Cooling and recovery of heat from underground railway tunnels for district heating

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Abstract

Temperatures in London's underground railway tunnels are rising year on year and new energy efficient, cooling solutions are needed. The MICAH (Metropolitan Integrated Cooling and Heating) project involves investigating the feasibility of combining cooling and ventilation of London's underground tunnels with recovering and reuse of the waste heat to supply a district heating network (DHN). A suitable site from the underground network has been identified, close to a DHN, to which the heat can be transferred. The temperatures of the ventilation shaft air are quite low i.e.17-28°C, so the recovered heat needs to be upgraded e.g. to 70°C using a heat pump, before delivering it to the DHN. A model has been developed which incorporates the proposed design and operational parameters for the combined cooling and heat recovery system, together with specifications for the heat pump and the equipment needed to transfer the heat to the DHN. The model permits evaluation of the performance of the system under a wide range of design, operating and environmental conditions, and for a number of configurations, enabling the model to be used to investigate the potential for waste heat recovery at a range of sites. Preliminary results from the model are presented and the potential benefits, limitations, and the effects of key design and operating parameters are discussed.

Keywords underground railway tunnels, waste heat recovery, heat pumps, district heating networks

1.0 Introduction

The underground railway transport system in London is seeing steady increases in the numbers of passengers, with the number of passenger journey increasing by 34% since 2001[1]. Consequently the frequency of the train services and the number of trains is also increasing.

Heat is mainly generated by the braking system of the trains, with additional heat generated by the passengers. The main method used to maintain the tunnel temperatures within a safe range has been to use tunnel ventilation shafts either in forced ventilation (FV) or draught relief (DR) mode. The tunnel ventilation shafts are able to supply air from street level to the tunnel or extract air from the tunnels to atmosphere using the piston effect of the trains in DR mode or ventilation fans in FV mode. Despite these measures, there is a long term trend for tunnel air temperatures to rise. The highest temperatures are experienced during the summer months (June to September).

Consequently, London Underground (LU) is investigating a number of active cooling methods that could be used to halt or reverse the long term trend. One approach is to cool the air before supplying it through the ventilation shaft into the tunnels. This can be achieved by passing it through an air to water heat exchanger (fan coil) unit. The heat removed from the air stream is transferred to low temperature hot water (LTHW) passing through the heat exchanger coil, increasing its temperature. Subsequently, this heat is usually dissipated to the ambient air; however, it could also be recovered and reused.

It has been estimated that at least 15 MW of heat could be recovered from the LU tunnel network using this approach, providing a significant heat resource. The feasibility of recovering heat in this way is the subject of the MICAH (Metropolitan Integrated Cooling and Heating) project. The project involves collaboration between LU, Islington Borough Council (IBC) and London South Bank University (LSBU) and is being funded by Innovate UK.

Key issues for reusing waste heat are: (i) how best to transport the heat to potential users; and (ii) the temperature of the waste heat in relation to the users' requirements. For the purposes of the MICAH project, it is planned to evaluate the effectiveness of connecting the waste heat recovery system to a district heating network (DHN). IBC already operate a DHN located in an area of London called Bunhill, and are planning to build a number of other DHNs across the borough. One of these DHNs is planned for the Caledonian Road area, and a LU ventilation shaft has been selected within this area to investigate the technical, energy and carbon saving, and the economic potential for a waste recovery system with connection to the DHN. The recovered waste heat will be transported as heated water between the ventilation shaft and the DHN. The heated water will be at a low temperature, ranging typically between 5°C and 20°C during the year. The DHN is planned to operate with a flow temperature of 70°C and a return temperature of 40°C, the waste heat will therefore need to be upgraded to an appropriate temperature, before transfer to the DHN.

This paper identifies an opportunity for reusing waste heat in London, while reducing carbon emissions and costs. It describes the proposed waste heat recovery scheme which aims to recover heat from a LU tunnel ventilation shaft and then transfer it to a DHN for reuse. The ventilation shaft will normally operate in either "extract" i.e. air extract mode, or "supply" i.e. air supply mode, by means of draught relief or forced ventilation (mechanical ventilation). This study deals with the air induced by forced ventilation. By using a reversible fan the ventilation shaft can operate in either mode, for example at different times of the year. In fact, the operational requirements for the chosen site are expected to dictate that the system is operated in extract mode only. The MICAH project will investigate a number of configurations for the ventilation system e.g. extract only or supply only throughout the year, or with different combinations of extract and supply modes during the year, so that the results from the project can be applied to a number of different scenarios and sites, in the future. A computer model has been developed to evaluate the performance of the system for a wide range of configurations and operating conditions and preliminary results from the model are presented and discussed.

1.1 Heat strategy for the UK and London

The 2008 Climate Change Act in the UK[2] commits the UK government to an 80% reduction in carbon emissions below 1990 levels by 2050. At present emissions from heating contribute approximately one third of the UK total of 562 million tonnes CO_2 equivalent[3] (CO_2e). The UK government have put forward their strategy for meeting this target in relation to heating emissions, in a report entitled: ‘The Future of Heating: Meeting the Challenge[4].’ There are 5 key strands to the strategy for heating suggested, namely: (i) decarbonising the electricity grid e.g. by using renewable energy sources; (ii) reducing emissions from industrial processes e.g. using carbon capture; (iii) expansion of heat networks (which provide only 2% of heat in the UK at present), and the use of waste heat; (iv) improving the efficiency of heating in buildings e.g. by reducing heat losses and using renewable energy; (v) adapting energy grids and infrastructure e.g. switching heating energy sources from gas boilers to heat pumps using electricity from renewable sources. The Mayor of London’s office have produced a number of reports on the future heating strategy for London and have suggested that up to 25% of London’s heating needs could be met from decentralised sources such as secondary waste heat by 2025[5]. This will involve greatly extending the number and scale of DHNs in London. Figure 1 shows the existing and proposed new DHNs for London.

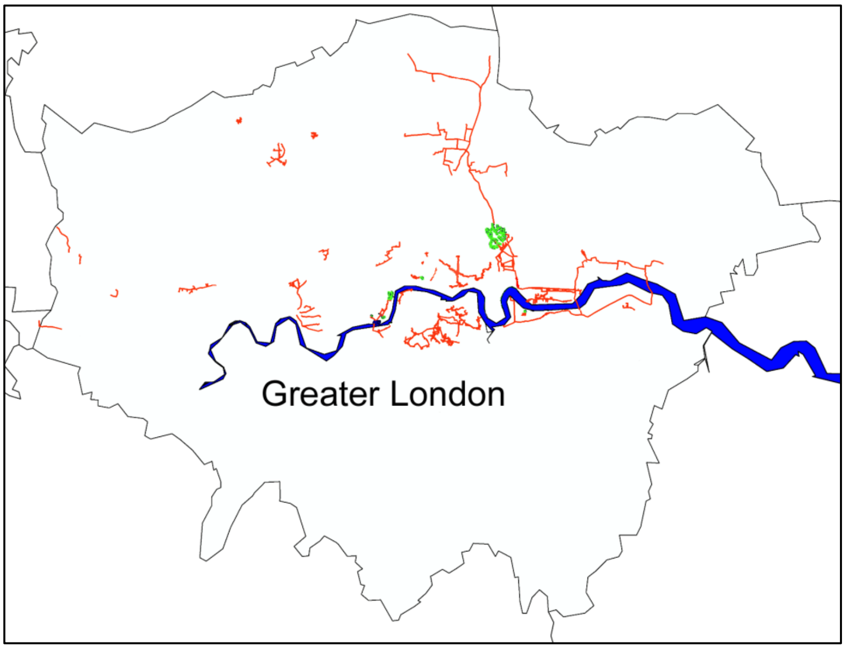


Figure 1 Existing and proposed DHNs in London[4]

Note: Green lines indicate existing DHNs and red lines indicate proposed DHNs.

1.2 Waste heat in London

A range of secondary waste heat sources that could be used to provide input to DHNs have been identified in London. Similar heat sources are likely to be found in many cities both around the UK and the world. Potential heat sources include: (a) power station waste heat; (b) building air conditioning heat rejection; (c) industrial waste heat; (d) underground railways; (e) electricity substations; (f) sewer heat mining; (g) canals and waterways; (h) data centres; (i) supermarkets; (j) roads and car parks. These waste heat sources vary in the total quantity of heat available and their temperatures. The air temperatures in the London Underground network vary between 17 ºC to 28 ºC during the year. It has been estimated that harvesting the heat from this air could provide up to 15 MW of heat for supply to DHNs[6].

2.0 Recovery of waste heat from LU tunnels

The MICAH project will consider two main options for recovery of heat from the air in underground railway tunnels, namely: (i) from the ventilation exhaust air, when operating in extract mode; and (ii) from the outside air prior to supplying cooled air to the underground tunnel network using the ventilation shaft i.e. supply mode. The shaft selected for the study could be operated using either mode, at different times of the year, by means of a reversible fan. For example, the ventilation shaft could operate in supply mode to provide cooling during the summer months, and in extract mode during the winter months, when cooling is not needed. The two options are illustrated in Figure 2.

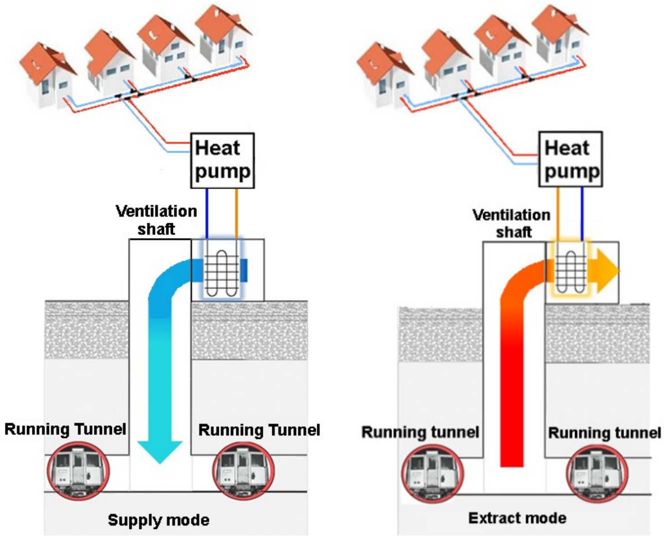
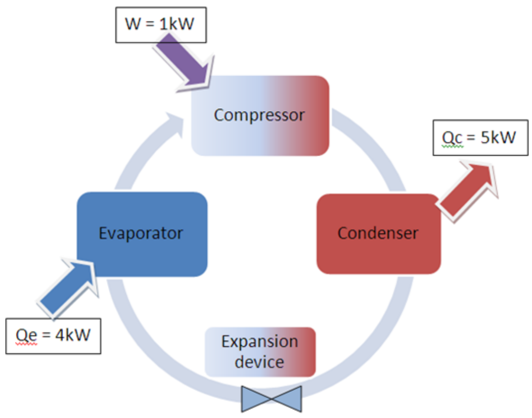


Figure 2 Supply and extract modes of operation for ventilation shaft

When operated in supply mode e.g. in summer, the MICAH system will be providing simultaneous cooling to the underground and delivering heat to the DHN. This will provide significant energy and carbon savings compared to using separate conventional cooling and heating systems.

2.1 Vapour compression systems

All vapour compression systems generate simultaneous cooling and heating, however, for most applications only one of these outputs is used i.e. either cooling or heating, and the other output is discarded. However, if both outputs can be used, the efficiency of the system, for a given energy input, can be maximised. The performance of vapour compression systems is usually characterised in terms of a coefficient of performance (CoP) value. CoP is defined as the ratio of useful output e.g. cooling or heating capacity in kW, to the work energy input to the system in kW. As shown in Figure 3, CoP can be defined in three ways depending on the way the system is used.



Modes of operation for vapour compression system:

(i) CoP_c= Qe/ W = 4/1 (cooling only mode i.e. refrigeration)

(ii) CoP_h = Qc/ W = 5/1 (heating only mode i.e. standard heat pump)

(iii) CoP_{c+h} = (Qc + Qe)/ W =9/1 (combined cooling and heating mode)

Figure 3 Efficiency benefit of combined cooling and heating system

For MICAH, the two modes of interest are heating only mode (when operating the ventilation shaft in extract mode), and combined cooling and heating mode (when operating the ventilation shaft in supply mode).

It should be noted that when operating in supply mode, heat is recovered from the outside air, which will have a lower temperature than the tunnel exhaust air at any given time through the year. Consequently, a lower evaporator temperature will be required for the heat pump, than when recovering heat from the tunnel air i.e. in extract mode. Therefore, the CoP for the combined cooling and heating mode will be higher than that for the heating only mode (as shown in Figure 3 above). However, some of the efficiency gains from using the combined cooling and heating mode will be offset by the lower evaporator temperatures needed for the lower outside air temperatures from which the heat is recovered. The efficiencies for the two different modes, and how these vary during the year, will be compared during the project.

2.2 Description of MICAH system and tasks to be undertaken

The MICAH system will be evaluated for a specific disused underground station in London. A waste heat recovery heat exchanger (i.e. fan coil) capable of capturing up to 900 kW of waste heat will be designed for installation at the site. The heat recovered will be transferred to LTHW which will then be pumped using a pipe work system to the Energy Centre proposed for the Caledonian Road DHN. There it will be upgraded to the required temperature and delivered to the DHN, by means of a heat pump.

The Energy Centre will also contain other heat sources, for example combined heat and power (CHP) systems providing both heat and electricity, and gas boilers. These heat sources will be used to meet all additional heat demand by the network and will provide a back-up system for the waste heat recovery/heat pump system.

Together, these systems will enable the heat supply and demand to be balanced throughout the year. It is currently proposed to site the Energy Centre (and heat pump) close to a swimming pool, which will provide one of the main base heat loads for the DHN as it requires heat throughout the year, including during the summer months. This will, however, require the heat recovered at the site to be transported as water for a distance of at least 300 m, potentially resulting in a significant pumping power requirement. However, a number of other options for siting of the Energy Centre relative to the heat recovery location will be evaluated during the project. A schematic of the proposed MICAH system is shown in Figure 4.

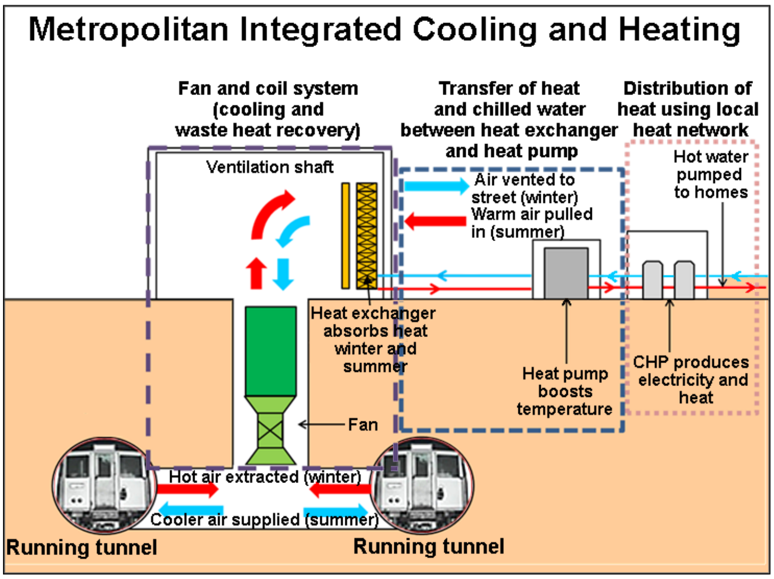


Figure 4 Schematic of MICAH system

The main tasks being undertaken by the project partners include:

(i) designing the heat recovery heat exchanger and water transport system to carry the waste heat to the heat pump;

(ii) designing the heat pump for upgrading the waste heat to the required temperature for transfer to the DHN;

(iii) development of a computer model to evaluate the operating performance of the system in a variety of modes to determine the optimum configuration and operating conditions under a range of environmental conditions. The model should permit the potential for waste heat recovery from the tunnel air to be evaluated for any LU site.

3.0 MICAH model

The model being developed is a Microsoft Excel spreadsheet based model, which simulates the heat recovery heat exchanger performance, calculating its heat absorption capacity for a range of operating conditions. It also calculates the required flow rates and resulting temperatures for the water circulating through the heat exchanger under these conditions. The air temperatures in the ventilation shaft will vary with the operating mode (i.e. supply or extract) and the time of year, as a result of the seasonal variations in both the tunnel and outside ambient air temperatures.

The model also simulates the pipe work system used to transport the heated water from the ventilation shaft heat exchanger to the heat pump. It accounts for the required flow rate, temperature difference and the diameter, length and roughness of the pipes. It also calculates the effects of bends, junctions, valves and fittings, and changes in elevation, as well as the pressure drops through the heat recovery heat exchanger and the heat pump evaporator heat exchanger. This enables the overall pressure drop for the system to be estimated and the potential pumping power and energy input required for circulating the water through the system to be calculated.

A variable speed pump will be required to control the flow rate of the water and thereby the rate of cooling (and heat recovery) by the ventilation shaft heat exchanger, as well as the flow and return temperatures for the water transport system. The water temperatures will also be influenced by the rate of heat removal by the heat pump evaporator. In addition, the rate of heat recovery will also vary with either the tunnel air or street level ambient air temperatures. The model also simulates the performance of the heat pump, which is required to upgrade the recovered waste heat to a suitable temperature for transfer to the DHN.

The DHN is expected to operate with a flow temperature of 70°C and a return temperature of 40°C, so that heat can be added to the DHN return at a temperature between the set point flow and return DHN temperatures, prior to it reaching a CHP system or gas boiler. The conventional heating system will then provide the final boost for the temperature, as required. The temperature to which the DHN return is raised will be varied, depending on the heat source i.e. either tunnel air or street level ambient air, and the quantity of heat recovered by the ventilation shaft heat exchanger. It will also depend on the heat delivery temperature set for the heat pump and the efficiency (CoP) desired. If the recovered heat is insufficient to meet the total heating demand for the DHN, the required flow temperature for the network will not be reached, however, the remaining heat demand and flow temperature requirement will be met by the CHP system or gas boilers, within the Energy Centre. By operating the heat pump at low condensing temperatures, a high CoP can be achieved.

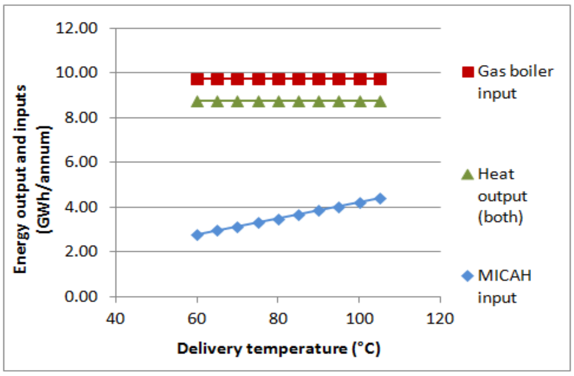
The model will be calibrated by comparing the individual processes in the MICAH system with existing waste heat recovery processes, where appropriate, both in the UK and worldwide, for example, Bunhill in the UK, and a number of systems in Sweden and Finland.

The model will investigate and determine the optimum operating temperatures both for the heat pump and the overall system. The heat pump electrical input energy together with the water transport system electrical pumping energy and the ventilation shaft fan energy represent the main energy inputs to the MICAH system.

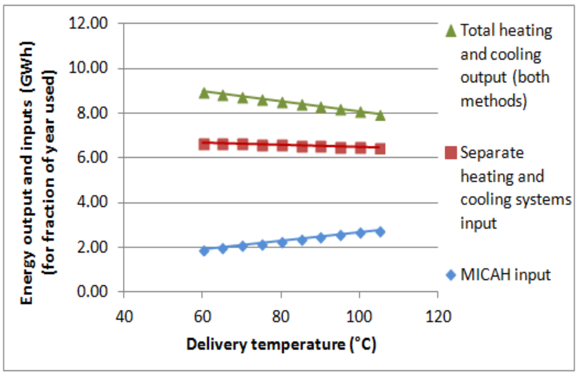
Based on the electrical energy input, the corresponding operating costs and CO_2e emissions for MICAH are calculated by the model. The energy inputs, CO_2e emissions and costs for MICAH can then be compared with those resulting for delivery of a similar amount of heat and cooling using conventional methods e.g. by a gas boiler or a conventional vapour compression refrigeration system. The heat delivered by the heat pump used in MICAH will be eligible for the UK government’s renewable heat incentive (RHI) scheme, for which the relevant current tariff rate is 2.57 p per kWh[7], when operated in heating mode only (i.e. extract mode for the ventilation shaft), providing the heat pump operates with a minimum CoP of 2.9, which the model indicates should be achieved. This significantly improves the economic case for MICAH. There are currently no plans to increase the tariff, but it has been proposed that for systems of > 45kW, some form of preliminary accreditation may be introduced in the future, to provide greater financial certainty.

4.0 Preliminary results from the model

Some preliminary results predicted by the model are shown in Figures 5 to 7 below.

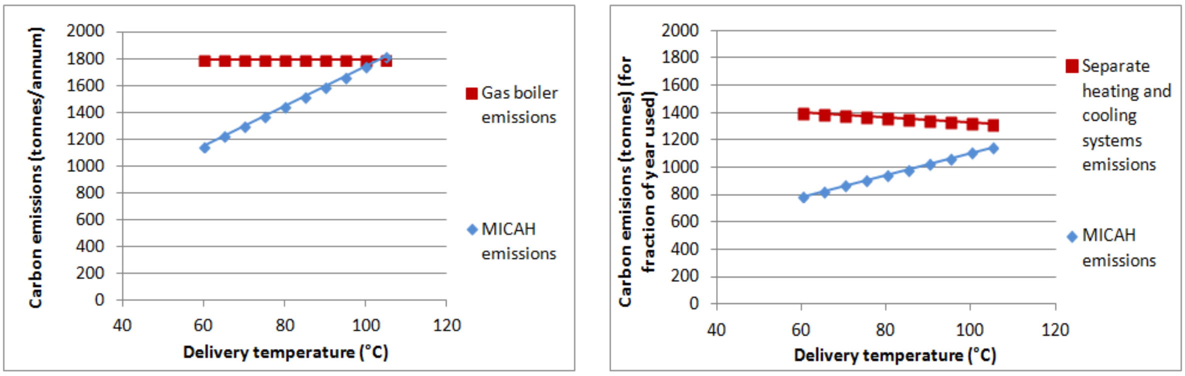


(a) Heating only mode (i.e. extract mode)



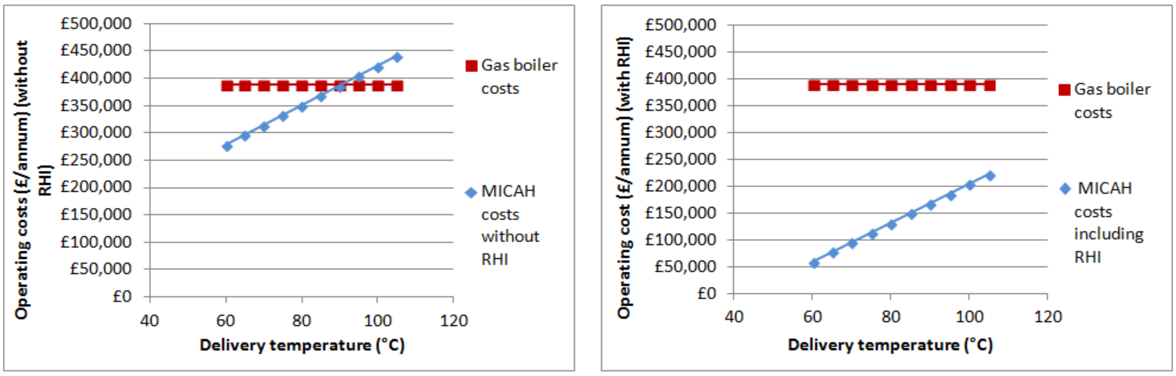
(b) Combined cooling and heating mode (i.e. supply mode)

Figure 5 Energy inputs and outputs for conventional heating and cooling systems compared with MICAH



(a) Heating only mode (i.e. extract mode) (b) Combined cooling and heating mode (i.e. supply mode)

Figure 6 Carbon emissions for conventional heating and cooling systems compared with MICAH



(a) Heating only mode (i.e. extract mode) (No RHI) (b) Heating only mode (i.e. extract mode) (With RHI)

Figure 7 Operational costs with and without RHI applied, for conventional heating systems compared with MICAH

Figures 5, 6 and 7 show graphs for energy inputs and outputs, carbon emissions and costs, plotted against delivery temperature i.e. the temperature at which the upgraded heat is delivered to the DHN. The delivery temperature is a key factor in determining the overall efficiency of the MICAH system. It is seen that the lowest energy inputs, carbon emissions and operating costs using MICAH are achieved at the lowest delivery temperatures, and the savings achieved compared to separate conventional cooling and heating methods are steadily reduced as the delivery temperature is increased.

For Figures 5 and 6, comparisons between energy inputs and outputs, and carbon emissions for conventional separate cooling and heating methods versus MICAH are shown, for (a) heating only (i.e. extract) mode; and (b) combined cooling and heating (i.e. supply) mode. For Figure 5 (a), it is seen that the energy input requirement for the MICAH system is significantly lower than that for a gas boiler for delivering the same quantity of heat. However the gas boiler is using gas energy, while the MICAH system uses electrical energy, and the carbon emissions from gas are significantly lower with a carbon factor of 0.184 kg CO_2e per kWh, compared with electricity which currently has a carbon factor of 0.41205 kg CO_2e per kWh[8]. The carbon factor for electricity should steadily decrease in the future, as the electricity grid is decarbonised, which should further increase the savings in CO_2e for MICAH.

As a result of the different carbon factors for gas and electricity, the overall savings in CO_2e emissions for MICAH compared to a gas boiler, as indicated by Figure 6 (a), are relatively low compared to the differences in energy input. A similar effect is seen for the combined cooling and heating (i.e. supply) mode graphs (Figures 5 (b) and 6 (b)), where the energy inputs for separate conventional cooling and heating methods and for the CO_2e emissions for separate conventional cooling and heating methods are compared with MICAH in the respective graphs.

It should be noted that the values predicted for the two modes i.e. heating only and combined cooling and heating, in Figures 5 and 6, differ in the numbers of operating hours assumed. For the results presented to date, it has been assumed that MICAH will only be operated in combined cooling and heating mode for part of the year, since if the outside ambient air temperatures are low e.g. less than 10°C (which is the case during the winter months in the UK), further cooling of the air will probably not be needed. Also, the low evaporator temperatures required under these conditions are likely to result in low efficiencies for the heat pump (recovered heat) upgrade process. However, MICAH could be operated in heating only (i.e. extract) mode throughout the year, and this assumption has been used in calculating the energy input and CO_2e emissions values shown in Figures 5 (a) and 6 (a). In fact, the model will also be used to evaluate the energy efficiency and carbon and cost savings of operating the system in the different modes i.e. heating only and combined cooling and heating, for a range of different periods during the year, including operating in year round combined cooling and heating mode, as this might be more appropriate at other sites.

The differences between the total for separate conventional cooling and heating methods and MICAH i.e. combined cooling and heating mode (in terms of energy input and CO_2e emissions, as shown in Figures 5 (b) and 6 (b), are a little lower than those for the heating only mode, as shown in Figures 5 (a) and 6 (a). This is mainly due to the reduced efficiency for the heat pump for MICAH in combined cooling and heating mode, due to the lower outside air temperatures used, as compared with the higher tunnel air temperatures available in heating only (i.e. extract) mode.

The graphs shown in Figure 7 (a) and (b) are for heating only mode. They compare the overall operating (energy) costs for heating with a conventional gas boiler with MICAH. However, they differ in that for Figure 7 (a) no RHI payments have been offset against the MICAH costs, while in Figure 7 (b) the RHI payment has been included (by subtracting it from the calculated operating cost for MICAH). It is seen that in both cases there is a cost saving for MICAH at delivery temperatures below

90°C, with the greatest savings at the lowest delivery temperatures. Where the RHI payment is included the economic benefits are significantly enhanced, as shown in Figure 7 (b). It is important that low operating costs for waste heat recovery processes are achieved, in order to justify the capital costs for the equipment and installation costs, as well as any additional maintenance costs.

5.0 Conclusions

There is a large amount of waste heat available from the underground network in London, which could provide a significant heat resource. An opportunity to recover waste heat from the tunnel air via underground ventilation shaft and transfer it to a DHN has been identified, and is being investigated. The waste heat recovered from the tunnel has a relatively low temperature and needs to be upgraded using a heat pump prior to transfer to the DHN. A model has been developed to evaluate and optimise the performance of the planned heat recovery system.

The following key factors for the system have been identified:
(1) the temperature at which the heat is delivered to the DHN;
(2) whether the ventilation shaft is operated in heating only mode or combined cooling and heating mode and for what period of the year;
(3) the variation in tunnel air temperatures over the year;
(4) the variation in outside ambient air temperatures over the year;
(5) the carbon factor for electricity. (The carbon savings available will increase as the electricity grid is decarbonised);
(6) RHI is important in justifying the economics of the waste heat recovery process, however this paper notes that RHI tends to be reduced for particular renewables technologies as the technology becomes “business as usual”.

The preliminary results from the model indicate that significant energy, carbon and cost savings are available using MICAH, as compared to separate, conventional cooling and heating processes e.g. use of vapour compression refrigeration systems and gas boilers. However, further investigations using the model are needed to determine the optimum operating conditions for the system and how they vary during the year. The components needed for the system can then be specified and commercial products or custom designed equipment from manufacturers and suppliers identified. The associated capital, installation and future maintenance costs can then be estimated. These costs can be incorporated into the model and compared with the predicted operating cost savings to provide an estimate for the overall economics of MICAH and potential payback periods, as well as estimating the energy and carbon savings achievable.

References

1. Transport for London Press Release (2015). Online: https://tfl.gov.uk/info-for/media/press-releases/2015/november/london-underground-carries-more-people-than-ever-befo Accessed 2-12-16
2. Climate Change Act 2008: Elizabeth II. (2008) London, Stationery Office.
3. DECC (2014) The Future of Heating: Meeting the Challenge. Presented at i-STUTE Breakfast Forum, London, UK-June 2104, by G. Gebrail on behalf of Department of Energy & Climate Change, UK. Online: http://www.i-stute.org/Other%20files/Presentations%20Breakfast%20Forum/Presentation%20Greg%20Gebrail.pdf Accessed 2-12-16
4. DECC (2013) The Future of Heating: Meeting the Challenge, Department of Energy and Climate Change, UK.
5. London's Zero Carbon Energy Resource: Secondary Heat (2013) Mayor of London Report. Online: https://www.london.gov.uk/sites/default/files/gla_migrate_files_destination/031250%20GLA%20Secondary%20Heat%20-%20Summary%20Report_0.pdf Accessed 2-12-16
6. Davies, G.F., Boot-Handford, N., Grice, J. Dennis, W., Rami, R., Nicholls, A. and Maidment, G. (2017) Metropolitan Integrated Cooling and Heating. Presented at ASHRAE Winter Conference, Las Vegas, USA, Jan 28th - Feb 1st 2017
7. Ofgem (2016) Tariffs and payments: Non-Domestic RHI. Online: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-non-domestic-rhi Accessed: 2-12-16
8. DEFRA (2016) UK Government GHG Conversion Factors for Company Reporting Department for Environment, Food and Rural Affairs. Online: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2016 Accessed 2-12-16

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