Metropolitan Integrated Cooling and Heating

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ABSTRACT

The potential for recovery and reuse of waste heat from cooling London's underground train tunnels as a heat source for district heating systems has been investigated. Cooling of London's underground system is needed to maintain the future underground environment at safe temperature levels. Cooling methods currently being applied across the network include the use of cooling coils in ventilation shafts, air handling units (AHUs) and cooling pipes in tunnels, although the latter method has only been applied on a theoretical basis. These systems use chilled water to cool the air in the tunnels by means of heat exchangers. The chilled water is normally generated using chillers and heat is rejected to atmosphere. District heating networks currently account for only about 2% of total heat used in the UK. However, there are a number of local government managed district heating schemes operating in London, at present. Heat is generally supplied by combined heat and power (CHP) generating plant, but it is planned to expand these schemes and to make use of secondary waste heat sources in the future. The present project, which is funded by Innovate UK, investigates the potential benefits of combining cooling of London's underground train tunnels with the transfer of heat to district heating networks. Instead of using air cooled chillers to cool the water to provide cooling to the air in the underground tunnels, it is planned to use water to water heat pumps to transfer the heat to a district heating network. This should significantly reduce the total energy input required for both the cooling and heating of the respective networks. It has been estimated that there is at least 15 MW of waste heat available from cooling London's underground system. To evaluate the benefits of the proposed approach, an energy, carbon and whole life costing calculator model will be developed to estimate energy, carbon and cost savings for a range of configurations and operating conditions. An inter-seasonal analysis will also be carried out to determine how the benefits vary during the year. Details of the model and the results of preliminary calculations of the potential benefits based on a case study are reported, and the configuration of the planned heat recovery system is presented. The results from the current project will be used to inform the design of a pilot scale trial. This heat recovery approach could be extended to other secondary waste heat sources.

INTRODUCTION

In 2008, the UK government published the Climate Change Act. This legislation introduced UK wide targets to

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achieve an 80% reduction in carbon emissions compared with the 1990 baseline for carbon emissions, by 2050. A minimum interim target of 34% reduction by 2020 has also been set. The Climate Change Act (2008) was created following the global acceptance of two fundamental ideas, namely:

a) Global warming and climate change exist, and can be scientifically proven
b) Global warming is largely attributed to man-made carbon emissions

These ideas have provided the driving force for a number of international agreements set out by the United Nations Framework Convention on Climate Change (UNFCCC), for example the Kyoto Protocol (1998), which set binding targets to cut greenhouse gas emissions. The UK was among many other countries that signed up to the agreement, which entered its first commitment stage in 2008 and led to the development of the UK Climate Change Act.

The building services industry is an important contributor to carbon dioxide equivalent (CO_2e) emissions, being responsible for around 50% of the UK's total emissions, with approximately 33% of emissions attributed to heating and cooling systems. Figure 1 shows the relative contributions of the different processes involved in heat related emissions.

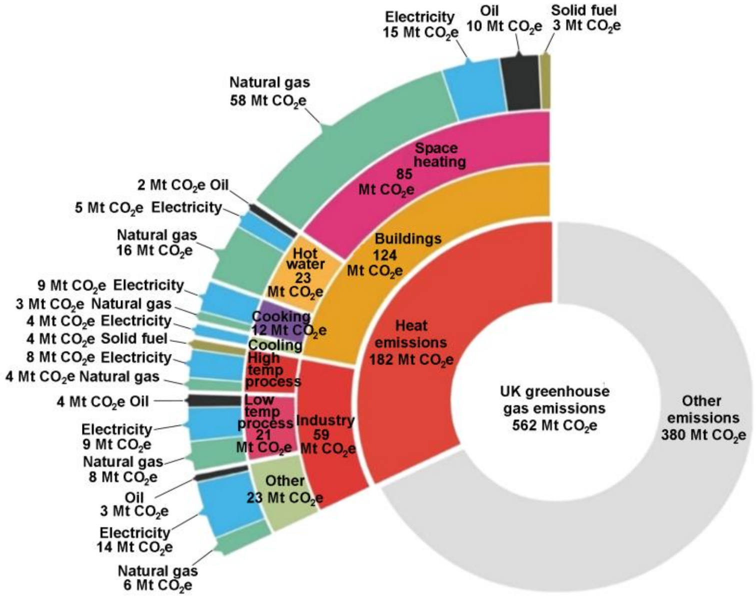


Figure 1 Chart showing contribution of heating to UK greenhouse gas emission (Gebrail, 2014)

From the chart above it is clear to see that a large percentage of greenhouse gas emissions can be attributed to heating in buildings. The UK has been incrementally introducing plans, which place emphasis on design to ensure that systems become more efficient, less carbon intensive and that the generation of waste heat is reduced.

In meeting the emissions targets the UK Government has investigated mitigation, for example through the 2050 Pathways Analysis (DECC, 2010) and the Future of Heating: Meeting the Challenge (DECC, 2013). These promote a range of key areas to focus on, in order to reduce emissions, including:

1. Decarbonising the Grid
2. Industrial Heat
3. Heat Networks and Waste Heat
4. Heat in Buildings
5. Grids and Infrastructure

In delivering on the above, a number of regulations and incentives have been set at UK level, to encourage changes in behaviour. These include the Renewable Heat Incentive (RHI) which incentivises the use of renewable heat with cash rebates linked to the quantity of heat generated (subject to qualification).

In London, there is additional legislation to promote the better use of energy, which 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 energy supply from decentralised or district energy schemes by 2025. One 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. However, in addition, district energy schemes allow waste heat to be captured and utilized.

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 cooling combined with heat recovery for a London Underground (LU) site, and its 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 UK industry waste heat applications have been investigated by Hammond and Norman (2014). They reported that the overall surplus heat that was technically recoverable from UK industrial sites, using a combination of technologies was estimated to be 14.4 TWh/year (491.4 million therm/year), and would save approximately 2.2 Mt CO_2e/year (2.42 million tons CO_2e/year), as compared to supplying the same amount of heat energy in a conventional manner. However, Element Energy (2014) investigated a range of industrial applications for waste heat and identified 48 TWh/year (1.64 billion therm/year) of potential industrial waste heat sources in the UK, i.e. around one sixth of overall industrial energy use.

There are a range of options available for reusing waste heat, as reviewed by Ebrahimi et al (2014), for example: (i) direct reuse for space heating or hot water e.g. by employing a district heating network; (ii) electricity generation using a variety of methods e.g. organic Rankine cycle, although all with low efficiency; (iii) desalination; (iv) absorption cooling. In general, however, the greatest proportion of usable heat recovered can be achieved by direct heat reuse. Typically, for many waste heat sources, temperatures are quite low e.g. 10 to 50°C (50 to 122°F), which may limit the range of reuse applications, although the heat can generally be readily upgraded to higher temperatures, by means of a heat pump, however, this requires the input of additional electrical energy. The current study focuses on recovery of waste heat from a cooling application by first upgrading it i.e. increasing the temperature of the waste heat using a heat pump, and then distributing it to domestic users for space heating and hot water, using a district heating network (DHN).

A range of cooling applications in London, for which the waste heat generated could be potentially recovered have been investigated by Davies et al (2016). A summary of the results of the analysis, indicating options for integrated cooling and waste heat recovery, is shown in Table 1. Many of these waste heat sources, together with others, are likely to be available in most cities around the world. The most useful heat sources and most energy efficient, in terms of heat reuse, are those with the highest temperatures. However, other factors such as year round availability and proximity to locations where the heat can be reused are also important in determining the usefulness of the heat.

In Table 1, where information is unavailable, it has been shown as N/A.

Table 1. Options for Integrated Cooling and Waste Heat Recovery

Type of Heat Source	Specific Application	Individual Cooling Demand (or Waste Heat Output) MW (MBTU/h)	Total Heat Output of Sector MW (MBTU/h)	Seasonal?	Waste Heat Temperature °C (°F)	Useful Source of Waste Heat?
Infrastructure	London Underground	0.6 (2.05)	15 (51.18)	More cooling required in summer	25-30 (77-86)	Low air temperatures; moderate quantity of heat; large number of sources
Infrastructure	UKPN substation	1.63 (5.56)	N/A	Cooling needed all year round	N/A	Moderate temperatures; moderate quantity of heat; small number of sources
Infrastructure	National Grid electrical infrastructure	6.8 (23.20)	40 (136.50)	Cooling needed all year round	55 (131)	Moderate temperatures; moderate quantity of heat; small number of sources
Building air conditioning	Offices	N/A	308 (1,051)	More cooling required in summer	28 (82.4)	Low air temperatures; large quantity of heat; large number of sources
Building air conditioning	Retail	N/A	616 (2,102)	More cooling required in summer	28 (82.4)	Low air temperatures; large quantity of heat; large number of sources
Commercial refrigeration	Supermarkets	0.5-1.0 (1.71-3.41)	32 (109.2)	Cooling needed all year round	32 (89.6)	Low air temperatures; moderate quantity of heat; large number of sources
Commercial refrigeration	Data centers	3.5 (11.94)	86 (293.40)	Cooling needed all year round	25-35 (77-95)	Low air temperatures; moderate quantity of heat; large number of sources
Industrial processes	Food manufacture and chemical processing	N/A	11.4 (38.90)	Cooling needed all year round	35-70 (95-158)	Low-moderate air temperatures; moderate quantity of heat; small number of sources
Power generation	Power stations	N/A	945 (3,224)	Cooling needed all year round	> 35 (> 95)	Moderate temperatures; large quantity of heat; small number of sources
Power generation	CHP	0.7 (2.39)	10.3 (35.14)	More heat rejected in winter	45 (113)	Moderate temperatures; moderate quantity of heat; small number of sources

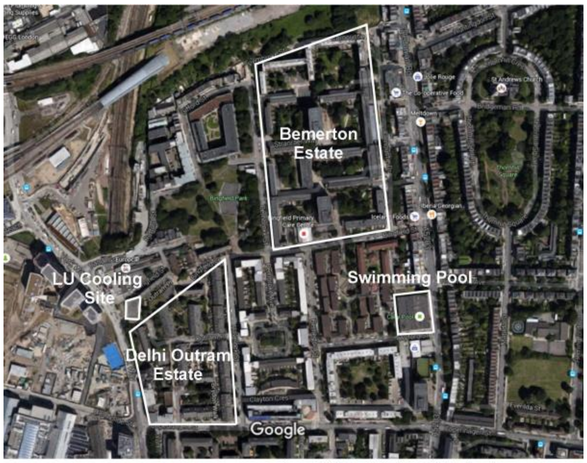
One large cooling application and waste heat recovery source shown in Table 1 is the London Underground (LU) railway system; the main sources of heat being the trains and passengers. The LU potential heat sources are widely distributed across London and are at a higher temperature than the surrounding ambient air, for most of the year. If the cooling system used at each LU site could be combined with a waste heat recovery system, and the heat reused, the overall efficiency compared to separate cooling and heating systems would be increased. This would provide significant energy, carbon and cost savings.

METROPOLITAN INTEGRATED COOLING AND HEATING

The current project, MICAH (Metropolitan Integrated Cooling and Heating) is an Innovate UK funded feasibility study investigating combining cooling of a LU site and integrating it with a waste heat recovery system enabling the heat to be reused in a DHN.

An earlier scheme, which is currently in construction, involves utilizing heat from air extracted from the Underground via a ventilation shaft. This system is installed at City Road, a disused LU station on the Northern underground line, in London. The temperature of the ventilation shaft exhaust air varies between 17 and 28°C (63 and 82°F), and the heat recovered from the exhaust air is transferred to the DHN using a heat pump to supply heat at 80°C (176°F), to provide heat for 500 homes in the surrounding Bunhill housing estate. The system capacity for the heat provided from the mid tunnel ventilation shaft exhaust air is 380 kW (1.297 MBTU/h), and supplements an existing combined heat and power (CHP) system. The operating temperatures for the DHN are 75°C (167°F) flow and 55°C (131°F) return.

For the current project, a cooling and waste heat recovery system is proposed to be installed at a ventilation site on the Piccadilly line. It is planned to provide 900 kW (3.07 MBTU/h) of cooling, with a corresponding amount of extracted waste heat being recovered and transported over distances of up to 350 m (1,148 feet) to a DHN. The DHN will then distribute the heat to a number of nearby social housing estates and a public swimming pool in the Caledonian Road area of London, which are owned and operated by Islington Borough Council. The heat will be transported using water pipes which will need to be routed through the roads between the LU site and the DHN. An aerial view of the area showing the location of the heat source (the LU site) in relation to the DHN heat recipients is shown in Figure 2 below.



Imagery ©2016 Google, Map data ©2016 Google 50 m

Figure 2 Aerial view showing proximity of heat source and heat users

The social housing estates consist of blocks of apartments, which are currently heated via a central gas fired boiler for each block. The DHN will therefore connect to the central heated water supply for each block, with the heat distributed to the individual apartments through the existing system. The current central gas boilers will be retained to add resilience to the heat supply, and to supplement the DHN heat, if required e.g. during particularly cold periods. The DHN will also incorporate a gas fired CHP system (providing both electricity and heat), as an additional heat source for the DHN, which can be varied depending on the availability of waste heat from the LU site. This will enable the DHN to maintain its designated heat supply temperature. It is planned to operate the DHN as a low temperature network, with a flow temperature of 70°C (158°F) and a return temperature of 40°C (104°F). This low operating temperature will enable the waste heat from the LU site, which is expected to be in the range 20 to 28°C (68 to 82°F) for most of the year, to be readily upgraded, using a heat pump, to the required DHN flow temperature.

There are a number of options for providing cooling, together with waste heat recovery from the tunnel air, across the LU network. These include: (i) the use of a fan coil heat exchanger in a ventilation shaft; (ii) the use of air handling units (AHUs), which involves the installation of heat exchangers located above underground station platforms, which are supplied with chilled water to provide cooling; (iii) the use of pipes running along the inside of the tunnel walls, through which cold water is pumped to supply cooling. It should be noted that the concept of cooling pipes on the LU network has yet to be proved, however the technology has been used in the Channel Tunnel [Fairbairn, 1995].

For the present study, a fan coil heat exchanger located at the head of a ventilation shaft only will be considered, to provide the cooling and waste heat recovery required. A schematic of the overall MICAH system involving simultaneous cooling and heat recovery (to a DHN) is shown in Figure 3.

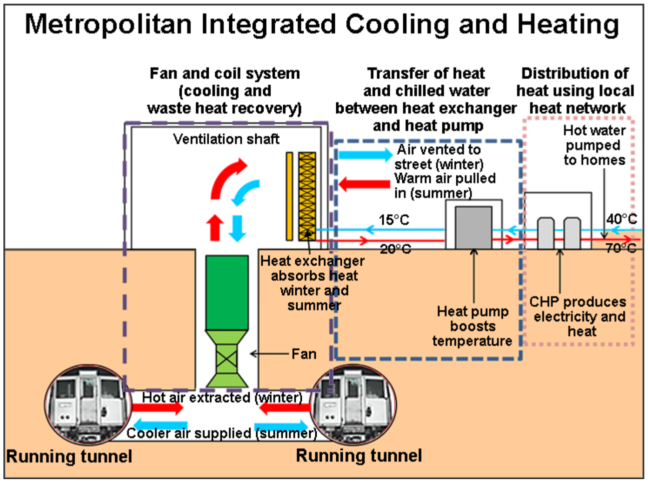
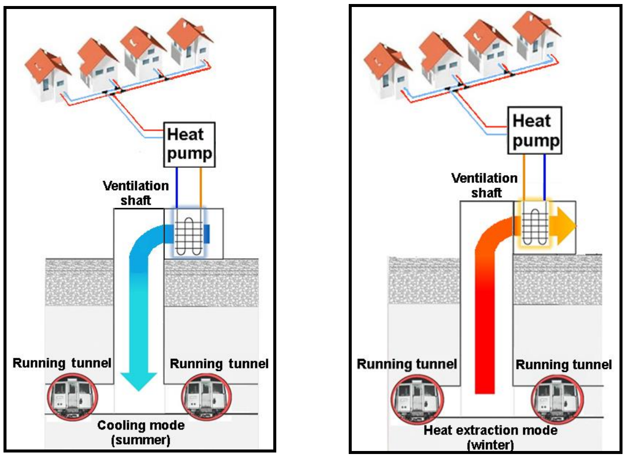


Figure 3 Schematic of MICAH system

It is seen from Figure 3 above, that the heated water extracted from the heat exchanger at the head of the ventilation shaft and transported to the heat pump is at approximately 20°C (68°F). In fact, the temperatures will vary depending on both the external ambient temperature and the tunnel air temperature. Water is returned to the ventilation shaft heat exchanger from the heat pump at a temperature of approximately 15°C (59°F). The heat pump is located at the DHN end of the heated water transport system, to minimize the potential for heat losses from the pipes, which would be expected at the higher temperatures found after upgrade by the heat pump.

The need for cooling at the LU site may vary during the year and may not be needed at all during the winter months. Therefore, the waste heat generated as a result of cooling will also vary, and no heat may be produced from cooling in the winter months, when the demand from the DHN is maximal. One method of providing heat in winter, however, is to reverse the fan in the ventilation shaft during this period, converting it to a heat extract system only. Heat can then be provided to the heat pump and DHN throughout the year. Figure 4 below shows the two operational modes i.e. winter and summer, for an LU ventilation shaft site heat recovery system.



(a) Summer mode (b) Winter mode

Figure 4 Comparison of heat recovery operational modes for MICAH system

Conversely, the greatest cooling requirement for the LU site, and hence maximum waste heat recovery potential is in the summer months, when heating demand for the social housing apartments supplied by the DHN is minimal. However, there will still be a base load heat requirement for domestic hot water in summer, and the inclusion of the swimming pool in the DHN loop, should provide a significant heat demand from the DHN, even in summer.

In fact, it is planned to investigate the effects of operation in cooling (i.e. summer) mode for a range of different periods e.g. 6 months, 9 months and all year cooling.

DEVELOPMENT OF MODEL FOR MICAH SYSTEM

To analyse and evaluate the effectiveness and potential performance for the proposed MICAH combined cooling and heating system, a model is being developed. The model is spreadsheet based and incorporates the key design details for the system. For example, it includes: (i) details of the ventilation shaft fan coil air/water heat exchanger cooling and waste heat recovery system e.g. expected ventilation shaft air flow rates and temperatures, and the heat exchanger surface area and heat transfer coefficient. The water flow rates and maximum water output temperatures for the recovered heat will be estimated by the model; (ii) details of the recovered heat water transport system e.g. distance, route i.e. number of bends and junctions needed. The model will estimate the size/diameter of the pipe needed and flow rates and pressure drops and pumping power required to provide the maximum heat transfer to the heat pump; (iii) details of the heat pump used to upgrade the recovered heat from e.g. 20°C (68°F) to 70°C (158°F) e.g. size of heat pump i.e. capacity and size of heat exchangers, overall dimensions, pressure ratio, COP expected, and refrigerant used. The model will estimate the input power needed.

The model will calculate both capital expenditure (CAPEX) and operating expenditure (OPEX) costs for operating the MICAH system in both summer and winter modes, for a range of different periods of the year, and this will be compared with the estimated costs of operating separate systems for conventional cooling e.g. using a chiller and chilled water system, and heating of the social housing compartments supplied by the DHN by conventional gas fired boilers. The potential energy carbon and cost savings for operating the MICAH system will be calculated.

Table 2 below shows the results of preliminary calculations for the potential savings available. This is based upon the following assumptions: (i) ammonia used as the refrigerant for the heat pump or vapor compression refrigeration cooling system; (ii) heat generation efficiency for combined heat and power (CHP) system of 75%; (iii) electricity cost of £0.12 per kWh ($4.57 per therm) and gas cost £0.04 per kWh ($1.52 per therm); (iv) renewable heat incentive (RHI) payment (for use of waste heat) of £0.025 per kWh ($0.95 per therm); (v) electricity carbon factor 0.5 kg CO_2e per kWh (33.3 lb CO_2e per therm) and gas carbon factor 0.18 kg CO_2e per kWh (11.63 lb CO_2e per therm).

Table 2. Comparison of Energy, Carbon and Cost Savings for MICAH Compared with Conventional Cooling and Heating

Parameter	MICAH		Conventional Cooling and Heating		
	Cooling	**Heating**	**Cooling**	**Heating (CHP system)**	**Total**
Temperature °C (°F)	5 (41)(evap)	70 (158)(cond)	5 (41)(evap) 35 (95)(cond)	>70 (>158)	-
Energy output kWh (therm)	68.7 (2.34)	100 (3.41)	68.7 (2.34)	100 (3.41)	-
COP	2.19	3.19	5.45	0.75	-
Input energy kWh (therm)	31.3 (1.07)		12.6 (0.43)	133.3 (4.55)	145.9 (4.98)
Cost of energy £ ($)	3.76 (4.89)		1.51 (1.96)	5.33 (6.93)	6.84 (8.89)
RHI £ ($)	2.50 (3.25)		-	-	-
Total cost £ ($)	1.26 (1.64)		1.51 (1.96)	5.33 (6.93)	6.84 (8.89)
Carbon emissions kg CO2e (lb CO_2e)	15.65 (34.50)		6.30 (13.89)	24.0 (52.91)	30.29 (66.78)

The results show that to generate 100 kWh (3.41 therm) of heat and 68.7 kWh (2.34 therm) of cooling, MICAH provides almost 114 kWh (3.89 therm) (79%) of combined heating and cooling input energy saving, £5.58 ($7.25)

(82%) cost savings and 14.64 kg (32.28 lb) (48%) carbon emissions savings.

CONCLUSIONS

It is seen that there is considerable potential for energy, carbon and cost savings by application of the MICAH approach. A full analysis to show energy and carbon savings and a comparison of the CAPEX and OPEX costs compared to the use of separate conventional cooling and heating systems will be provided by the model being developed. As well as providing a detailed evaluation of the specific LU site being considered, the model will permit evaluation of the potential benefits and savings available from applying similar combined cooling and heat recovery systems across the LU network. The results from the current study will provide supporting evidence for a proposal to develop a pilot scale cooling and waste heat recovery system at the selected site.

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