stage compressor	50.0	90.1	0.94	-158.1
		OILC U2HS	Oil cooler, UNIT 2 High stage compressor	50.0	90.1	1.93	-328.4
		ISDS U1	Interstage desuperheater, UNIT 1	50.0	90.0	1.65	-276.0
		ISDS U2	Interstage desuperheater, UNIT 2	50.0	90.0	1.85	-312.0
		OILC U1LS	Oil cooler, UNIT 1 low stage compressor	50.0	90.1	0.34	-57.7
		OILC U2LS	Oil cooler, UNIT 2 low stage compressor	50.0	90.0	0.65	-110.6
						Total heating capacity	**-7430.8**
Cooling	Cooling stream	EVAP U1	Evaporator, UNIT 1	4.0	2.0	309.97	2607.7
		EVAP U2	Evaporator, UNIT 2	4.0	2.0	311.03	2583.0
						Total heat extraction from river water	**5190.7**

Table 2: Work input required by compressors

	Symbol	Component	Electrical power input, W_{in} [kW]
Work input	U1LS COMP	Low stage Compressor, Unit 1	585.3
	U1HS COMP	High stage Compressor, Unit 1	521.9
	U2LS COMP	Low stage Compressor, Unit 2	651.8
	U2HS COMP	High stage Compressor, Unit 2	664.7
		Total	**2423.7**

As shown in Table 1, the total amount of heat that the system would be able to supply is the total capacity of the water heating, which amounts to 7.43 MW of heat (Q_{out}). This heat would be supplied to the university campus at a temperature of 80 °C. The total heat required from the River Kelvin is 5.19 MW (Q_{in}) which will be extracted at a river temperature ≥4 °C. It would extract this heat via the total input of 2.423 MW of electrical energy (W_{in}) as shown in Table 2. It is important to note that the 80 °C would be the maximum supply temperature ever required by the university. The 4 °C river water temperature would be the minimum river water temperature that the heat pump would ever have to operate at. These would be the most demanding operating conditions of the heat pump system and would therefore require the largest work input (W_{in}). Therefore the system would have the lowest COP during these operation conditions since the work input affects the COP of the system.

$$COP = Q_{out}/W_{in} = 7.43/2.423 = 3.08 \tag{1}$$

It is important to determine the amount of water that is available for use in the River Kelvin. The proposed system needs to extract Q_{in} =5.19 MW of heat from the River Kelvin. The system would only be allowed to cause ΔT = 2 K temperature drop in river water. Equation (2) is used to determine the required mass flow rate of water being supplied to the heat pump system. The specific heat of water, $C_p = 4200\ [Jkg^{-1}K^{-1}]$ and the density of water, $\rho = 1000\ [kg/m^3]$.

$$\dot{m} = \frac{Q_{in}}{\rho C_p(\Delta T)} = \frac{5.19\times10^6}{1000\times4200\times2} = 0.618\ [m^3s^{-1}] \quad (2)$$

SEPA imposes an abstraction flow rate for periods of low river flow. During low flow, only 40% of the river water can be abstracted and used in the heat pump system. The minimum river flow rate $\dot{m}_{total}$ needed in order to achieve the 0.619 m^3s^{-1} mass flow rate $\dot{m}$ for this system is calculated using Equation 3.

$$\dot{m}_{total} = \dot{m}\ /0.40 = 0.618/0.40 = 1.55[m^3s^{-1}] \quad (3)$$

Figure 7 shows that a river flow rate of 1.55 m^3s^{-1} is predicted to occur for ~98% of the flow period of the 1st October to the 30th April each year. It is important to note that the 1.55 m^3s^{-1} mass flow rate will most likely be the maximum mass flow rate required by the heat pump system at any given time during operation. The mass flow rate of the River Kelvin is usually much larger than this for the rest of the flow period.

5. COMPARISON WITH OTHER HEATING TECHNOLOGIES

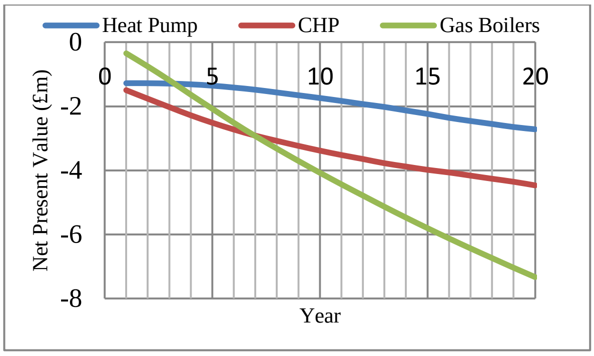

Figure 11: 20 Year NPV

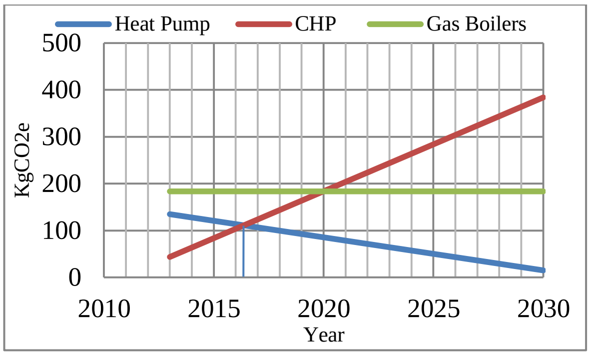

Figure 12: Carbon Footprint 2013-2030 (1MWh)

The Renewable Heat Incentive (RHI) is a scheme that has been introduced by the UK government to help reduce greenhouse gas emissions and meet targets for reducing the effects of climate change (Department of Energy & Climate Change, 2014). In order to be eligible for the Renewable Heat Incentive tariff, the heat pump system has to have a COP of ≥2.9. The designed heat pump has a COP about 3.08 and therefore is eligible for RHI scheme. RHI is included in the financial analysis in this Section. In order to further investigate the feasibility the application of this heat pump system, three different heating systems were compared based on their net present value (NPV). The three technologies being compared are heat pump, combined heat and power (CHP) and gas boilers.The heat pump and CHP will require backup boilers in periods of very high heat demand, boilers are already in place on campus and maintenance for them has been accounted for. NPV is the present value of net cash inflows generated by a project, less the initial investment on the project (Net Present Value (NPV), 2012). Present value is a future amount of money that has been discounted to reflect its current value, as if it existed today (Henderson, 2007). NPV is a reliable method of capital budgeting because it accounts for the time value of money by using discounted cash flows (Net Present Value (NPV), 2012). Obviously the heat pump is the most cost effective, representing a saving of £1.75M compared to combined heat and power and a saving of £4.6M compared to gas boiler. Furthermore Figure 11 shows that the payback period for a heat pump is about 3 years and the CHP payback is 7 years. Like any technique that offers operational expenditure savings, utilisation is important to a lower NPV. There is a significant danger in deploying CHP as the primary source of heat, as it is evident from Figures 2 and 3 that CHP or heat pumps are perhaps not required 5 months of the year. It is certainly wrong to define base load (the permanent minimum load that a power supply system is required to deliver) as summer usage when a more flexible solution would excel. The heat pump system at Drammen (Star Refrigeration, 2010) in Norway runs from 2MW to14MW with gas only used above 14MW in the coldest winter periods, which proves the technology's capabilities. The heat pump does not produce carbon directly; the carbon emissions are based on the initial grid electricity value of 0.445 $KgCO_2/kWh$ (Department of Energy and Climate

Change, 2013). The gas burning technologies will be producing 0.184 $KgCO_2$/kWh; this will remain constant as the same units of gas will be required for heating throughout. Conversely the carbon intensity of electricity will decrease as the grid "cleans", through increasing use of renewable energy sources. Scotland has set a target to cut carbon emissions from electricity generation by more than four-fifths by 2030. This target will be 0.05$kgCO_2$/kWh, in line with independent advice from the UK Committee on Climate Change (Offshore Wind Industry Group (OWIG), 2013). This target will be used as the basis for long term carbon footprint, with a linear decrease year on year. Assuming that the government is able to meet this target, the carbon crossover for the heat pump would occur early 2016 and by 2030 would have the smallest carbon footprint. Conversely the CHP will initially have low carbon emissions due to the electricity offset produced, however emissions increase as the grid "cleans" because the CHP is still committed to carbon intensive fossil fuel burning.

6. CONCLUSION

The studies of this paper suggest that the River Kelvin contains substantial heat that can be sourced by a large heat pump system to heat the selected buildings of Glasgow University's main campus. The analysis from this paper suggests that a 7.43 MW heating capacity heat pump system would be able to operate for the vast majority of the operation period (October to April). In the event that the heat pump system cannot perform due to low river temperatures or very high water heating demands of the Campus, other stand-by systems such as fast acting boilers can be utilised to quickly meet the heating deficit created. The heat pump could be "supplier of first choice". Further river temperature data has to be collected during the months of February, March and April, as well as other years in order to fully validate the viability of this heat pump system. The introduction of a heat pump would potentially save the university £4.6M over 20 years with a payback of 3 years. Furthermore it will have the lowest carbon emissions by 2016 and emissions will continue to fall with the potential to provide carbon free heating.

7. ACKNOWLEDGEMENTS

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