Heat Recovery Potential from Urban Underground Infrastructures

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ABSTRACT

This paper describes the results from a collaborative research project in the UK, focussing on the recovery of waste heat from underground railway tunnels, using London as a case study. The aim of the project was to investigate the feasibility of combining cooling of London's underground railway tunnels with a waste heat recovery system. The recovered heat will then be transferred to a heat pump to upgrade its temperature, before delivery to a district heating network for reuse. The paper describes the proposed design for the combined cooling and heating system and the model that has been developed to evaluate its performance. A range of results from the study are presented and the potential benefits in terms of energy, carbon and cost savings are highlighted. The paper also introduces a related project, which builds on this case study and aims to identify and quantify the potential for waste heat recovery from a range of urban subterranean infrastructures, such as sewers and cable tunnels, as well as underground railway tunnels. Potential heat recovery and delivery methods will be investigated, in relation to the size and location of local end-user heat demand. Both of these projects focus on waste heat recovery in London, however, the results are applicable to most cities with underground infrastructure systems, both elsewhere in the UK and around the world.

INTRODUCTION

An introduction to the MICAH (Metropolitan Integrated Cooling and Heating) project was presented at the ASHRAE winter conference in Las Vegas, in 2017 (Davies et al, 2016). This was a collaborative research project in the UK, involving London Underground (LU), as the waste heat supplier, Islington Borough Council (IBC), as the heat user (via a district heating network (DHN)), and London South Bank University, who have developed a modeling tool for evaluation of the proposed system. MICAH involves the provision of cooling for London Underground's tunnel network, with the waste heat from the cooling process being recovered, upgraded (using a heat pump) and then delivered to a DHN. Where cooling and heating can be combined in this way, there are greater opportunities for energy, carbon and cost savings, than for separate cooling and waste heat recovery systems.

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In London, legislation has been introduced to promote the better use of energy in buildings, both for domestic and industrial/commercial use. This is laid out in the London Plan (2004), which puts the focus 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 energy schemes is that they enable the use of highly efficient centralised plant, as compared to the operation of a large number of individual systems, of varying and generally lower efficiency. District energy schemes also facilitate the capture and reuse of waste heat.

A number of opportunities for waste heat recovery and reuse are considered below, and the potential for using heat from underground railways is highlighted. This paper investigates the use of cooling combined with heat recovery for a LU site. The recovered heat is then upgraded using a heat pump and transferred to a district heating network for distribution and reuse for domestic space heating and hot water heating in nearby social housing. The paper describes the technology used and its proposed method of application, and investigates the technical, environmental and economic advantages of these systems.

OPPORTUNITIES FOR WASTE HEAT RECOVERY

A range of cooling applications in London for which the waste heat generated could be potentially recovered was reported by Davies et al (2016). A list of selected applications, together with a number of other subsequently identified waste heat sources, which mainly focus on urban subterranean infrastructures, are shown in Table 1 below.

Table 1. Potential waste heat sources

Waste Heat Source	Extent of infrastructure	Total Heat Output of Sector MW(MBTU/h)	Waste Heat Temperature °C (°F)	Potential as a Waste Heat Source?
Electricity cable tunnels	Many hundreds of km (miles)	40 (136.5)*	55 (131)	High temps, medium to large quantity
Sewers	Many hundreds of km (miles)	N/A	10-22 (50-71.6)	Low temps, unknown quantity/likely large
Underground railways	136 km (85 miles) of deep tube tunnels	15 (51.18)	17-28 (63-82)	Moderate temps, medium quantity
Data centers	75 co-location data centers (+ large number of enterprise data centers) in London	86 (293.4)	25-35 (77-95)	Moderate temps, medium quantity
Food manufacture and chemical processing	N/A	11.4 (38.9)	35-70 (95-158)	High temps, medium quantity
Power stations	5-10	945 (3224)	>35 (>95)	High temps, large quantity
Electricity substations	Hundreds	>30 (102.3)	50 (122)	High temps, medium quantity
Building air conditioning (offices and retail)	Throughout London	924 (3153)	28 (82.4)	Moderate temps, large quantity

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

The London Mayor's 2050 Infrastructure Plan involving the supply of a quarter of London's energy from the capital's waste heat resources (London's Zero Carbon Energy Resource: Secondary Heat, 2013) estimates that the total waste heat that could be delivered from secondary sources in London is of the order of 71 TWh/year (2.42 billion therms/year). This is more than the city's total heat demand which was estimated to be 66 TWh/year (2.25 billion therms/year) in 2010. However, some of the heat sources 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.

Subterranean infrastructure systems, such as electricity cable tunnels, sewers (Perez et al, 2016), and subway railway tunnels (Nicholson et al, 2014) are often in close proximity to areas of high heat demand and could potentially provide a year round heat supply. These infrastructure systems can be found in many big cities and urban areas throughout the world. One example which has been investigated is MICAH. The MICAH project is a feasibility study aimed at developing and evaluating a combined cooling and waste heat recovery scheme for extracting and recovering heat from London's underground railway tunnels, for use in a DHN. Details of the MICAH system are provided in the next section.

METROPOLITAN INTEGRATED COOLING AND HEATING (MICAH) SYSTEM

The MICAH (Metropolitan Integrated Cooling and Heating) project was funded by Innovate UK and involved investigating the feasibility of combining cooling of a LU site and integrating it with a waste heat recovery system, with the heat being reused in a DHN.

The main method of supplying cold air or extracting heated air from London's underground railway tunnels, at present, is by means of ventilation shafts, which are widely distributed, being located every few kilometres (miles) along the tunnels. Some of the ventilation shafts operate in air supply mode and some in extract mode, as dictated by tunnel air distribution requirements. For MICAH, it is proposed to install a combined cooling and waste heat recovery system at a ventilation shaft site on the Piccadilly line. The scheme involves the use of a fan coil heat exchanger located close to the head of the shaft. The fan is reversible, enabling its use in either: (a) supply mode, whereby ambient air is drawn through the heat exchanger and cooled, with the chilled air generated being supplied to the underground tunnels via the ventilation shaft; or (b) extract mode, whereby heated air exhausted from the tunnels is directed across the heat exchanger. In both cases the heat extracted from the air is transferred to cold water, flowing through the heat exchanger, raising its temperature. It is proposed that for the initial design, the capacity of the heat recovery fan coil heat exchanger, whether operated in supply or extract mode, will be 900 kW (3.07 MBTU/h).

The heated water exiting the heat exchanger is then transported through a pipework system to a heat pump, where its temperature is upgraded to the level required for reuse i.e. in this case for a DHN. In extract mode, the temperature of the ventilation shaft exhaust air typically varies between 17 and 28°C (63 and 82°F) during the year, while in supply mode i.e. supplying chilled air to the tunnels, the ambient air varies between 4 and 21°C (39 and 70°F) during the year. In fact, since the fan is reversible, the heat exchanger can be operated in either supply or extract mode for different periods of the year. The effects of operating the system in different modes for different periods of the year have been modeled, and the results will be presented later.

Heat will be supplied to the DHN through an energy center acting as a hub for the planned DHN. The energy center will be located at a site adjacent to a public swimming pool in the Caledonian Road area of London. Within the energy center there will be a gas fired combined heat and power (CHP) system, with the capacity to supply the whole DHN, if necessary, as a back-up to the heat supplied by the waste heat recovery system. The CHP system will also be used to top up the heat supplied by the waste heat recovery system ensuring that there is always sufficient heat available to meet the DHN demand. The heat pump used to upgrade the recovered heat may be located at either the energy center i.e. the swimming pool site (designated layout option 1), or at the LU heat recovery site (designated layout option 2). Both options have been evaluated using the model. The direct distance between the LU site and the DHN energy center is approximately 350 m (1,148 feet), however, due to the need to route the pipe work through the roads, the actual distance will be of the order of 420 m (1,378 feet). It is planned to operate the DHN as a low temperature network, with a delivery temperature of 70°C (158°F) and a return temperature of 40°C (104°F). Figure 1 provides an aerial view showing the proximity of the heat source i.e. LU site, to the planned DHN.

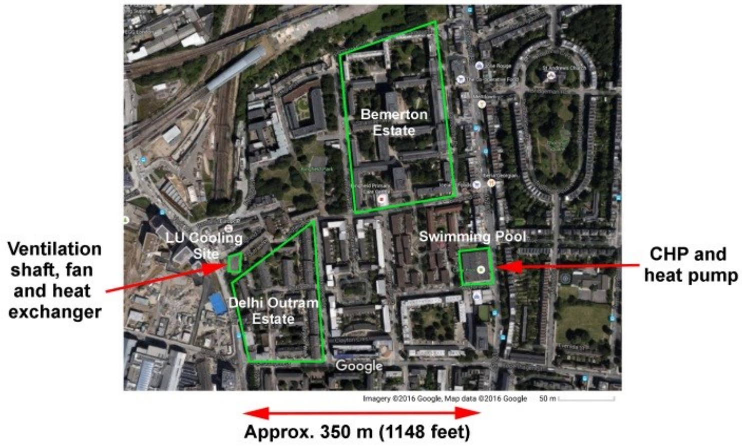


Figure 1 Aerial view showing proximity of heat source to DHN

The proposed DHN comprises the Caledonian Road swimming pool and two nearby social housing estates, all owned and operated by Islington Borough Council (IBC). The gas fired CHP at the DHN energy center (i.e. swimming pool) site will provide both electricity and heat. Some of the electricity generated will be used to supply the heat pump, and the heat will be used to as an additional heat source for the DHN. A schematic of the MICAH system, representing design layout option 1 is shown in Figure 2.

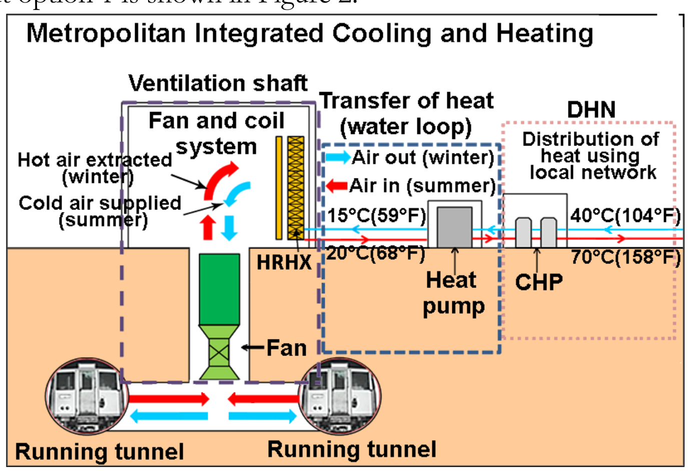


Figure 2 Schematic of MICAH system

In Figure 2, it is seen that the heat exchanger extracts heat from air (whether in extract or supply mode) and transfers the heat to water. The water then recirculates in a loop carrying the heat to the heat pump evaporator heat exchanger, where its temperature is upgraded to 70°C (158°F), as required for delivery to the DHN. The efficiency of the heat pump as measured by its coefficient of performance (CoP) varies with the temperature of the water transported to the heat pump evaporator heat exchanger, which in turn depends on the air on temperature for the (fan coil) heat recovery heat exchanger (HRHX).

The HRHX can be operated in either (i) supply mode, to deliver chilled air to the underground tunnels, when there is a need for cooling e.g. in the summer; or by reversing the fan, (ii) extract mode, where heat is recovered from the hot air exhausted from the tunnels. The system is more likely to be operated in exhaust mode in winter, when cooling may not be needed.

MODELLING OF MICAH SYSTEM

A schematic indicating the four main processes comprising the MICAH system, as simulated in the model, is shown in Figure 3 below.

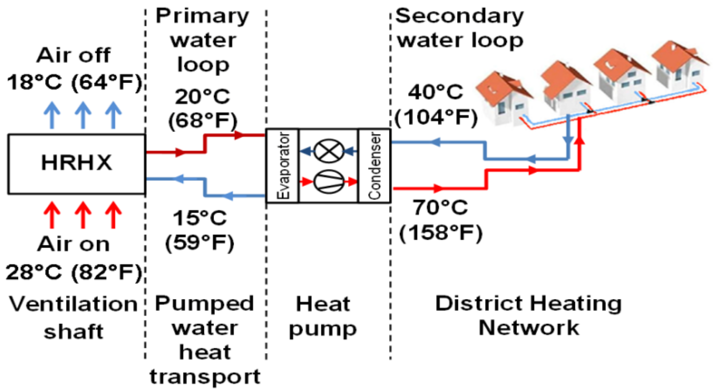


Figure 3 Schematic of MICAH model

The model, which is spreadsheet based, uses the relationships between the different input parameters to calculate the performance of the system for different operating conditions. Full details of the model will be provided in a future journal publication. As indicated previously, two different design layout options were considered: (1) design option 1, where both the CHP and heat pump were located at the DHN energy center; and (2) design option 2, where the CHP was located at the DHN energy center, and the heat pump at the LU (HRHX) site.

Details of the model and assumptions used include: (i) both the tunnel and outside air temperatures were varied within the model using weekly averaged measured temperature values for the LU site; (ii) a fixed quantity of heat was assumed to be recovered from the HRHX, throughout the year, whether operating in extract or supply mode. This was achieved by maintaining the temperature difference between the HRHX air on temperature and the temperatures in the primary water loop, by allowing the water temperatures to fall. This, in turn, required the heat pump evaporator temperature to vary. Since the delivery temperature for the heat pump was fixed at the required delivery temperature of 70°C (158°F), the coefficient of performance (CoP) of the heat pump needed to vary with the evaporator temperature. The CoP for the heat pump was predicted from the evaporator temperature within the model, based on manufacturer supplied data; (iii) The efficiency of the water pumps used to circulate the water in the primary and secondary loops was assumed to be 50% for the current model; (iv) heat losses per unit length through the walls of the pipes used to transport the water from the LU site to the heat pump, and from the heat pump to the DHN, were calculated from temperature differences between the inside and the outside of the pipe and manufacturer data for heat losses through the (insulated) pipe wall; (v) Assumptions relating to the calculation of energy costs and carbon emissions include: (a) cost of electricity £0.098 per kWh ($3.72 per therm)(BEIS, 2017); (b) cost of gas £0.022 per kWh ($0.84 per therm)(BEIS, 2017); (c) Carbon factor for electricity 0.41 kg CO_2e per kWh (26.5 lb CO_2e per therm) (DEFRA, 2016); (d) Carbon factor for gas 0.184 kg CO_2e per kWh (11.89 lb CO_2e per therm) (DEFRA, 2016); (e) Renewable heat incentive (RHI), (UK government) payment for renewable heat delivered by heat pumps £0.025 per kWh ($0.95 per therm)(Ofgem, 2016). It should be noted that RHI is only applicable for heat pumps operating in heating mode i.e. extract mode for the MICAH system. Key design parameters used for the MICAH system model for the selected site, operating in extract mode, are shown in Table 2 below.

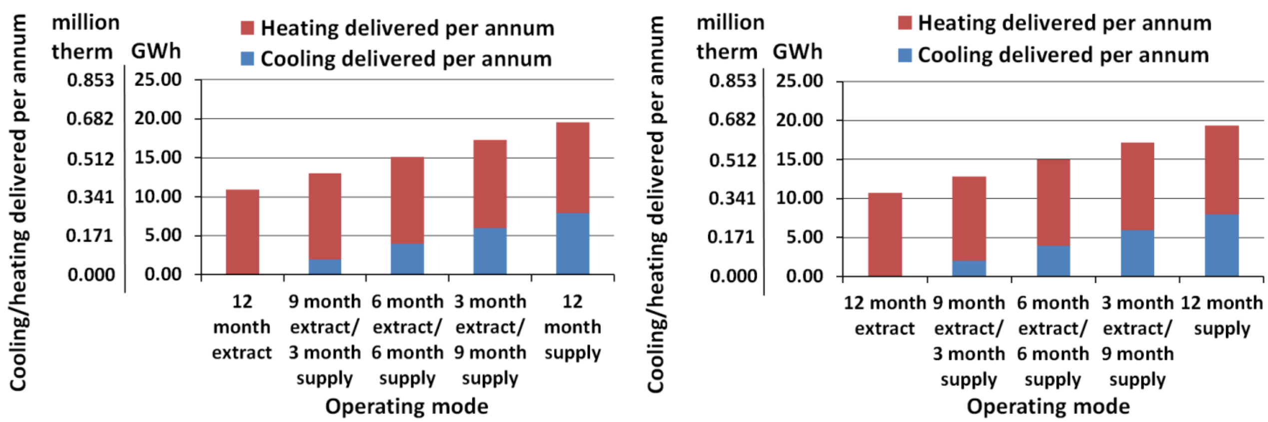
Table 2. Key Design Parameters

Parameter	Value
HRHX air on temperature	17 to 28°C (63 to 82°F)
Typical water temperature flowing into HRHX	15°C (59°F)
Typical water temperature flowing out of HRHX	20°C (68°F)
Cooling capacity (of HRHX)	900 kW (3.07 MBTU/h)
Delivery temperature to DHN	70°C (158°F)
DHN return temperature	40°C (104°F)

In terms of the operational modes used, five different operational scenarios were simulated, with regard to the ventilation shaft air flow direction i.e. either extract or supply mode, over the course of a year. These were: (i) 12 months in extract mode; (ii) 9 months in extract mode and 3 months in supply mode; (iii) 6 months in extract mode and 6 months in supply mode; (iv) 3 months in extract mode and 9 months in supply mode; (v) 12 months in supply mode.

RESULTS FOR THE MICAH MODEL

Some of the results predicted by the MICAH model are presented below. A comparaison of cooling and heating energy benefits for the five different operating mode scenarios, for design layout options 1 and 2 are shown in Figure 4 below.

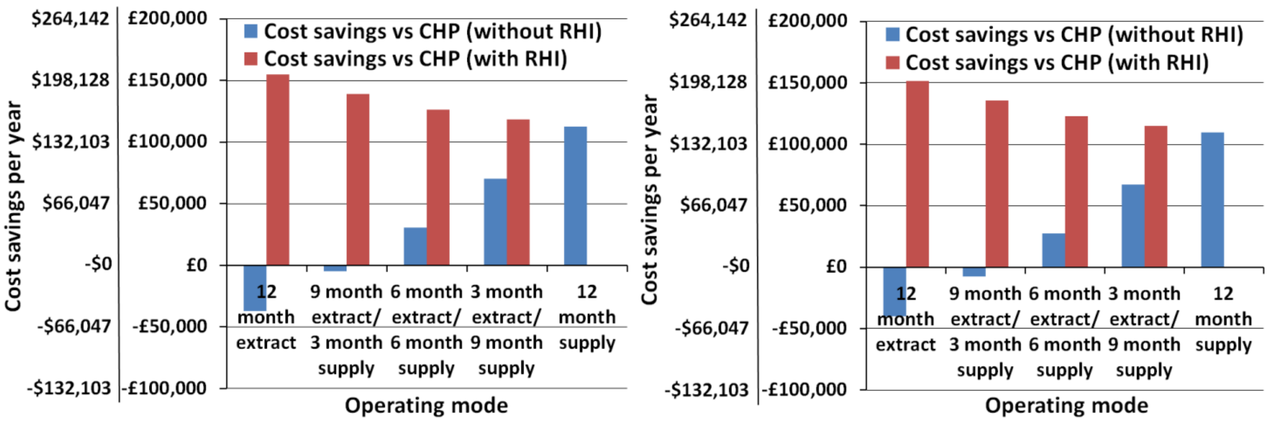


(a) Design layout option 1 (b) Design layout option 2

Figure 4 Cooling and heating benefits for MICAH for different operating modes for layout options 1 and 2

It is seen from Figure 4 that the cooling and heating benefits are similar for layout options 1 and 2, for all five operating modes, although marginally reduced for option 2. The heating benefit i.e. heat delivered to the DHN, is fairly constant throughout the year, although there is a small increase in heat delivered as the proportion of the year operated in 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 needed. The quantity of cooling provided increases steadily with the proportion of the year operated in supply mode, for both options. Due to the high specification wall insulation used for the pipe transporting the water and the relatively small temperature differences across the pipe wall, heat losses were calculated to be low/negligible for both design options 1 and 2.

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 are shown in Figure 5 below. Cost savings are shown both with and without RHI applied.

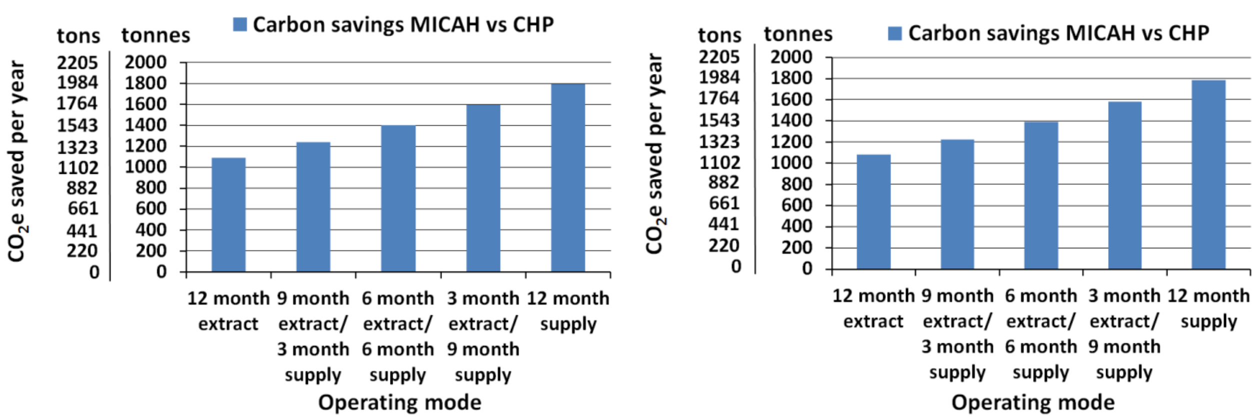


(a) Design layout option 1 (b) Design layout option 2

Figure 5 Cost savings for MICAH compared with conventional cooling and heating

Figure 5 shows that there is only a marginal increase in cost savings for design layout option 1 compared to option 2, for all five operating modes. In terms of the different operating modes, it is seen that with RHI included, the greatest savings are achieved when operating for 12 months in extract mode, however, these savings decrease steadily, as the proportion of the year operated in supply mode increases. In contrast, if RHI is not included, cost savings increase steadily, as the proportion of the year operated in supply mode increases. This reflects the fact that under current rules, RHI can only be applied when operating the system in heating only mode i.e. corresponding to extract mode for the ventilation shaft air flow direction.

The potential carbon savings available for MICAH compared to conventional cooling and heating systems are shown in Figure 6 below.



(a) Design layout option 1 (b) Design layout option 2

Figure 6 Carbon savings for MICAH compared with conventional cooling and heating

Figure 6 shows that the carbon savings for MICAH compared to conventional cooling and heating systems are substantial i.e. ranging from approximately 1100 to 1800 tonnes (1212 to 1984 tons) CO_2e saved per year. The quantity of CO_2e saved increases steadily with the proportion of the year that the system is operated in supply mode. The carbon savings available are similar, although marginally greater for design layout option1, as compared to layout option 2.

OTHER UNDERGROUND INFRASTRUCTURE HEAT SOURCES

In a related project, starting in September 2017, London South Bank University (LSBU) and University College London (UCL) will investigate the potential of heat energy recovery from a range of subterranean structures such as sewers and electricity cable tunnels in London, in the UK. This will be carried out through an innovative research project called LUSTER (London Urban Sub-Terrain Energy Recovery). Within LUSTER, the feasibility of different heat recovery applications will be visualised on geo-spatial heat maps. These heat maps will identify areas in London with the highest potential for carbon, energy and revenue savings. This is expected to lead to many opportunities for LUSTER applications across London and elsewhere. The project will first help to identify how subterranean structures could contribute to the heating needs of London, but also how the utilisation of waste heat from a range of sources could subsequently contribute to sustainable city planning.

CONCLUSIONS

It is seen from the results presented in Figures 4 to 6 that substantial carbon and cost savings are available for MICAH compared to the use of conventional cooling and heating systems. The availability of RHI has a significant effect on cost savings. In general, cost savings increase with the proportion of the year operated in supply mode. However, if RHI is available, the greatest cost savings are achieved, as the proportion of the year operated in extract mode increases. It is next planned to develop a pilot scale trial of the MICAH system described in this paper. In a separate project, it is also planned to investigate waste heat recovery from other underground infrastructures, as outlined above.

ACKNOWLEDGEMENTS

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