Assessing the Performance of District Heating Networks Utilising Waste Heat: A Review

Henrique Lagoeiro Akos Revesz, PhD Gareth Davies, PhD

Daniel Curry Gareth Faulks Michal Murawa

Graeme Maidment, PhD, PE

ABSTRACT

In order to combat climate change, many countries have been focusing their efforts on how to accelerate the transition towards a clean energy future, expanding access to energy across the world whilst significantly reducing the global carbon footprint. In the UK, as heating and cooling account for nearly half of the energy consumption and a third of carbon emissions, district heating and cooling networks represent a key technology for facilitating a smooth transition from current fossil fuel based energy to future low-carbon energy sources. A key contributor to these low carbon energy sources has been identified as the use of waste heat sources in urban environments, which can help to tackle both climate change and fuel poverty within cities. Despite their known advantages and wide application in many countries, heat networks currently supply only a small fraction of demand (~2% of heating needs) in the UK. This paper reviews how a new generation of district heating networks utilising waste heat can deliver massive carbon savings and are key to meeting future targets. In order to guarantee an efficient operation of the heat network, the installation of integrated control and monitoring systems is essential, as they allow measuring and adjusting key parameters, such as temperatures, pressures and flow rates, assuring that the system achieves optimum performance and stays within safe operating limits. This paper focuses on understanding how the performance of waste heat based district networks can be assessed by exploring best practices identified in the literature relating to control and monitoring of heat networks. Based on the review, the paper also provides recommendations for the best approach for monitoring the performance of a recently developed waste heat recovery system in Islington, London, involving the capture of waste heat from the London Underground, which is then upgraded and used to supply a local district heating network.

INTRODUCTION

The climate emergency is one of the greatest challenges ever faced by mankind. Since the Industrial Revolution, the economic development of the world has been based on the use of fossil fuels to meet global energy demand. With the growing climate threat, many governments have worked to accelerate the uptake of clean or low carbon energy sources, particularly for the generation of electricity. For instance, the United Kingdom (UK) has managed to achieve a significant reduction of Greenhouse Gas (GHG) emissions in recent years, cutting them by 43% since 1990 (CCC, 2019). These results can mainly be attributed to the power sector, which has seen a considerable reduction in the use of coal as an energy source and an increase in the use of renewable sources. As a matter of fact, in the year of 2017, 27.9% of the electricity generated in the UK came from renewables, whilst renewable heat and transport only represented, respectively, 7.7% and 4.6% of the national demand (BEIS 2018a). If the UK is to honour its recent pledge to reach net zero carbon emissions by 2050, much greater efforts will be required, especially from the heating sector, which is responsible for nearly half the energy consumption and around one third of carbon emissions in the UK (BEIS 2018b).

Sustainable heating is also a problem for London, where nearly 90% of the heating sources used to warm buildings are gas-fired boilers, posing a threat not only in climate terms but also due to air pollution. London’s homes produce one third of the capital’s total GHG emissions and nearly 75% of the energy consumed by homes is used to provide space and hot water heating. Meanwhile, workplaces account for approximately 40% of the city’s emissions, with half of their energy demand being related to heating (GLA 2018). It is clear that, if London and the UK want to decarbonise their energy systems, heat generation all over the country must be shifted towards a wide deployment of efficient and low carbon heating sources.

Waste heat recovery systems represent a unique opportunity to make use of the surplus heat that is wasted in a variety of urban infrastructures, which could be widely exploited in London and other cities across the UK and globally. These systems unlock the potential to generate and distribute energy locally through heat networks, which increase the efficiency of the overall energy system, helping to reduce the carbon footprint associated with heating whilst also tackling fuel poverty. In the UK, heat networks supply only around 2% of the overall heating demand (ADE 2018), whilst in London, 6% of the energy demand is supplied via district systems (GLA 2018). The Committee on Climate Change (2019) recognises that waste heat based district heating will play an important role in decarbonising the heating of buildings in the UK, being an essential technology in reaching the net-zero GHG emission target by 2050, whilst the London Environment Strategy (2018) has already set a target of increasing the energy supply from district schemes and renewable sources to 15% by 2030. As the deployment of waste heat recovery schemes is expected to grow in the future, this study analyses how these new low carbon heat sources can be introduced into district energy systems, helping to identify how their performance can be monitored to guarantee an efficient, safe and reliable operation.

Performance ANalysis

The performance of waste heat recovery systems and district energy networks depend on a wide variety of aspects and can be approached in different ways. According to BEIS (2018c), when optimising the performance of district heating, the objectives of such optimisation might be related, amongst others, to economic, social, environmental and technological benefits. From a technical point of view, the incorporation of waste heat sources into future district energy systems poses a great challenge for district energy operators, as waste heat must be able to effectively replace traditional heat sources without compromising the reliability, safety and cost-efectiveness of the heat supply. As in any energy system, the purpose of monitoring and controlling operating parameters for waste heat recovery schemes and district heating networks (DHNs) relates to increasing their overall energy efficiency. This means setting out control strategies that are able to deliver the required amount of heat whilst consuming the lowest energy possible, leading to clear financial and environmental benefits. This paper focuses on analysing the key operating parameters that need to be monitored in order to guarantee a smooth integration between a heat pump utilising waste heat from the London Underground and a DHN in the London Borough of Islington.

Heat Networks

The Heat Networks Code of Practice for the UK (CIBSE/ADE 2015) aims to guarantee that district heating remains a cost-competitive supply of heat compared to conventional heating methods, maintaining a high level of reliability and customer satisfaction, while reducing carbon emissions and energy consumption. In order to achieve this, the Code suggests how to improve the quality of the whole network by covering all components of a district heating scheme, including heat generation plants, the heat distribution network, and substations that connect the main network to end users. One essential aspect highlighted by the Code of Practice that can optimise the performance of heat networks is the use of data. The Heat Networks (Metering and Billing) Regulations 2014 state that all buildings connected to heat networks must incorporate heat meters by default. Introducing additional meters at different points of the network, such as temperature and pressure sensors and flow meters, can optimise the management of a DHN by providing detailed information regarding its operation. The data gathered by these meters can help monitoring peak demands, heat losses and operating temperatures, making it much easier to analyse the efficiency of a heat network and identify potential improvements that could be made.

Energy efficiency can be obtained mainly by reducing heat distribution losses and lowering the energy inputs to the system. Many authors have reported how heat distribution losses can be lowered. Jangsten et al. (2011) modelled how different heat densities can affect the distribution losses of a DHN and reported how smaller pipe configurations and lower operating temperatures can lead to higher efficiency. However, it is important to highlight that lower operating temperatures require higher flow rates to deliver the same amount of heat, so the savings associated with reducing distribution temperatures might be offset by increased power consumption for pumping. Vesterlund et al. (2017) modelled a multi-source district heating network to investigate how operating costs related to heat generation and delivery could be minimised. The authors analysed a Swedish case study and showed that generation plants with higher efficiencies and lower fuel consumption, which consisted of biomass boilers and industrial waste heat, led to greater cost savings when compared to oil and electric boilers. Another interesting finding was that lower operating temperatures, which can be obtained with waste heat sources, reduced the overall operational costs of the network, even though the pumping costs were increased. Flexibility in thermal networks can also help to achieve lower operating temperatures by reducing peak demands, either through the use of thermal storage devices or by exploiting the thermal inertia of the distribution network or the buildings connected to it (Vandermeulen et al. 2018). This can be especially beneficial for waste heat recovery systems, as heat pumps can convert excess renewable electricity into thermal energy, helping to balance the intermittent renewable power supply and alleviating the pressure on the grid.

Over the years, district heating has evolved significantly towards lower operating temperatures, higher energy efficiency and lower use of fossil fuels to produce heat. Lund et al. (2014) showed how the 4th Generation of District Heating (4GDH) is defined by low temperature networks based on flexibility and the use of renewable and waste heat sources, being linked to electrical grids to form smart energy systems. Buffa et al. (2019) showed how cooling is also an important part of the future of energy, introducing the 5th Generation District Heating and Cooling (5GDHC), which involves not only smart coupling of sectors, but also the provision of both heating and cooling through the same network, operating at very low temperatures with negligible thermal losses and high energy efficiencies. Both 4GDH and 5GDHC will play a key role in future energy systems, which will increasingly involve the use of waste heat as one of the main sources of energy, shifting the heating sector towards decarbonisation, smart coupling and energy savings.

Waste Heat Sources

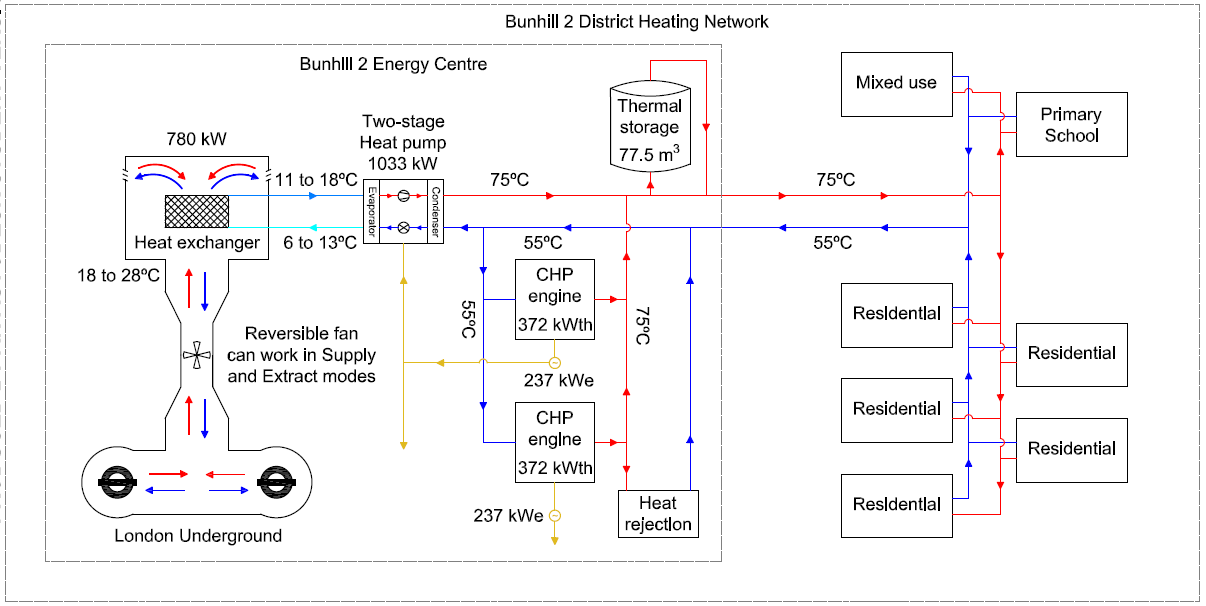
The integration of waste heat sources into district energy systems provides a wide range of possibilities as heat can be recovered from any heat source of sufficient temperature. Urban environments are particularly interesting for waste heat exploitation, as there are many opportunities for recovering and reusing surplus heat generated in cities. Potential urban waste heat sources include data centres, electrical systems, industrial plants, sewage systems, supermarkets and railway tunnels, amongst others. Due to its typical low grade, urban waste heat can be well integrated into district heating, either directly or after being upgraded by a heat pump, which will depend on the temperatures of both the source and the network. The design of a waste heat recovery system typically involves a heat recovery heat exchanger, which recovers heat from either air or a liquid, and a heat pump in case the heat needs to be upgraded. For that reason, the performance of waste heat recovery systems is related mainly to the energy efficiency of these two components. Many authors have reported the benefits of heat pumps in enhancing energy efficiency, being able to minimise costs and environmental impacts of heating systems, which include district energy schemes. These advantages can be even greater when utilising waste heat, as more constant source temperatures can improve the coefficient of performance (COP) of heat pumps when compared to conventional air-source systems (Chua et al. 2010).

Underground railway tunnels represent a particularly interesting waste heat source for cities like London, where public transportation heavily relies on metro systems. The potential of exploiting the London Underground’s waste heat was investigated by Gilbey et al. (2011), who showed that average platform temperatures can be as high as 20°C (86°F) on a cold winter’s day and reach up to 32°C (90°F) during summer. Duffy (2018) reported that nearly 500 GWh (17 million therms) of heat per annum is produced in the Underground tunnels and stations. This heat could be efficiently recovered and utilised by a heat pump, delivering low carbon heat while providing cooling to the tunnels, which is also beneficial. As the technology to recover waste heat from underground railways is still very incipient, being closely linked to the recent 4th and 5th generations of district heating, which reflect efforts to increase energy efficiency of heating systems and reduce their carbon footprints, there is still a lot to be explored on this topic. The heat distribution through district heating networks, on the other hand, is a very well established technology, being widely reported in current literature. For that reason, this paper focuses on understanding how waste heat can be effectively recovered from underground railway tunnels by proposing a metering strategy to help monitoring the performance of the system, serving as an important learning experience for future similar developments in the UK and abroad.

The BUNHILL WASTE HEAT RECOVERY SYSTEM

The Bunhill Waste Heat Recovery System is the extension of an existing heat network, Bunhill 1, located in the London Borough of Islington, being often referred to as Bunhill 2. The system is based on the installation of an air-to-water heat exchanger within a ventilation shaft of the Northern Line of the London Underground network. The heat captured is distributed to a two-stage water-to-water R717 (ammonia) heat pump, which upgrades it to a suitable temperature for distribution to local buildings through a heat network. The Energy Centre of Bunhill 2 consists of the waste heat recovery heat pump, two combined heat and power (CHP) units, as well as a thermal storage tank. The heat pump has an average capacity of 1,033 kWth (3.52 MMBTU/hr), with 780 kW (2.66 MMBTU/hr) of that heat being recovered from the ventilation shaft. The two CHP units, each with an output of 237kWe (318 hp)/372kWth (1.27 MMBTU/hr), add resilience and flexibility to the system, although its output heat could be rejected through dry air coolers if not needed. A thermal store of 77.5 m3 (27,368.87 ft3) will also be installed in order to add flexibility, helping to manage peak demands. The network operates with return and flow temperatures of 55°C (131°F) and 75°C (167°F), respectively. The system is expected to provide heating to 455 dwellings in 5 building blocks of a local housing estate, a primary school and a mixed use building, being able to incorporate other buildings in the future.

The heat exchanger used for this waste heat recovery system is a fan coil unit. The ventilation shaft had to be upgraded to accommodate both the coils and the variable speed reversible fan that enables the system to work in both Extract and Supply modes. The benefits of operation in these two different modes have been previously investigated by Davies et al. (2017) and consist of reversing the flow direction of the fan, allowing the system to operate by either extracting hot air from the Underground, which can then be used to warm the water in the coils, or using ambient air, which would be cooled by the coils and then supplied to the Underground, with the heat extracted being recovered by the heat exchanger. Extract mode would be used during the colder months of the year, when the heat demand is at its peak and the underground air is warmer. Supply mode would be used to supply cooling to the Underground during the summer, when ambient temperatures are higher. Figure 1 shows a schematic of the Bunhill Waste Heat Recovery system.



**Figure 1** Schematic of the Bunhill Waste Heat Recovery System.

The Bunhill Waste Heat Recovery System is a pilot project that can pave the way for London to become a truly smart city in terms of energy, unlocking the potential of urban waste heat and district heating as turning points for the heating sector in the UK. The advantages of the system have been investigated by Lagoeiro et al. (2019), who analysed the benefits of meeting all the heat demand of Bunhill 2 using only the waste heat based heat pump as a source for the DHN. This scenario was compared to a reference case where each building would have its own communal gas boiler instead of being connected to the heat network. The results indicated that the waste heat recovery system could potentially deliver carbon savings of 82% and cost savings of 14% when compared to conventional gas-fired heating. After simulating the potential benefits of the system, the next steps of the research involve planning how to evaluate its performance, which will start with the metering strategy proposed in this paper.

Monitoring system

In order to investigate the performance of Bunhill 2, it is important to have high quality data available, which should reflect accurately and consistently the operation of the system in an appropriate timescale. This can only be achieved by deploying a reliable monitoring system, and this paper identifies the critical parameters that need to be measured, as well as sets out a metering strategy, involving the type of meters that should be installed and where they should be placed within the system. As this paper focuses on waste heat recovery, the other heat sources that comprise the Energy Centre, namely the CHP units and the thermal storage, will not be analysed in detail. The performance of the waste heat recovery system will be investigated from two main perspectives, heating and cooling. This will allow evaluating the system’s efficiency as a heat source for district heating, as well as calculating the amount of cooling that is delivered to the Underground tunnels when the system operates in Supply Mode. These perspectives are reflected on the following aims and objectives:

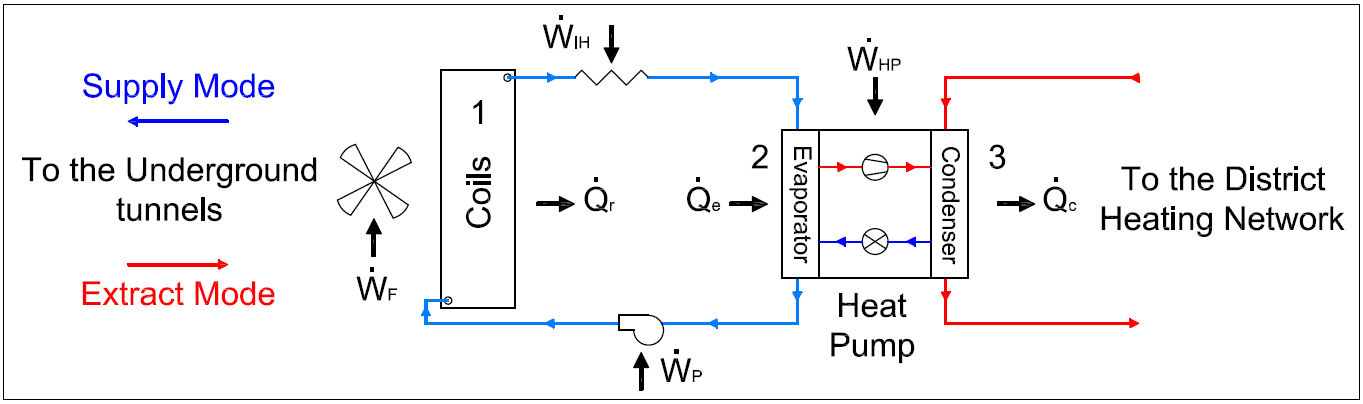
**Aims.**

1. To investigate how efficiently the waste heat recovery system generates heat;
2. To evaluate the cooling benefit to the London Underground when the system operates in Supply mode.

**Objectives.**

1. To identify key operating parameters that must be monitored so as to assess performance;
2. To investigate what meters/sensors would be required in order to measure the operating parameters;
3. To define the best location within the system for the meters/sensors to be installed.

Figure 2 shows the waste heat recovery system, highlighting the key points (1, 2 and 3) where a heat transfer process occurs, namely the air to water heat exchanger coils (1) and the evaporator (2) and condenser (3) of the heat pump, as well as all the energy inputs to the system. The energy balance at these points of the system will enable the identification of the key parameters that should be monitored, as well as the best location for meters to be placed.



**Figure 2** Schematic highlighting energy inputs and outputs associated with the waste heat recovery system.

Heating

The performance of a heat source is reflected by its energy efficiency, which is a function of both the energy entering the source, such as the electricity being used by system components, and the energy leaving it, which corresponds to the heat that is being produced. The energy inputs to the system consist of the power input to the heat pump (HP), the power input to the water pump (P) used to circulate water through the coils and back to the heat pump’s evaporator, the power consumption of the reversible fan (F) within the ventilation shaft, and the power consumed to heat up the electric immersion heater (IH), used to provide protection against frost accumulating on the coils. The useful energy output is equivalent to the heat that is generated at the heat pump’s condenser (c). Based on these values, the overall energy efficiency of the waste heat source (η) can be calculated as in Equation 1.

(1)

The heat output of the waste heat recovery system (c), can be calculated using the energy balance at the condenser of the heat pump (point 3 in Figure 2). As the kinetic and potential energy terms are negligible compared to the heat transfer, the energy balance will involve only the heat being supplied by the R717 refrigerant () and the heat being absorbed on the water side of the condenser () (Tran et al. 2012), as shown by Equation 2. As the condenser operates in steady conditions (constant mass flow for both refrigerant and water streams), as in any heat exchanger, the change in total energy of the control volume is zero ( = 0).

(2)

For that reason, the heat being rejected by the refrigerant is equal to the heat being absorbed by the water going through the condenser (. Therefore, the rate of heat being generated by the heat pump (c) can be calculated either on the refrigerant or on the water side. Equation 3 shows the heat output calculation on the refrigerant stream, which is based on the mass flow rate of the refrigerant () and its change in enthalpy between the inlet () and outlet () of the condenser. The heat transfer rate calculation on the water side is provided in Equation 4. In this case, as the fluid does not undergo a phase change, it is possible to calculate the heat transfer rate as a function of the water mass flow rate (), the specific heat capacity of water at constant pressure () and the inlet () and outlet () temperatures of the condenser (Incropera et al. 2002). It is also common for flow meters to calculate the heat transfer rate as a function of the volume flow rate () and the water density (), which is also shown in Equation 4.

(3)

(4)

Cooling

The analysis of the amount of cooling being provided to the Underground relates to the heat recovery heat exchanger. The relation established by Equation 2 also applies in this case, so the cooling delivered to the air stream, i.e. the heat extracted from the air, is equivalent to the heat recovered by the water side of the heat exchanger (). Ideally, the heat being recovered at the coils () should be equal to the heat provided to the heat pump’s evaporator (). As there might be some heat losses in the water loop that delivers the recovered heat to the heat pump, the analysis of the cooling benefit will consider only the energy balance at the heat exchanger (point 1 in Figure 2). At point 1, the cooling being delivered can be calculated either on the air side or on the water side. On the water side, Equation 4 can be used to calculate the heat transfer rate. For the air stream, as there is a risk of condensation forming on the coils, the calculation of the heat transfer rate of the heat exchanger () must be based on the mass flow rate of the air () and its enthalpy difference at the inlet () and outlet () of the coils, as shown in Equation 5 (Naphon & Wongwises 2005). In this case, the enthalpy of air has to be based on its specific humidity (), the specific heat of air at constant pressure (), the air temperature () and the enthalpy of saturated water vapour (), as shown in Equation 6.

(5)

(6)

Measurements

In order to calculate the energy efficiency of the waste heat source, as shown in Equation 1, many operating parameters of the system need to be monitored, which means sensors and meters need to be placed at different locations within the system. In terms of power input to the system (), The ASHRAE Handbook – Fundamentals (2017) suggests that Wattmeters should be used to measure the active power of a given circuit, which can then be used to calculate the electricity consumption of the machinery connected to that circuit. An electrical energy meter using a current transformer (CT) will be applied to measure the power input to each of the aforementioned equipment, as they enable multiple measurements to be made and can also record energy consumption over time. The device is able to measure currents, voltages, power and energy consumption of three-phase electrical circuits with an accuracy of 0.5%.

As for the heating and cooling aspects of the waste heat recovery systems, critical parameters can be monitored by placing meters in different locations within the system. Table 1 summarises what are these parameters, the medium in which they will be measured and their related units of measurement. The list of instruments that could be used for monitoring and their typical uncertainty values are also provided.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Table 1. Critical parameters and instruments for performance evaluation of the Bunhill Waste Heat Recovery System (Tran et al. 2012)1 (ASHRAE 2017)2. | | | | | |
| Evaluation | Medium | Parameter | Unit | Instruments (quantity) | Typical Uncertainty |
| Heating | Refrigerant | Pressure | kPa (psi) | Pressure gauges (2) | 0.25%1 |
| Temperature | °C (°F) | Platinum RTD (2) | 0.12 to 0.8 K1 |
| Flow rate | kg/s (lb/s) | Coriolis/ultrasonic (1) | 0.2%1 |
| Density | kg/m3 (lb/ft3) | Coriolis/ultrasonic (1) | 0.2%1 |
| Heating/Cooling | Water | Flow rate | m3/s (ft3/s) | Ultrasonic (1H,1C) | 1.2%1 |
| Temperature | °C (°F) | Platinum RTD (2H,2C) | 0.051 to 0.1 K2 |
|  |  | Relative humidity | % | Hygrometer (2) | 0.2 to 7% RH2 |
| Cooling | Air | Flow rate | m3/s (ft3/s) | Anemometer (1) | 2 to 10%2 |
|  |  | Temperature | °C (°F) | Thermistor/Pt RTD (2) | 0.1 K1,2 |

As shown by Equations 3 and 4, the heat being delivered by the heat pump () can be monitored either on the refrigerant or on the water side of the condenser. On the refrigerant stream, its enthalpy and mass flow rate need to be measured in order to calculate its heat transfer rate. According to Tran et al. (2012), the mass flow rate has to be measured at the outlet of the compressor, where the refrigerant is always in gas phase. This can be done by using either a Coriolis or an ultrasonic flow meter. Measuring the enthalpy of the refrigerant requires temperature and pressure measurements at both inlet and outlet of the condenser. At the outlet, as the refrigerant may be biphasic, measuring its enthalpy will require an additional flow meter that can measure its density. This method is challenging as the flow meters might not be accurate with biphasic refrigerants (Tran et al. 2012). The other option would be measuring the heat on the water side by applying a heat meter, which links temperature sensors to a flow meter and calculates the heat transfer rate, as shown in Equation 4. This is more practical as less instruments need to be installed (see Table 1), which will reduce the risk of error propagation. Platinum Resistance Temperature Detectors (RTDs) will be used to measure the inlet and outlet temperatures combined with an ultrasonic flow meter, which are commonly used for district heating applications (CIBSE/ADE 2015).

The measurements related to the cooling being supplied to the Underground tunnels can be taken either inside the ventilation shaft or in the water loop that delivers heat to the heat pump’s evaporator. As shown in Equations 5 and 6, the parameters that would require monitoring on the air side would be the air mass flow rate (), as well as the air temperatures () and specific humidities (), used to calculate air enthalpy () at both the inlet and outlet of the heat exchanger. The mass flow rate () would have to be determined by measuring volume flow rates and air density, being a potential source of error, as density would be based on the specific humidity of air (), which can be measured with uncertainties of up to 7% (ASHRAE 2017). The volume flow rate would be measured by placing anemometer probes to determine the average air velocity in an axial plane of the shaft (ASHRAE 2017). As for the water side, the measurements would be taken using a heat meter, the same method proposed for calculating the heat output at the heat pump’s condenser. Thermometers will also be placed within the tunnels to investigate the impact of the cooling supplied on the tunnel temperatures. For evaluating both the cooling delivered/heat recovered () and the heat generation (), monitoring should be carried out on the water side, as it would involve less uncertain measurements and require fewer instruments, which is beneficial as it reduces installation costs and the propagation of uncertainty.

CONCLUSION

The climate crisis will demand combined international efforts not only to make the global energy matrix cleaner, but also to make use of existing energy resources more efficiently. As thermal confort in cities consumes significant amounts of energy, the adoption of sustainable solutions for heating and cooling in urban environments will be essential to meet future energy demands and climate targets. This is materialised by the 4th and 5th generations of district energy, which represent a shift towards efficient and low carbon technologies as it unlocks the potential of utilising renewable and waste heat in thermal networks. Recovering and reusing waste energy will play an important role in meeting the growing energy requirements of urban populations, particularly as the world moves away from fossil fuels. As many cities in the world rely on metro systems for their everyday operation, the exploitation of waste heat from railway tunnels represents an opportunity for cities to decarbonise their heating systems and enhance the energy efficiency of the built environment.

Metering and monitoring are critical activies to guarantee an efficient performance of any energy system. As waste heat recovery schemes are not yet an established technology, measuring their performance as a heat source in pilot projects will indicate their benefits in terms of increasing energy efficiency and reducing costs and carbon emissions associated with heating. This paper introduced a strategy to measure key operating parameters of a novel scheme that recovers waste heat from railway tunnels, and aims to guide future studies and waste heat recovery projects, not limited to railway tunnels, to develop effective metering strategies that allow their performances to be optimised and their expected benefits to be achieved, helping waste heat recovery to become a competitive and reliable form of heating.

ACKNOWLEDGMENTS

The authors would like to express their gratitude for the support given by Transport for London, London South Bank University and the Engineering and Physical Science Research Council (EPSRC) through projects LUSTER - London Urban Sub-Terrain Energy Recovery project [EP/R001294/1] and LoT-NET - Low Temperature Heat Recovery and Distribution Network Technologies [EP/R045496/1]. The authors are also grateful to the London Borough of Islington for their support in providing valuable information for this project.

REFERENCES

ASHRAE. 2017. ASHRAE Handbook—Fundamentals. SI edition. Atlanta: ASHRAE.

The Association for Decentralised Energy (ADE). 2018. Market Report: Heat Networks in the UK. Available online: https://www.theade.co.uk/resources/publications/market-report-heat-networks-in-the-uk (accessed 4 November 2018).

Buffa, S., Cozzini, M., D’Antoni, M., Baratieri, M. & Fedrizzi, R. 2019. 5th generation district heating and cooling systems: A review of existing cases in Europe. Renewable and Sustainable Energy Reviews 104: 504-522.

Chartered Institution of Building Services Engineers (CIBSE) and The Association for Decentralised Energy (ADE). 2015. CP1: Heat Networks: Code of Practice for the UK. United Kingdom.

Chua, K. J., Chou, S. K. & Yang, W. M. 2010. Advances in heat pump systems: A review. Appled Energy 87(12): 3611-24.

Committee on Climate Change (CCC). 2019. Net Zero – The UK’s contribution to stopping global warming. Available online: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/ (accessed 19 May 2019).

Department for Business, Energy & Industrial Strategy (BEIS). 2018a. Digest of UK Energy Statistics (DUKES): renewable sources of energy. Available online: https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes (accessed 27 June 2019).

Department for Business, Energy & Industrial Strategy (BEIS). 2018b. Heat Networks Investment Project, Introduction to the Scheme. United Kingdom.

Department for Business, Energy & Industrial Strategy (BEIS). 2018c. Optimisation of Heat Networks: Issues for Project Sponsors to consider. United Kingdom.

Duffy, S. 2018. Opportunities to Utilise Transport for London’s Secondary Heat Sources. Proceedings of the CIBSE Technical Symposium, London, UK, 12 – 13 April, 2018.

Gilbey, M. J., Duffy, S. & Thompson, J. A. 2011. The Potential for Heat Recovery from London Underground Stations and Tunnels. Proceedings of the CIBSE Technical Symposium, Leicester, UK, 6 – 7 September, 2011.

Greater London Authority (GLA). 2018. London Environment Strategy. Available online: https://www.london.gov.uk//what-we-do/environment/london-environment-strategy (accessed 30 October 2018).

Incropera, F. P., DeWitt, D. P., Bergman, T. L. & Lavine, A. S. 2002. Fundamentals of heat and mass transfer, 6th edition. New York: J. Wiley.

Jangsten, O., Aguiló-Rullán, A., Williams, J. & Wiltshire, R. 2011. The Performance of District Heating in New Developments: Application Guidance, Bracknell: BRE Group.

Kwon, O., Cha, D. & Park, C. 2013. Performance evaluation of a two-stage compression heat pump system for district heating using waste energy. Energy 57: 375-381.

Lagoeiro, H., Revesz, A., Davies, G., Maidment, G., Curry, D., Faulks, G. & Bielicki, J., 2019. Heat from Underground Energy London. Proceedings of the CIBSE Technical Symposium, Sheffield, UK, 25 – 26 April, 2019.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F. & Mathiesen, B. V. 2014. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy 68: 1-11.

Naphon, P. & Wongwises, S. 2005. Heat transfer coefficients under dry- and wet-surface conditions for a spirally coiled finned tube heat exchanger. International Communications in Heat and Mass Transfer 32(3): 371-385.

Tran, C. T., Rivière, P., Marchio, D. & Arzano-Daurelle, C. 2012. Refrigerant-based measurement method of heat pump seasonal performances. International Journal of Refrigeration 35(6): 1583-94.

UK Government. 2014. The Heat Network (Metering and Billing) Regulations. Available onlne: http://www.legislation.gov.uk/uksi/2014/3120/pdfs/uksi\_20143120\_en.pdf (accessed 14 March 2019).

Vandermeulen, A., van der Heijde, B. & Helsen, L. 2018. Controlling district heating and cooling networks to unlock flexibility: A review. Energy 151: 103-115.

Vesterlund, M., Toffolo, A. & Dahl, J. 2017. Optimization of multi-source complex district heating network, a case study. Energy 126: 53-63.