**Combining cooling of underground railways with heat recovery and reuse**

Abstract

The paper concerns the recovery and use of secondary/waste heat and identifies secondary heat sources in London of 71TWh i.e. c10% more than demand. London Underground (LU) railway tunnels generate significant quantities of low grade heat. There is also a requirement for active cooling to reverse the long term trend of rising tunnel temperatures. A novel combined cooling and heat recovery scheme for LU tunnels, utilising existing ventilation shafts, was proposed. Recovered heat was upgraded using a heat pump, for reuse in a local district heating network (DHN). A new model was developed to investigate the thermodynamic performance, economic feasibility and potential carbon savings available. It was concluded that the system could simultaneously provide 900 kW of cooling to the tunnel, and after upgrading to 70°C, approximately 1.1 MW of heat, which could be used as a source for a DHN. The model predicted that this could be carried out economically and could deliver massive carbon and cost savings. With 200 ventilation shafts in London, >360,000 tonnes of carbon could be saved annually, while generating revenues of £40,000,000. Applying this technology to 50% of 150 metro systems worldwide would enable more than 27 million tonnes of carbon savings.

Key words

Cooling; waste heat recovery; heat pump; heat reuse; district heating; energy, cost and carbon savings

**1. Introduction**

1.1 Background

Climate change is one of the greatest challenges faced by mankind over recent years and is generally attributed to human actions on the environment, such as burning fossil fuels, intensive farming and deforestation, all of which increase the emission of greenhouse gases (GHGs) into the atmosphere (WWF, 2018). The United Kingdom is the 5th largest national economy in the world (World Bank, 2017), but only the 17th largest global carbon emitter (in 2016), with carbon dioxide equivalent (CO2e) emissions of 389 Mt (Global Carbon Project, 2017). In the UK there has been significant focus on sustainable development, in order to cut carbon emissions and stimulate the use of renewable energy sources, and continued adoption of sustainable development measures should make a progressive contribution towards meeting the UK Climate Change Act (2008) target of reducing carbon emissions by 80% of its 1990 baseline level by 2050. The Climate Change Act (2008) was established to meet the UK’s obligations under the Kyoto Protocol (1998). Carbon reduction measures adopted to date include: phasing out of coal fired power stations; increased use of renewable energy resources; improvements in the efficiency of vehicles, electrical and electronic equipment; and new building performance requirements. A recent Committee on Climate Change, (2018) report suggests that the UK is on track to achieve the interim 2020 carbon reduction target. However, achieving the UK’s 2050 carbon emissions target is likely to be more difficult and will require significantly more radical solutions than the measures and technologies considered to date.

Urban environments represent the main source of carbon emissions but also have the potential to host a paradigm shift in the way energy is utilized. Cities consume about 70% of the world’s resources and are major consumers of energy and signiﬁcant contributors to GHG emissions. This is due to the urban population density, the intensity of related economic and social activities, and also to the inefﬁciency of the built environment (Bibri and Krogstie, 2017). In the UK, 83% of the population live in urban areas (UK Government, 2016) and the United Nations has estimated that by 2050, 66% of the global population will live in cities. Therefore, cities should adapt governance instruments to support low carbon energy transition and stimulate urban transformation to achieve sustainable and resilient cities (Carter et al., 2015). There have been many reviews of the characteristics of smart sustainable cities and the measures that need to be implemented for their successful deployment (e.g. Bibri and Krogstie, 2017, Bonafoni et al, 2017, Addanki and Venkataraman, 2017). An overarching conclusion reached from these studies is that in order to improve and maintain sustainability, future energy systems and technologies will need to be smart, integrated, reliable and resource efficient.

A key contributor to the UK’s carbon emissions, particularly in cities, is the supply of heating and cooling. Approximately one third of carbon emissions in the UK arise from heating and cooling, with these services accounting for the discharge of 182 Mt of CO2 equivalent into the atmosphere in 2014 (Gebrail, 2014). Space heating and hot water for buildings alone make up 20% of GHG emissions and 40% of energy consumption in the UK (Committee on Climate Change, 2016). Although heating and cooling have a considerable influence on how energy is consumed, only a small proportion of their supply comes from renewable energy sources at present. When compared to other European Union countries, the UK has the lowest share of renewable sources providing heating and refrigeration, representing only 5.5% of the energy used (EEA, 2017).

In order to meet its future emissions targets, the UK government has put forward a strategy for mitigating future carbon emissions from heating and cooling, as described in, for example, the 2050 Pathways Analysis (DECC, 2010) and The Future of Heating: Meeting the Challenge (DECC, 2013). Key areas for reducing carbon emissions are summarized in Table 1 below.

Table 1 – Key areas for reducing UK carbon emissions

|  |  |
| --- | --- |
| Key areas for reducing carbon emissions | Details/technologies |
| Decarbonisation of energy supply grids | Reduce carbon emissions associated with both electricity and gas use, including switching to biogas and hydrogen |
| Managing heating and cooling demand for buildings | Reduce building heat losses e.g. wall and loft insulation, triple glazing; reduce internal temperatures in buildings; use of smart meters; improved controls; reduce hot water demand |
| Transforming building heating and cooling systems | High efficiency condensing gas boilers; micro CHP; air source and ground source heat pumps; solar PV and solar thermal; bioenergy; use of heat storage |
| Developing heating and cooling networks in the UK | Low carbon heating and cooling networks, especially in cities; for heating networks, heat sources to include CHP, renewable energy; bioenergy; recovered waste heat; deep geothermal; large heat pumps. For cooling networks, cold sources include CCHP and cold water drawn from a central location |
| Transforming industrial heat | Reduce energy intensity of manufacturing; change energy sources to low carbon types or renewables; adopt innovative technologies, chemistries and materials and/or use carbon capture and storage. |

Since 83% of the population of the UK live in urban areas, it is clear that UK cities have a considerable impact on the carbon footprint of the United Kingdom. Therefore London, as a global and capital city, with an estimated population of 8.83 million (13.4% of UK’s population) (ONS, 2017), can provide an important vanguard role in confronting climate change, setting an example not only for the UK, but also for other cities worldwide. In fact, London has already started promoting the use of renewable energy sources, for example, the London Plan (2004) focuses on securing a low carbon energy supply for London and sets a target of achieving 25% of London’s heat energy supply from decentralized or district energy schemes, by 2025. A particular advantage of district heating networks (DHNs) is that they also facilitate the capture and reuse of waste heat. There are many opportunities for recovering and reusing heat in cities and a range of these will be discussed in the next section, highlighting how waste heat sources can be connected to DHNs in order to meet the heating requirements of a world with ever-growing cities and populations. In section 1.2, a range of potential sources of heat in cities are discussed, and in section 1.3, the need for cooling London’s underground railways together with the large quantities of waste heat generated, are highlighted. The remainder of the paper then provides details of a study carried out to investigate cooling combined with heat recovery and from underground railways, and how the performance of this system compares with conventional heating and cooling.

1.2 Potential sources of waste heat in cities

Characteristics that may be used to evaluate these waste heat sources include the quantity of waste heat available for the particular source, its temperature, and whether it is constant or varying. Table 2 provides brief details of these characteristics for a range of heat sources.

Table 2 - Potential sources of waste heat in London

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Specific  Application | Individual Heat Source MW | Total Heat  Output of Sector MW | Seasonal | Waste Heat  Temp-erature  °C | Waste Heat  Characteristics | References |
| Underground railway infrastructure | 0.6 | 15 | More heat generated in  summer | 25-30 | Low air temperatures;  moderate quantity of heat;  large number of sources | Ninikas et al (2016)  Chai et al (2017)  Liu et al (2018) |
| UKPN  Substation infrastructure | 1.63 | N/A | High heat output all year round | N/A | Moderate temperatures;  moderate quantity of heat;  small number of sources | Zhao et al (1995)  Shrestha (2013) |
| National Grid  electrical  infrastructure | 6.8 | 40 | High heat output all year round | 55 | Moderate temperatures;  moderate quantity of heat;  small number of sources | National Grid (2018) |
| Office buildings | N/A | 308 | More heat generated in  summer | 28 | Low air temperatures;  large quantity of heat;  large number of sources |  |
| Retail buildings | N/A | 616 | More heat generated in  summer | 28 | Low air temperatures;  large quantity of heat;  large number of sources |  |
| Supermarkets (commercial refrigeration) | 0.5-1.0 | 32 | High heat output all year round | 32 | Low air temperatures;  moderate quantity of heat;  large number of sources | Ge and Tassou (2014) |
| Data centers (commercial refrigeration) | 3.5 | 86 | High heat output all year round | 25-35 | Low air temperatures;  moderate quantity of heat;  large number of sources | Ebrahimi et al (2014) |
| Food  manufacture  and chemical processing (industrial heat) | N/A | 11.4 | High heat output all year round | 35-70 | Low-moderate air  temperatures;  moderate quantity of heat;  small number of sources | Mukherjee et al  (2017) |
| Power  stations (electricity generation) | N/A | 945 | High heat output all year round | > 35 | Moderate temperatures;  large quantity of heat;  small number of sources | Safa (2012) |
| CHP (electricity generation) | 0.7 | 10.3 | More heat  generated in  winter | 45 | Moderate temperatures;  moderate quantity of heat;  small number of sources | Kang et al (2015) |

N/A = Not available; temps = temperatures; \* = heat output identified to date

With a wide variety of heat sources available in the urban environment, as seen in Table 2, some cities have decided to invest in waste heat recovery from their own infrastructure as a means to provide greener and cheaper heating for their populations. The Heat Roadmap Europe (HRE) (David et al, 2017), which analysed the use of large-scale heat pumps in district heating systems, predicted substantial future growth in DHNs, such as to supply 50% of Europe’s entire heat demand by 2050, with approximately 25-30% of the heat delivered being supplied using heat pumps. The HRE also analysed various current DHNs that rely on heat pumps across Europe. Results showed that these DHNs use a range of different types of heat sources, including waste heat recovery from sewage and waste heat from industrial plants. DHNs allow the waste heat energy, which would otherwise be lost, to be distributed to local heat users. Since not all of the heat is at the required temperature level, heat pumps are used to upgrade it accordingly.

The HRE research also showed that sewage systems are widely used in Europe as a heat source, and have the advantage of providing a stable long-term resource. Heat pump systems using sewage heat recovery have been installed in some cities, including those with very large heating capacity requirements, for example in Stockholm (230 MW), Gothenburg (160 MW), Helsinki (90 MW) and Oslo (40 MW). In Finland, another waste heat recovery scheme has been taking heat exhausted from data centres, and after upgrading, it is distributed to heat homes in the city of Mäntsälä. A single data centre, operating at a capacity of 10 MW, is estimated to supply 3.6 MW of recovered waste heat to the local DHN. TelecityGroup also operates 5 data centres in Finland, producing district heating for a total of 4500 block apartments and 500 detached houses every year (Wahlroos et al, 2018).

In London, local authorities are keen to foster waste heat recovery initiatives. The London Mayor’s office has produced a number of reports investigating the potential for using secondary waste heat in London. It has been estimated that the total waste heat that could be delivered from secondary sources in London is of the order of 71 TWh/year (Mayor of London, 2013). This is greater than the city’s total heat demand which was estimated to be 66 TWh/year in 2010. However, some of the heat sources that were identified are only available at a particular period of the year, or they are located too far away from where the heat is needed to be useful. One of the waste heat sources listed in Table 2 above is underground railways. As indicated in the table, underground railways produce more heat in summer, however, they do generate significant quantities of heat throughout the year. They also have the advantages of being well distributed across London, with many stations and ventilation shafts across the city providing access to the underground heat. In addition to providing a potential heat source which could be recovered and reused, underground railways also have a requirement for increased cooling.

1.3 Waste heat and cooling of London Underground (LU)

Underground railways generate significant quantities of waste heat. It has been estimated that up to 15 MW of heat could potentially be recovered from London’s underground network and reused (Davies et al, 2017). This heat is mainly generated by the braking systems of trains, although with significant contributions from aerodynamic friction and the electric motors driving the trains. Some of the heat is also generated by the passengers. The main method used at present to dissipate this heat, and maintain tunnel temperatures within a safe range, is the use of ventilation shafts, which are located at intervals of e.g. 1 to 2 kilometres, along the tunnels. The ventilation shafts, which incorporate fans, may be operated in either forced ventilation (or supply) mode, whereby ambient air is supplied to the tunnels, or in draught relief (or exhaust) mode, whereby the heated air is exhausted from the tunnels. The movement of air through the tunnels is enhanced by the piston effect of the trains. The local tunnel air distribution requirements dictate whether a particular ventilation shaft is operated in supply or exhaust mode.

Traditionally, these methods have been sufficient to control the tunnel air temperatures, however, there is a long-term trend for these temperatures to rise. Consequently, LU is investigating a number of active cooling methods aimed at halting or reversing the long-term trend. These include the introduction of chilled air at stations e.g. using platform air handling units (PAHUs) (Dragoni et al, 2016), and the supply of chilled air through ventilation shafts, which is discussed below.

A scheme to recover waste heat from London Underground is currently being developed in the London Borough of Islington. The project is an extension of the existing Bunhill Heat Network, which uses a gas fired CHP in order to provide heating to over 850 local households via district heating. The extension, also referred to as Bunhill II, will capture heat from a ventilation shaft, which will then be upgraded by a heat pump and delivered to around 500 households (Islington Council, 2018).

As a large-scale trial, there is no evidence at present supporting the performance of the Bunhill II scheme, and thus further research and analysis on this type of waste heat recovery system needs to be conducted in order to fully estimate its benefits, challenges and expected outcomes. With that in mind, a project has been undertaken to evaluate the feasibility of combining both cooling and heat recovery from underground railways. The Metropolitan Integrated Cooling and Heating (MICAH) project, has involved investigating the potential benefits and barriers involved in implementing a system for combining cooling of a LU site with waste heat recovery. The recovered heat would then be distributed through a DHN. This paper provides details of the MICAH study, including a detailed description of the MICAH system and the model developed to evaluate its performance. The results from the model are also presented and discussed, and conclusions drawn regarding the next steps for the MICAH system.

**2.0 The MICAH study**

2.1 Description of MICAH system

For MICAH, it is proposed to install a combined cooling and waste heat recovery system at a ventilation shaft site on the Piccadilly line. This involves the use of a fan coil heat exchanger located close to the head of the shaft, incorporating a reversible fan, enabling its use in both supply and exhaust modes. In each case, heat is extracted from the air passing over a cold water, heat exchanger coil, whereby the heat is transferred to the water, raising its temperature. The design capacity for the heat exchanger, whether operating in supply or exhaust mode, is 900 kW, providing a total annual heat supply of 7.88 GWh.

The tunnel air temperature typically varies between 16 and 27°C during the year, while the ambient air passing over the heat exchanger coil when in supply mode, varies between 3 and 23°C during the year. Since the fan is reversible, the heat exchanger can be operated in either supply or exhaust mode, as required. The effects of operating the system in the different modes for different periods of the year will be presented later.

The next stage of the heat recovery process involves the heated water which exits the heat exchanger being transported through a pipe work system to a heat pump, where its temperature is upgraded to the level required for reuse e.g. of the order of 70°C for a low temperature heat network.

The recovered, upgraded heat will be delivered to the DHN through an energy centre acting as a hub for the network. The energy centre will be located at a site adjacent to a public swimming pool in the London Borough of Islington. The energy centre will also house a gas fired combined heat and power (CHP) system, with sufficient capacity to supply the whole DHN, as a back-up for the waste heat recovery system. The planned DHN is expected to have a total heat requirement of the order of 9.06 GWh (Ramboll, 2016) so the CHP system will generally be used to top up the 7.88 GWh of heat supplied by the waste heat recovery system in order to meet the DHN demand.

The direct distance between the LU site and the DHN energy centre is approximately 350 m, however, the pipe work needs to be routed through the roads, so the actual distance for transporting the heated water will be of the order of 420 m. Figure 1 provides an aerial view of the proposed DHN.



**Figure 1 Aerial view showing location of DHN**

Figure 1 shows the area to be supplied with heat by the proposed DHN, which will chiefly consist of a swimming pool and two nearby social housing estates, all owned and operated by Islington Borough Council (IBC). The gas fired CHP will be located at the DHN energy centre (i.e. swimming pool) site and provide both electricity and heat. Some of the electricity generated will be used to power the heat pump, while the heat will be used to balance the total quantity of heat supplied to the DHN. A schematic showing the overall MICAH system is shown in Figure 2.



**Figure 2 Schematic of MICAH system**

It can be seen in Figure 2, that the heat exchanger continually extracts heat from air (whether the ventilation shaft is operating in exhaust or supply mode) and transfers the heat to water. The water is then recirculated in a loop transporting the heat from the fan coil, heat recovery heat exchanger to the heat pump’s evaporator heat exchanger, where the heat is absorbed. The heat pump then upgrades the heat to the required temperature, before delivering it to the DHN. The efficiency of the heat pump is represented by its coefficient of performance (CoP), which varies with the temperature of the water transported to the heat pump evaporator heat exchanger, and this in turn depends on the air on temperature for the (fan coil) heat recovery heat exchanger (HRHX). In general, the water transported to the heat pump evaporator is at a lower temperature when the system is operating in supply mode i.e. when heat is recovered from ambient air, than when the system is operated in exhaust mode, with heat recovered from the exhausted (i.e. heated) tunnel air. Consequently, heat pump CoPs are generally lower when operating the system in supply.

Since the ventilation shaft fan is reversible, it can be operated in either supply or exhaust, in response to operational requirements. In exhaust mode, no cooling is provided, although heat is still recovered from the tunnel air.

The heat pump used to upgrade the recovered heat may be located at either the energy centre i.e. at the swimming pool site (layout option 1), or at the LU heat recovery site (layout option 2). The two design layout options are shown in Figure 3 below.



(a) Layout option 1

Figure 3b - Layout - option2.tif

(b) Layout option 2

**Figure 3 Design layout options for MICAH system**

Both layout options have been evaluated using a model, described below.

2.2 Description of MICAH model

A Microsoft Excel spreadsheet model has been developed which simulates the heat transfer processes comprising the MICAH system, and links the key input parameters to the performance output parameters. A schematic of the model is shown in Figure 4.



**Figure 4 Schematic of MICAH model**

It is seen in Figure 4 that the key processes simulated by the model are: (1) the recovery of heat from the air passing over the fan coil HRHX; (2) a primary water loop which pumps the heated water exiting the HRHX and transports it to the heat pump evaporator; (3) upgrading the temperature of the recovered heat using a heat pump; (4) a secondary water loop for transferring the upgraded heat to the DHN. The process is effectively the same for both design layouts 1 and 2. Key design parameters for the MICAH model, for each of the four processes comprising the model are shown in Table 3.

**Table 3 Key design parameters**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **System part** | **Parameter** | **Total heat demand (MWh)** | **Hot water Base demand (MWh)** | **Base heating rate (MWh)** | **Source of data** |
| Heat loads | Social housing estate 1 | 4653 | 2860 | 0.326 | Unpublished local government report |
| Social housing estate 2 | 2403 | 1548 | 0.176 | Unpublished local government report |
| Swimming pool | 1405 | 987 | 0.113 | Unpublished local government report |
| Misc. - library, school, offices | 4453 | 2438 | 0.278 | Unpublished local government report |
| Total | 12914 | 7833 | 0.893 |  |
| Vent-ilation shaft | Airflow rate | 75 m³ s-1 | | | Design specification (TfL) |
| Fan power | 15.63 kW | | | Design specification |
| Vent shaft temperature | Range 16° C to 27° C | | | Experimental measurements |
| Ambient air temperature | Monthly range from 3 to 23° C. | | | UK Met Office data (for London) |
| Heat recovery  for air-liquid heat exchanger (HRHX) | Type of heat exchanger | Counterflow | | | Manufacturer design specification  (HC Coils) |
| Heat exchanger construction | Aluminium fins & copper tubes | | |
| Capacity | 900 kW (i.e. 4 x 225 kW) | | |
| UA value | 125.5 kW/K (i.e. 4 x 31.375 kW/K) | | |
| Air side ΔP | 49 Pa | | |
| Air-side ∆T | 10K | | | Design data |
| Liquid | 30% propylene glycol /water mix | | |
| Liquid-side ∆T | 5K | | |
| HRHX approach temperature | 0.1K | | |
| Pipe work for primary water loop | Pipe diameter | 10 inch (273 mm OD, 254 mm ID) | | | Design specification |
| Liquid | 30% propylene glycol /water mix | | | Design specification |
| Liquid volumetric flow rate | 0.043 m3 s-1 | | | Design specification |
| Pipe work length (option 1) | 840 m | | | Design specification |
| ΔP through pipes | 43 kPa | | | Calculated |
| ΔP across HRHX | 55 kPa | | | Design specification (HC Coils) |
| ΔP across HP evaporator HX | 55 kPa | | | Design specification (assumed) |
| ΔP - fittings, bends, valves | 280 kPa | | | Design specification (calculated) |
| Total ΔP (option 1) | 433 kPa | | | Calculated |
| Pump efficiency | 0.5 | | | Design specification (assumed) |
| Pumping power (option 1) | 37.3 kW | | | Calculated |
| Pipe work length (option 2) | 30 m | | | Design specification |
| Pumping power 1 (option 2) | 34.0 kW | | | Calculated |
| Pipe work for secondary water loop | Pipe work length (option 1) | N/A | | | Assumed incorporated into DHN |
| Pumping power (option 1) | N/A | | | Assumed no pumping needed |
| Pipe diameter | 6 inch (168.3 mm OD, 154 mm ID) | | | Design specification |
| Secondary loop liquid | Water | | | Design specification |
| Temperatures | 70°C/40°C | | | Flow / return temperatures for DHN |
| Liquid volumetric flow rate | 0.010 m3 s-1 | | | Design specification |
| Pipe work length (option 2) | 840 m | | | Design specification |
| Total ΔP (option 2) | 370 kPa | | | Calculated |
| Pumping power 2 (option 2) | 7.43 kW | | | Calculated |
| Heat pump (HP) | Evaporator HX type | Shell and plate heat exchanger | | | Design specification |
| Capacity | 900 kW | | |
| UA value | 199 kW/K | | |
| Liquid | 30% propylene glycol /water mix | | | Design data |
| Liquid-side ∆T | 5K | | |
| Evap approach temperature | 2.5 K | | |
| Heat pump fluid | Ammonia | | | Design specification |
| COPheating delivery at 70°C | Range 2.8 – 3.9 | | | Calculated |
| Condenser heat exchanger | Shell and plate heat exchanger | | | Design specification |
| Delivery side liquid | Water | | |
| Delivery side ∆T | 70°C/40°C | | |
| Cond approach temperature | 0.3K | | |

N/A = Not applicable; Misc. = miscellaneous; Evap = evaporator; Cond = condenser

A graph of coefficient of performance (CoP) for the heat pump at different operating conditions, for a condensing temperature of 70.3°C, was constructed from manufacturers’ data, and is shown in Figure 5.

Figure 5 - insert.tif

**Figure 5 Graph of CoP versus Evaporator temperature for selected heat pump**

A number of assumptions were used for the model, including:

(i) a fixed quantity of heat was recovered from the HRHX throughout the year, whether the ventilation shaft was operated in exhaust or supply. This was achieved by allowing the water temperatures to fall in the primary water loop, to maintain the difference between the air on temperature and the water in the heat exchanger coil;

(ii) the heat pump was able to deliver heat to the DHN at a temperature of 70°C for all operating conditions;

(iii) the coefficient of performance (CoP) for the heat pump varied with the evaporator temperature. The CoP for the heat pump was calculated from the evaporator temperature using manufacturer data;

(iv) the energy input needed for the heat pump was calculated from either the quantity of heat absorbed or rejected and the CoP for these conditions;

(v) the water pump efficiency used for both the primary water loop and for the secondary water loop where used, was assumed to be 0.5. The pump efficiency used is actual efficiency over maximum theoretical flow rate and is a conservative estimate from manufacturers’ data;

(vi) cost of electricity £0.098 per kWh (BEIS, 2017);

(vii) cost of gas £0.022 per kWh (BEIS, 2017);

(viii) carbon factor for electricity 0.41 kg CO2e per kWh (DEFRA, 2016);

(ix) carbon factor for gas 0.18 kg CO2e per kWh (DEFRA, 2016);

(x) renewable heat incentive (RHI) (UK Government) payment for renewable heat delivered by heat pumps £0.025 per kWh (Ofgem, 2016)

RHI is currently only applicable to heat pumps delivering heat only (i.e. no simultaneous cooling), for non-domestic installations, therefore RHI has only been applied when operating the ventilation shaft in exhaust mode.

The model was used to investigate the performance of the MICAH system throughout the year, using measured, weekly averaged, tunnel air temperatures and ambient air temperatures, as input data. In addition, the effects of operating the MICAH system in either supply (i.e. integrated cooling and heating) mode or exhaust (i.e. heating only) mode for different periods through the year was investigated. The model is based upon meeting a base load and all of the heat being utilised. If heat is rejected this will reduce the cost benefit accordingly.

When the MICAH system is operated in supply mode, it should be noted that the temperature of air flowing through the HRHX varies with ambient temperature.

**3.0 Results and discussion**

Some of the results from the model are presented in Figures 6 to 13 below. The analysis includes temporal variation in ambient air temperature and is implicit in each of the figures.

3.1 Comparing design layout options

A comparison of cooling and heating energy benefits for different periods of the year in integrated cooling and heating mode (with the remainder in heating only mode), for design layout options 1 and 2 is shown in Figure 6 below.

Figure 6b.tif

**Figure 6 Cooling and heating benefits for MICAH for layout options 1 and 2**

It is seen from Figure 6 that the cooling and heating benefits are similar for layout options 1 and 2, although the heating delivered is marginally less for option 2. This is due to a small amount of heat loss while transporting the high temperature i.e. 70°C, water leaving the heat pump for layout option 2. Overall, the heating delivered to the DHN increases steadily for both layouts as the number of months in integrated cooling and heating mode i.e. supply mode, increases. This is due to the lower air on temperatures in supply mode, which leads to a small increase in the energy input to the system being needed, resulting in a corresponding increase in heat output. The quantity of cooling provided increases steadily with the number of months in integrated cooling and heating mode.

The cost savings for MICAH compared with supplying the same amount of heat by CHP and the same amount of cooling by conventional vapour compression refrigeration (VCR) are shown in Figure 7 below. Cost savings are shown both with and without RHI applied, for layout options 1 and 2.

Figure 6c.tif

**Figure 7 Cost savings (with and without RHI) for MICAH compared with CHP heating and VCR cooling for layout options 1 and 2**

Figure 7 shows that there is a marginal increase in cost savings for design layout option 1 compared to option 2, both with and without RHI, under all operating conditions. It is seen that with RHI included, the greatest savings are achieved when operating for 0 months in cooling and heating mode (12 months in heating only i.e. exhaust mode). However, these savings decrease steadily, as the number of months operated in integrated cooling and heating i.e. supply mode increases. In contrast, if RHI is not included, cost savings increase steadily, as the proportion of the year operated in integrated cooling and heating mode increases. This reflects the fact that under current rules, RHI can only be applied when operating the system in heating only mode.

Capital costs and payback periods for the various systems and scenarios were also investigated and payback periods of around 20 years were calculated.

The potential carbon savings available for MICAH compared to conventional cooling and heating systems are shown in Figure 8 below.

Figure 7c.tif

**Figure 8 Carbon savings for MICAH compared with CHP heating and VCR cooling for layout options 1 and 2**

Figure 8 shows that the carbon savings for MICAH compared to conventional cooling and heating systems are substantial, ranging from approximately 1100 to 1800 tonnes CO2e saved per year. The quantity of CO2e saved increases steadily with the number of months that the system is operated in integrated cooling and heating mode.

3.2 Sensitivity analysis

A number of factors have been investigated using the model to determine their effects on cost and carbon savings. These include the effect of: (i) the anticipated additional fan power required due to fouling, on cost and carbon savings; (ii) the distance between the ventilation shaft and the DHN, for the heat recovery system considered, on cost savings; (iii) the effect of delivery temperature on the cost savings; (iv) the price of gas on cost savings. The sensitivity analysis results shown are for layout option 1 only, however very similar results were found for layout option 2.

3.2.1 Effect of fan power

The effect of the fan power on the cost savings achieved is shown in Figures 9.

Figure 9d.tif

**Figure 9 Effect of fan power on cost savings (with and without RHI) for MICAH compared with CHP heating and VCR cooling**

The 3 different fan powers considered in Figure 9 above are: (i) for a clean heat exchanger with a resistance of 49 Pa (based on manufacturer data), which results in a fan power requirement of 6.125 kW; (ii) for maximum blockage of the heat exchanger, which from previous trials [Dragoni et al, 2016], could give a resistance of up to 200 Pa, resulting in a fan power requirement of 25 kW; and (iii) an average resistance of 125 Pa, resulting in a fan power requirement of 15.63 kW. All of the model results presented elsewhere in this report are based on the inclusion of a fan power requirement of 15.63 kW. It is seen from Figure 9, that the fan power does have some impact on the overall cost savings, however, for the range of fan powers considered here, their overall influence on cost savings is relatively small.

The effect of the three different fan powers on carbon emissions savings are shown in Figure 10.

Figure 10f.tif

**Figure 10 Carbon savings for three different fan powers for MICAH compared with CHP heating and VCR cooling**

3.2.2 Effect of distance between the ventilation shaft and the DHN

Figure 11 shows the effect of distance between the ventilation shaft and the DHN i.e. distance for heat transfer using water, on the cost savings for MICAH compared with CHP heating and VCR cooling.

Figure 11.tif

**Figure 11 Effect of distance between ventilation shaft and DHN on cost savings (with and without RHI) for MICAH compared with CHP heating and VCR cooling**

It is seen from Figure 11 that the distance between the ventilation shaft and the DHN has only a marginal effect on cost savings, with a slight decrease in cost savings with distance. The reason for this is that the pressure head and pumping costs for moving the water over a distance of 840 m (i.e. 420 m flow and 420 m return) which result from the pipe wall friction are only small proportion of the overall pressure head for the pumping system. The largest influence on the pumping power required is the effect of the heat exchangers, valves and strainers which add a significant pressure drop, and it has been assumed that the same number of these will be needed irrespective of the distance pumped. Figure 11 shows the results for the layout option 1 configuration only, however, a similar marginal effect was found for layout option 2. In fact, the influence of the distance pumped is even lower for layout option 2, as the water flow rate needed is lower for the secondary water loop, which becomes the main heat transport system for carrying the heat between the ventilation shaft and the DHN for layout option 2. This is in contrast to layout option 1, where the primary water loop is the main heat transport system.

The reason why distance is not a significant factor is due to the large diameter of pipe used. This was intentional since capital cost is marginally dependent on pipe size due to the controlling cost of the civil works. Whereas pumping costs become prohibitive with smaller pipe sizes.

3.2.3 Effect of delivery temperature on cost savings

The effect of delivery temperature on cost savings is shown in Figure 12. The effects of delivery temperatures of 60°C, 65°C and 70°C, are compared.

Figure 11d.tif

**Figure 12 Effect of delivery temperature on cost savings (with and without RHI) for MICAH compared with CHP heating and VCR cooling**

Figure 12 shows that delivery temperature has a marked influence on the cost saving for MICAH compared to CHP heating and VCR cooling. Where RHI is included, for 0 months in integrated cooling and heating mode, cost savings of £196,000 are available at a delivery temperature of 60°C, as compared with £154,000 at a delivery temperature of 70°C. Where RHI is not included, there is a steady increase in cost savings as the number of months in integrated cooling and heating i.e. supply mode increases. There are greater cost savings at the lowest delivery temperature of 60°C. It may be concluded from Figure 12, that there is a case for operating MICAH at a reduced delivery temperature of e.g. 60 or 65°C. However, delivering heat at lower temperatures could have implications for consumers e.g. the need for larger radiators in order to receive the same amount of heat.

3.2.4 Effect of gas price on cost savings

The model results presented to date are all based on the assumption of a gas price of £0.022 per kWh [DECC, 2016], which is the average industrial gas price at present. The domestic gas price is currently £0.029 per kWh [DECC, 2016]. Figure 13 shows the effect of three different gas prices in relation to the current industrial electricity price of £0.098 per kWh [DECC, 2016] on the cost savings available for MICAH compared to CHP heating and VCR cooling.

Figure 12g.tif

**Figure 13 Effect of gas price on cost savings (with and without RHI) for MICAH compared with CHP heating and VCR cooling**

It is seen in Figure 13, that gas price is a major factor influencing the cost savings for MICAH relative to CHP heating and VCR cooling. Considering the cost savings for 0 months in integrated cooling and heating mode, with RHI, it is seen that for an increase in gas price from its current industrial price of £0.022 per kWh to the current domestic gas price of £0.029 per kW, the cost savings increase from £154,000 to £250,000 per year. The price of gas is expected to increase further in the future, and carbon taxes may be levied on fossil fuels such as gas. The cost of gas e.g. for CHP or gas boilers, can significantly influence the cost of heating using these methods as compared with MICAH, which could substantially increase the cost savings for MICAH.

3.2.5 Effect of CoP of heat pump on cost savings for MICAH

Another key factor affecting the cost savings achieved for MICAH is the coefficient of performance (CoP) for the heat pump. Small increases in CoP can provide large increases in energy, carbon and cost savings for MICAH. The CoPs assumed in the current model were derived from performance data provided by a heat pump manufacturer (personal communication with GEA, 2016) and are based on the use of a 2-stage ammonia heat pump. In fact, recent information supplied by the heat pump manufacturer suggests that significantly higher CoP values i.e. of the order of +0.5 could be achieved with a custom designed heat pump system based on the expected operating conditions, which would provide significantly increased energy, carbon and cost savings. Other factors which could increase the heat pump CoP include the use of transcritical CO2 as the primary loop heat transfer fluid to transfer heat from the HRHX to the heat pump evaporator. This would enable the temperature difference to be significantly reduced to e.g. 1-2 K, as compared with a current flow- return temperature difference of 5 K, plus log mean temperature differences (LMTDs) of 7.2 K and 4.5 K for HRHX and heat pump evaporator heat exchangers respectively. As a result, the heat pump evaporator temperature could be increased significantly with a corresponding increase in CoP (i.e. of the order of 4% per 1K increase in evaporating temperature). However, an alternative approach would be to simply reduce the LMTD for the HRHX, by increasing the HRHX size. This would also permit the evaporator temperature to be increased, thereby increasing the CoP for the heat pump.

**4.0 Conclusions**

The MICAH system performance has been evaluated in terms of energy use, carbon emissions and costs, and shown to provide significant savings compared with CHP heating and VCR cooling. The performance was similar for both configuration options i.e. layout options 1 and 2. For example, carbon savings ranging from 1080 to 1800 tonnes per year for the different operating modes (i.e. range of periods operating in either integrated cooling and heating or heating only modes) can be achieved with current electricity grid carbon factors. The results showed that this system could deliver massive carbon and cost savings. With 200 ventilation shafts in London, it is possible to save annually more than 360,000 tonnes of carbon and generate revenues of £40,000,000, compared to conventional cooling and heating systems. If this technology can be applied in 50% of 150 metro systems worldwide (UITP, 2015), more than 27 million tonnes of carbon savings will be achieved. This is expected to increase further as the electricity grid continues to be decarbonised, as the proportion of renewable energy sources increases, in the future. Cost savings vary with a range of factors as discussed above, but with optimisation, and with RHI applied, significant savings can be achieved.

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