Waste Heat Recovery from Underground Railways – Evaluating the Cooling Potential

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Abstract
The Bunhill Waste Heat Recovery (WHR) System is a first of its kind scheme that will recover waste energy from a ventilation shaft of the London Underground (LU) network. The system is based upon the installation of a heat recovery heat exchanger that consists of cooling coils and a reversible fan. The coils are connected to a heat pump that supplies low carbon thermal energy to the Bunhill Heat Network in the London Borough of Islington. One particularly important aspect of the Bunhill WHR system is its ability to operate in a way that not only provides heating to the local heat network, but can also simultaneously supply cooled air to the LU tunnels depending on the operation of the reversible fan. The current paper provides an analysis of the heating and cooling duties and their associated cost and carbon savings against conventional technologies based upon a mathematical model of the WHR system. The model is able to predict the condition of the coil surface according to air inlet parameters, and this is used to calculate the latent and sensible cooling loads, which are applied to simulate how the system impacts the local tunnel environment, with peak temperature reductions of up to 7.2 °C being estimated for adjacent stations in 2030. The results from these analyses are reported, together with recommendations for further development and future deployment of heat recovery from metro systems.

Keywords Heating and cooling, heat pumps, waste heat, heat networks, district energy, London Underground, railway tunnels, modelling

1. Introduction

1.1. Background

The decarbonisation of the UK economy, driven by the national net-zero target, will require the large-scale electrification of important energy sectors, such as transport and heating, which are heavily reliant on fossil fuels. This is related to the increasing uptake of renewable energy sources for electricity production in the UK, with renewables reaching an all-time record of 37% of the power generated in 2019 [1], a number expected to grow continuously in the coming years. As the UK aims to further reduce its contribution to climate change and deliver net-zero, decarbonising heat becomes one of its main challenges, as the sector is responsible for nearly half the energy consumption and a third of carbon emissions in the country [2]. Within that context, heat networks represent a key technology, particularly in densely populated urban areas, as they enable the coupling between heating and other energy vectors and can benefit from economies of scale. Another advantage of district heating is its ability to make use of waste heat from a variety of urban infrastructures, which could be widely exploited in London and other cities across the UK and globally. Currently, district heating only meets 2% of the UK heat demand [3], but its ability to reduce the carbon footprint of buildings has been recognised by the Committee on Climate Change [4] and the latest London Plan [5], unlocking the potential for waste heat to play an important role in the energy transition.

1.2. Waste Heat from the London Underground

There are many sites in urban settings from which it is possible to capture waste heat, such as industrial plants, data centres, electricity distribution systems, sewers and supermarkets. One source of particular interest in the UK is the London Underground, as it covers a large area of London and the operation of its trains generates significant amounts of thermal energy. In 2016/2017, the Underground consumed over 1,700 GWh of electricity, with around 500 GWh of energy ending up degraded and released as waste heat [6]. The current thermal environment of the LU means that there is significant potential for recovering waste heat from tunnels, while cooling solutions are expected to gain importance as air temperatures rise in the future due to climate change, which is likely to increase train service delays [7]. This opportunity led to the development of the Bunhill WHR System, a first of its kind scheme that will recover waste energy from a ventilation shaft of the LU network, whilst also being able to supply cooling to the tunnels, as introduced in [8]. This paper analyses the cost and carbon benefits of the WHR system from both heating and cooling perspectives, with focus on the cooling effect generated by the heat recovery coils (HRC) and its implications for the LU environment.

2. The Bunhill Waste Heat Recovery System

The London Underground WHR system was introduced into the Bunhill Heat Network as part of an extension project known as Bunhill 2. This project involved constructing a new energy centre, which also houses a 50 m^3 thermal store and two 237kW_e/372kW_{th} combined heat and power (CHP) units. These additional heat sources, together with the energy centre from Bunhill 1, enable the system to operate flexibly when meeting a heat demand associated with 1,350 dwellings, two leisure centres and a local primary school. As the main novelty of Bunhill 2 is associated with heat recovery from the Underground, this paper will focus on the performance of the WHR scheme. The system recovers waste heat from the City Road ventilation shaft, located on the Northern Line between Angel and Old Street stations. The main components of the WHR system are a reversible fan, the HRC with a nominal capacity of 780 kW, a 1MW two-stage ammonia heat pump and a coolant loop that connects the coils to the heat pump. More information on system design can be found in [8].

An essential feature of the Bunhill WHR system is its ability to supply cooled air to the LU tunnels whilst simultaneously delivering heat to the local heat network. This depends on the direction in which the reversible fan operates. If operating in extract mode, the system utilises tunnel air as the heat source and no cooling is provided to the network. However, when operating in supply mode, the system recovers heat from ambient air, which is cooled down in the process, before being supplied to the tunnels. Both extract and supply modes are illustrated in Figure 1.

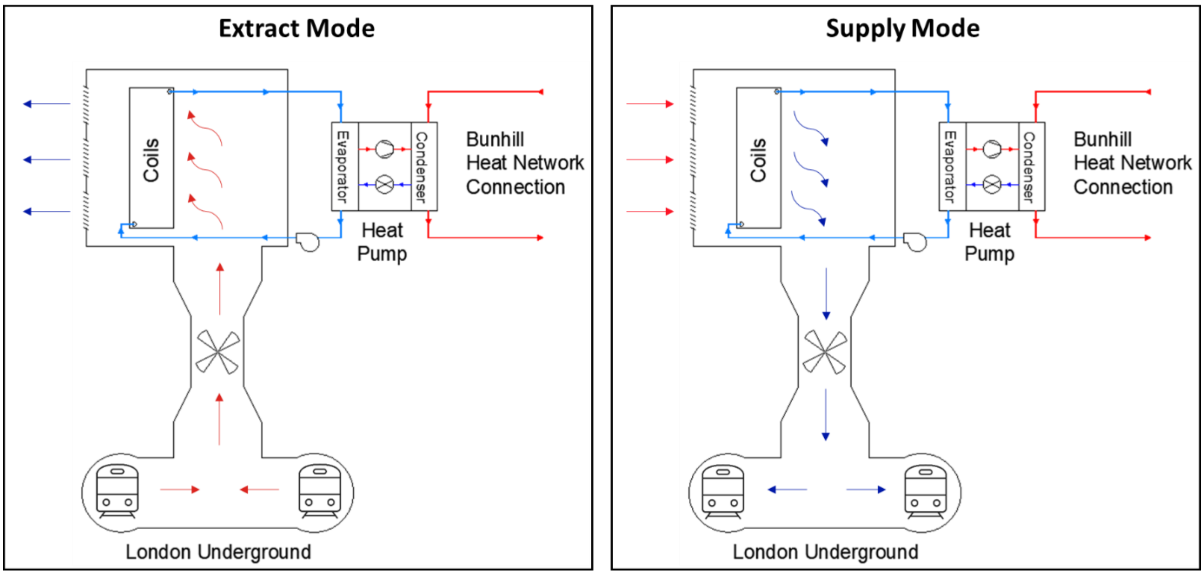


Figure 1 – Conceptual schematics of the WHR system operating in extract and supply modes.

3. Modelling of the WHR System

In order to investigate the performance of the WHR system, a mathematical model was developed using the commercial software tool Engineering Equation Solver (EES) [9]. The WHR model is able to iteratively solve thermodynamic balance equations across the system, being used to determine its energy consumption, as well as heating and cooling outputs. The energy consumption calculations are associated with the electricity used to run the reversible fan (W_F), the coolant circulation pump (W_P) and the heat pump (W_{HP}) when delivering a heat output of Q_{cond}. Based upon full load design, as well as inputs for air temperature and humidity, the model is able to calculate the heat recovered by the heat exchanger (Q_{rec}), which is assumed to be equal to that absorbed by the heat pump's evaporator (Q_{evap} = Q_{rec}). A schematic of the main energy inputs and outputs of the model is shown in Figure 2.

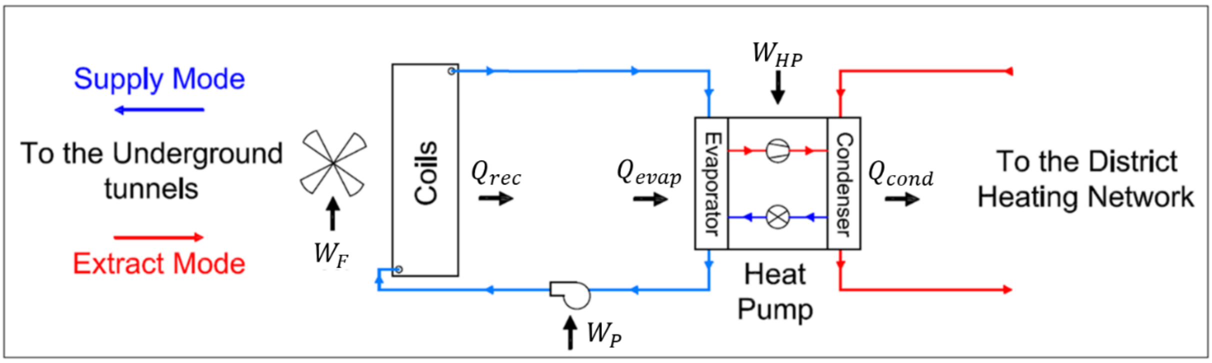
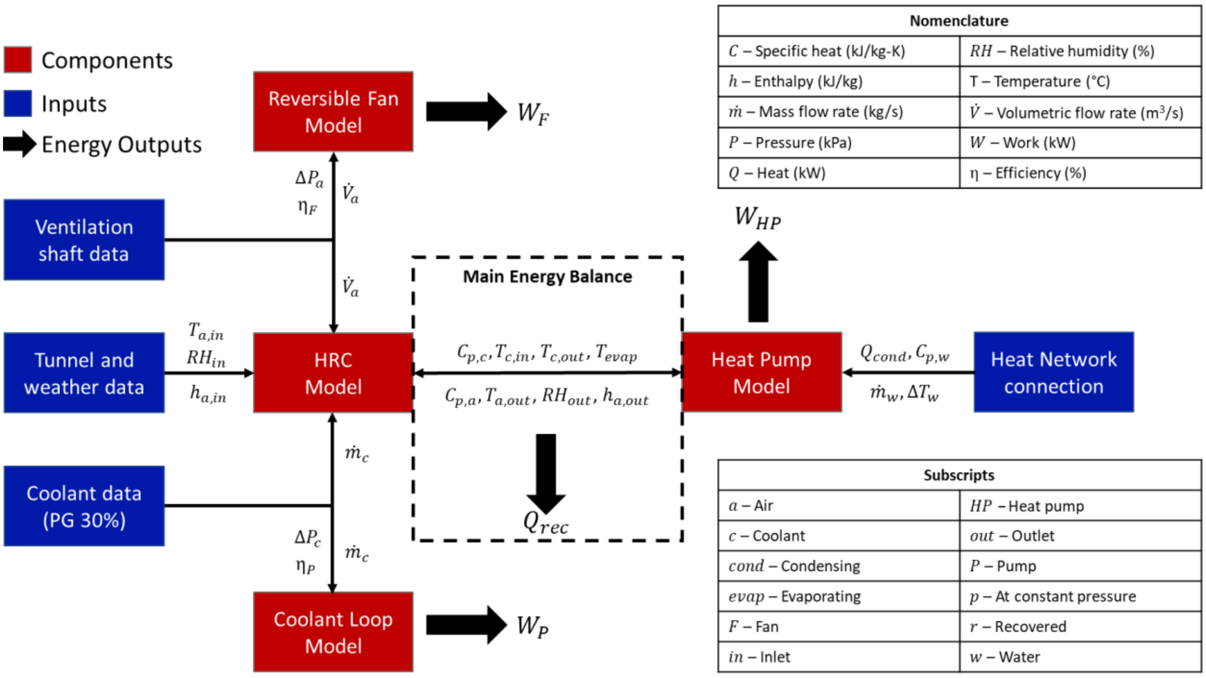


Figure 2 – Schematic highlighting energy inputs and outputs associated with the WHR model.

The WHR model simulates each of the components illustrated in Figure 2 and its outputs are calculated by solving the mass and energy balance between the coils and the heat pump. These outputs are illustrated in Figure 3, together with the main inputs and connections between the different components of the model. The model was validated against manufacturer's data. The calculations are done in hourly time steps, based on temperature and relative humidity recordings from the ventilation shaft and the nearest available weather station, which were provided by Transport for London (TfL) and the Meteorological Office, respectively, for the period from January 2013 to January 2014. A brief description of each modelled component is provided in the following subsections, with emphasis on the HRC model, which is used to predict the air outlet conditions and the associated cooling effect produced by the WHR system.



Nomenclature	
C – Specific heat (kJ/kg-K)	RH – Relative humidity (%)
h – Enthalpy (kJ/kg)	T – Temperature (°C)
$\dot{m}$ – Mass flow rate (kg/s)	$\dot{V}$ – Volumetric flow rate (m³/s)
P – Pressure (kPa)	W – Work (kW)
Q – Heat (kW)	η – Efficiency (%)

Subscripts	
a – Air	HP – Heat pump
c – Coolant	out – Outlet
$cond$ – Condensing	P – Pump
$evap$ – Evaporating	p – At constant pressure
F – Fan	r – Recovered
in – Inlet	w – Water

Figure 3 – Framework for the WHR model, highlighting components, inputs and outputs.

3.1. Two-stage Heat Pump

The two-stage heat pump was designed to operate with heat network flow and return temperatures of, respectively, 75°C and 55°C. The main components of the low stage are two plate-and-shell heat exchangers (PSHEs), namely a desuperheater and a flooded evaporator that is connected to a small separator vessel, as well as a 6-cylinder reciprocating compressor with a nominal motor power of 280 kW. As for the high stage, its main components include two parallel reciprocating compressors with 4 cylinders and a nominal motor power of 90 kW each, as well as three PSHEs that act as a desuperheater, a condenser and a subcooler. The two cycles are connected by a separator tank, where saturated ammonia is kept at constant pressure. The model determines the coefficient of performance (COP) of the heat pump by calculating different evaporating temperatures associated with the energy balance illustrated in Figure 3. Based upon the data shown in [8], a correlation between isentropic efficiency and low-stage pressure ratio can be derived. The high-stage is modelled as a single heat exchanger with a fixed UA value, as the heat output and network temperatures are assumed constant. The pressure drops associated with components, as well as the suction and discharge lines for both stages, are also considered.

3.2. Reversible Fan and Coolant Pump

The reversible fan and the coolant pump were modelled in order to estimate their power consumption. The reversible fan model is based upon the additional pressure drop associated with the WHR system that needs to be overcome by the fan, as described in [8]. The calculations considered a fan efficiency of 59.5% and pressure drops of 105.9 and 106.2 Pa associated with extract and supply modes, respectively. The pumping power is modelled as reported in [10], considering the coolant mass flow rate, an assumed pump efficiency of 50% and the pressure drops associated with the pipework, the evaporator and the HRC. The pipework was assumed to be a 20-metre loop consisting of DN150 stainless steel pipes and a minimum number of fittings.

3.3. Heat Recovery Coils

The HRC represent the location within the system where heat is recovered from either tunnel air or ambient air and cooling is delivered depending on the operation of the reversible fan. The coils consist of two banks, each with three 6-row deep modules of copper tubes with 4 fins per inch. The HRC are modelled as a single 12-row bank with 158 tubes each for reducing computational effort. The heat exchanger dimensions are 4.75 x 6.04 x 0.29 m, yielding a face area of 28.69 m^2 and a surface area (A) of 2800 m^2. The secondary working fluid or coolant considered for this application was a propylene glycol/water mixture, with a concentration of 30%. Propylene glycol was chosen as it has extremely low environmental, health, fire and corrosion risks [11]. The energy balance at the heat recovery coils is determined by calculating the heat transfer rate (Q_{rec}) through different equations. These equations include the sensible heat transfer on the coolant side (Equation 1), the change in enthalpy on the air stream side (Equation 2), as well as an additional equation that calculates heat transfer by determining the overall heat transfer coefficient of the coils.

$$Q_{rec} = \dot{m}_c C_{p,c}(T_{c,out} - T_{c,in}) \tag{1}$$

$$Q_{rec} = \dot{m}_a(h_{a,in} - h_{a,out}) \tag{2}$$

The thermodynamic phenomena associated with HRC requires complex modelling as it involves both heat and mass transfers from the air stream due to condensation. Mitchell and Braun [12] proposed a methodology for modelling humid air cooling coils that relies on an analogy of sensible heat transfer that simplifies calculations whilst estimating coil performance accurately. The methodology is based upon different heat transfer coefficient calculations for both fully dry and fully wet conditions, whilst a partial configuration can be represented by a combination of both dry and wet models, whereby the coil is divided into “dry” and “wet” sections, as shown in Figure 4.

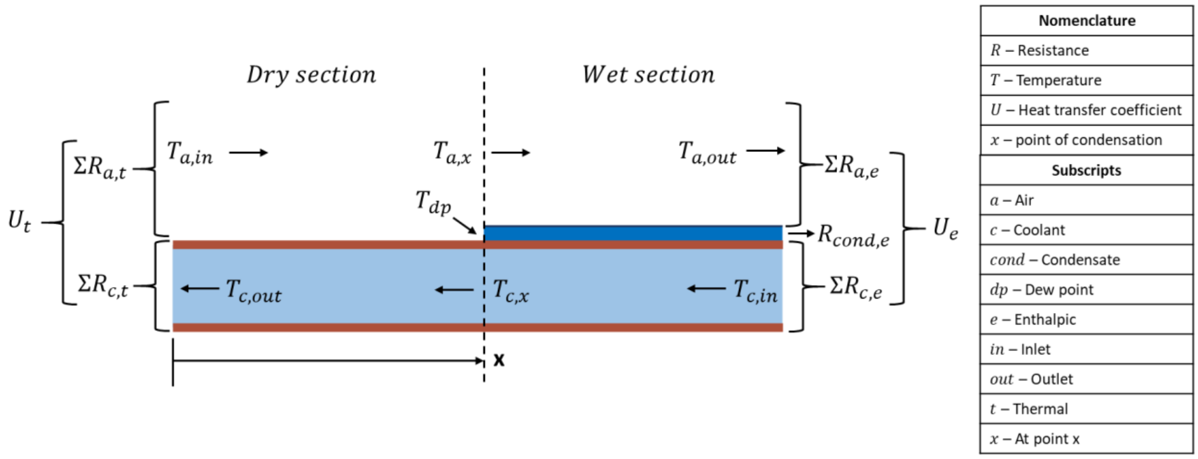


Figure 4 – A schematic illustrating a counter-flow heat recovery coil with a partially wet surface.

The dry section corresponds to the initial fraction of the heat exchanger (up to point x), where the coil surface temperature is above the dew point (T_{dp}) and the air does not condense, causing the heat transfer to be entirely sensible. As for the wet section, it is characterised by the point beyond which the coil surface temperature is below the dew point, leading to the transfer of both heat and mass from the air stream and a different heat transfer coefficient, as a wetted surface alters the heat transfer process between both fluids. In this case, the heat transfer is calculated based upon the fictitious enthalpy of air at the coolant temperature. Therefore, separate equations for the dry (Equation 3) and wet (Equation 4) sections must be introduced to satisfy the energy balance, with the heat recovered being the sum of the dry and wet heat transfers ($Q_{rec} = Q_d + Q_w$), where X represents the ratio of the coil surface that is dry. The overall heat transfer coefficient (U) is calculated based on the thermal (R_t) and enthalpic (R_e) resistances for the dry and wet sections, respectively, and the log-mean temperature ($LMTD$) and enthalpy ($LMED$) values. The resistance of the condensate layer ($R_{cond,e}$) can be neglected due to its small thickness and conductive nature [12]. Equation 5 is also introduced to the balance, as it calculates the air ($T_{a,x}$) and coolant ($T_{c,x}$) temperatures at point x. The model is bound by X values between 0 and 1, which correspond, respectively, to fully wet and fully dry surface conditions.

$$\mathrm{Q}_d = X * U_t * A * LMTD \tag{3}$$

$$\mathrm{Q}_w = (1 - X) * U_e * A * LMED \tag{4}$$

$$\frac{(T_{a,x} - T_{dp})}{\Sigma R_{a,t}} = \frac{(T_{c,x} - T_{dp})}{\Sigma R_{c,t}} \tag{5}$$

The energy and mass balances calculated by the WHR model also include the change in the moisture content of air, which is critical in estimating the amounts of latent and sensible cooling associated with the heat recovery process, and can be calculated based upon the enthalpy-effectiveness method [13]. The modelling approach described herein allows the coil surface and air outlet conditions to be determined, providing better understanding of the cooling produced by the WHR system and its impacts on the LU environment.

4. Integrated Benefit Analysis

The WHR model is initially applied to assess the benefits of recovering waste heat from the LU against typical technologies used for both heating and cooling. This is achieved by comparing the annual costs and carbon savings associated with the WHR system, air-source heat pumps (ASHPs) and a CHP system against a reference case of communal gas boilers and a ventilation shaft chiller system. The cost analysis considers energy running costs for all investigated technologies when meeting the same demands for both heating and cooling. The carbon savings calculations are based upon the carbon intensity of the fuels used to meet the reference loads. In both cases, the performance of the WHR system will be analysed for the five different scenarios described in Table 1, which also provides the annual average system COP, accounting for the fan and pumping power, calculated for each scenario.

Table 1 – Different modelling scenarios for the WHR model, based upon fan operation mode.

Scenario	Operating Condition	System COP	Description
1	12E/0S	3.28	Fan operating in extract mode for the entire year (12 months).
2	9E/3S	3.24	Fan operating in supply mode during meteorological summer (Jun/Jul/Aug), and in extract for the rest of the year.
3	6E/6S	3.13	Fan operating in supply mode for half the year, from May to October, and in extract for the remaining 6 months.
4	3E/9S	2.96	Fan operating in extract mode only during meteorological winter (Dec/Jan/Feb), and in supply for the rest of the year.
5	0E/12S	2.75	Fan operating in supply mode for the entire year (12 months).

The annual heat demand considered was approximately 7,780 MWh, equivalent to the heat pump's annual output, assuming a continuous operation with a 5% downtime and primary heat network losses of 10%, which is the maximum loss rate expected for district heating [14]. The cooling demand was assumed to be the maximum annual cooling output from the WHR system, which was equal to 5,875 MWh, considering the same downtime. A seasonal COP of 2.68 was assigned for ASHPs, based on the survey reported in [15]. As for the CHP counterfactual, respective thermal and electrical efficiencies of 55.6% and 35.4% were considered, equal to the units installed for Bunhill 2. The heat network losses factor was also applied to the CHP scenario. An efficiency of 80% was assumed for the gas boilers [16], whilst a COP of 2.70 was estimated for the chiller system, considering an existing TfL case study, as well as fan and pumping power calculations similar to those for the WHR model.

The fuel prices and carbon factors were estimated using the latest central projections from BEIS [17], both considering commercial/public sector use over a 20-year period (2021-2040). This approach led to average energy tariffs of 14.40 p/kWh and 3.64 p/kWh for electricity and natural gas, respectively. The average carbon factors for the same period were calculated as 0.184 $kgCO_{2e}$/kWh for gas and 0.140 $kgCO_{2e}$/kWh for electricity, reflecting the expected decarbonisation of the electricity grid in the coming years. An electricity export price of 5.30 p/kWh was assumed in order to account for the revenue from the electricity produced by cogeneration [16]. The cost analysis is summarised in Figure 5, whilst Figure 6 provides the results for carbon savings. Both analyses were carried out for each of the scenarios shown in Table 1 and all technologies were compared against communal gas boilers (heating) and a ventilation shaft chiller (cooling).

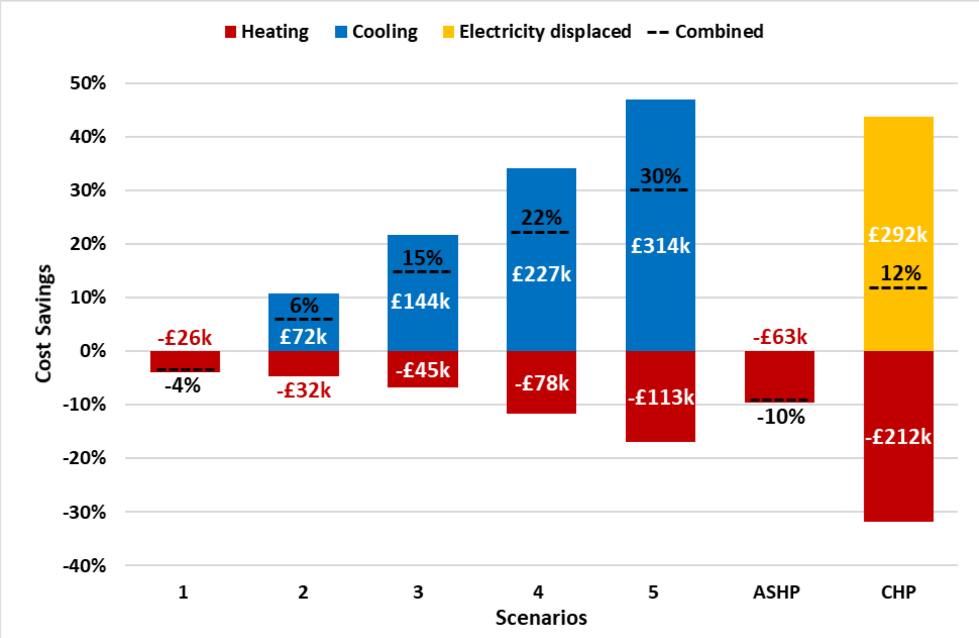


Figure 5 – Annual energy cost savings for the analysed scenarios against gas boilers and a vent shaft chiller system.

The cost analysis highlights how the cooling benefit can have a significant impact on the economic performance of the WHR system, with maximum savings (30%) obtained for scenario 5, which corresponds to year-round operation in supply mode. The WHR system would increase heating costs in all scenarios, as high electricity prices lead to negative heating cash flows against the fossil fuel counterfactual, although elements such as flexibility and integration with other energy vectors in low-temperature networks might increase system performance, as reported in [18]. As for the carbon savings, it can be observed from Figure 6 that the reduction in emissions is mainly due to switching the fuel used for heating, as the efficiency of the WHR system leads to a much lower energy consumption when providing the same amount of heat. Overall, the annual carbon savings varied from 68% for scenario 1, when no cooling is provided, to 78% for scenario 5, when cooling is provided throughout the year. This means that the energy savings associated with cooling are able to compensate for the lower energy efficiency experienced by the heat pump when it operates for longer periods in supply mode. The ASHPs were found to yield the lowest cost savings due to their lower COP, although significant carbon savings of 66% were observed. However, these savings are still lower than every WHR scenario, even though they include heat network losses and energy consumption of ancillary equipment. As for the CHP counterfactual, its electricity revenue makes it 12% less costly than the reference case, but this would come at a cost of increasing emissions by 63%, particularly as cogeneration would displace cleaner electricity from the grid.

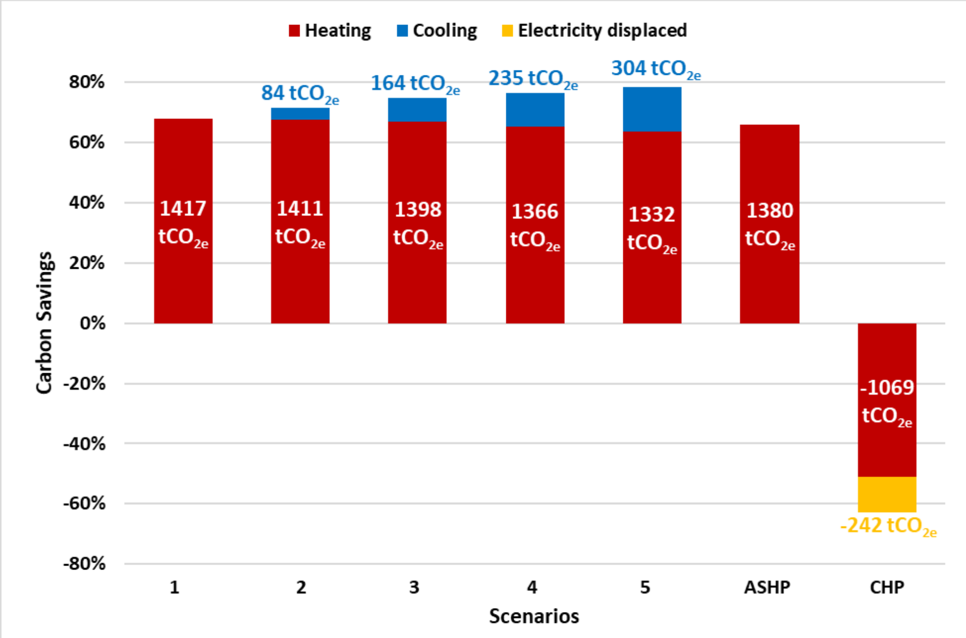


Figure 6 – Annual carbon savings for the analysed scenarios against gas boilers and a vent shaft chiller system.

One potential issue is that the recipient of the cooling benefit is the railway operator, whilst the heat network operator is the stakeholder having to bear the higher costs of producing low-carbon heat using electricity as fuel. This indicates the need for strong policy as enablers for WHR schemes, as the disparity in price between gas and electricity and the higher levies applied to the latter represent a risk for the electrification of heat supply and the exploitation of low-grade waste heat sources in the UK. Previous policies such as the Renewable Heat Incentive [19] and the Heat Networks Investment Project [2] played an important role in making waste heat a feasible investment, but current plans for supporting such systems have not yet been defined. It is expected that future actions such as the Green Heat Networks Fund [20] can fill the policy gap for heat decarbonisation, allowing urban waste heat recovery to flourish as the UK moves towards net-zero.

5. Cooling the London Underground

The cooling benefits behind the WHR system are also assessed in terms of the potential reduction in platform temperatures that can be achieved at the nearest stations to the ventilation shaft. This investigation was carried out in collaboration with the engineering team at TfL in order to simulate how future network temperatures would be affected by the WHR system, utilising a bespoke modelling tool based upon the Subway Environment Simulation (SES) platform. SES is able to perform 1D simulations of the operation of trains in tunnels, being suited to model many different aspects of a subway environment, such as airflows, temperatures and humidity throughout stations, tunnels and ventilation shafts [21]. The thermodynamic simulations in SES consist of breaking down the network into smaller components of constant temperature and humidity. The heat generated within each component over time, based upon train profiles and airflow patterns, is then used to calculate energy and mass balances at nodes connecting subsequent components, whilst also taking into account the conductive heat transfer between tunnel walls and the surrounding soil [22]. This approach is used for both aerodynamic and thermodynamic calculations, and an example of how different network sections are modelled is shown in Figure 7.

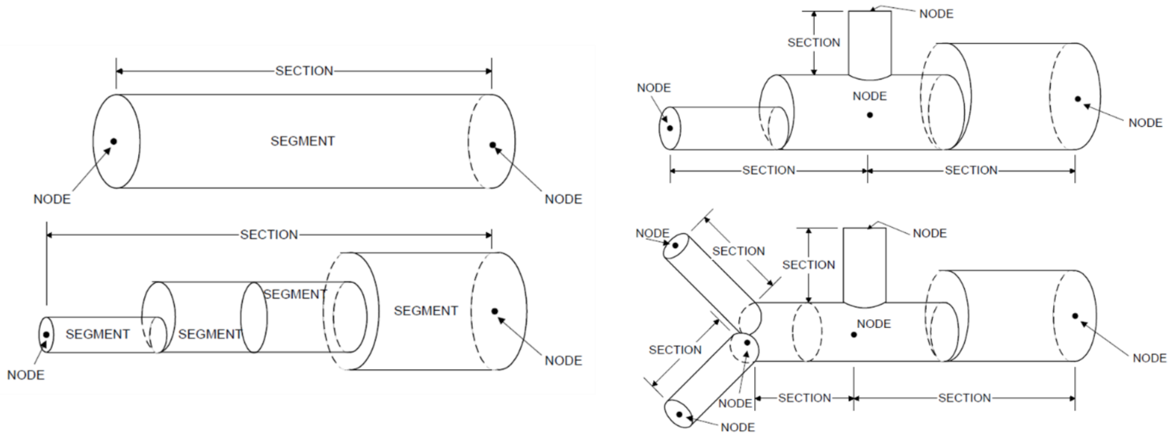


Figure 7 – Examples of network sections and their components as simulated in SES [22].

The results from the WHR model were used as inputs for SES, enabling the analysis of how the stations of Angel, Old Street, King's Cross and Moorgate would respond to the provision of cooling for the Table 1 scenarios over the long term, considering 2030 as the target year. The simulations work by adjusting the dry and wet-bulb temperatures of the air that is supplied at the ventilation shaft node to the conditions predicted by the WHR model. The novelty behind this approach is enabling the use of an accurate representation of the cooling process, which is achieved with the WHR model, to investigate the impacts of cooling coils on the LU environment.

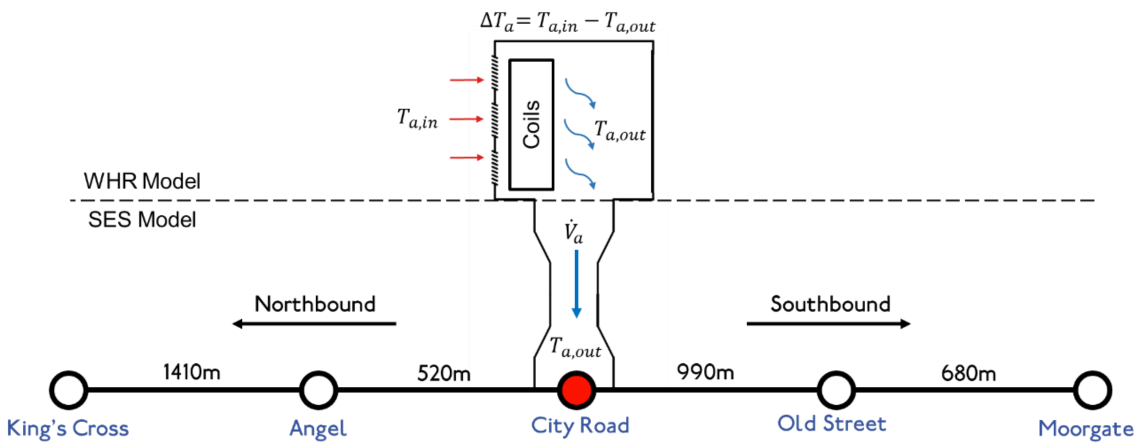


Figure 8 – Schematic highlighting the inputs from the WHR model to the SES simulations.

The SES model developed by TfL is calibrated to utilise 2006 weather data as the basis for simulations, and the UK climate projections (UKCP) from 2009, along with train frequency profiles, are utilised to yield future platform temperatures. Therefore, the WHR model had to be run with 2006 weather data in order to provide the necessary inputs for this investigation, and the link between the WHR and SES models are provided in Figure 8. The cooling effect calculated by the WHR model considers both sensible and latent cooling loads associated with the heat recovery process in supply mode, and the data used for simulation is summarised in Figure 9.

As shown in Figure 9, supply mode operation results in significant proportions of latent cooling, with an average of 34% of the total coil duty annually. This leads to a lower air temperature reduction (ΔT_a) than would be achieved if no condensation took place. Overall, the annual average ΔT_a was calculated as 5.4°C, although values as high as 9.6°C were predicted for an entirely sensible cooling process, highlighting the relevance of considering latent loads when analysing the cooling potential of the WHR system. For each scenario from Table 1, supply mode operation was modelled using the air outlet temperatures corresponding to the months the system would be operating in supply mode. Extract mode was modelled with no air supply through the vent shaft, and a mixed operation was simulated by combining the results from both extract and supply simulations. The results are expressed in terms of average evening peak temperatures for the hottest week of the year. This corresponds to the worst-case scenario the stations would be exposed to, representing how the cooling provided can alleviate temperatures during critical periods. The results from the SES analysis are illustrated in Figure 10.

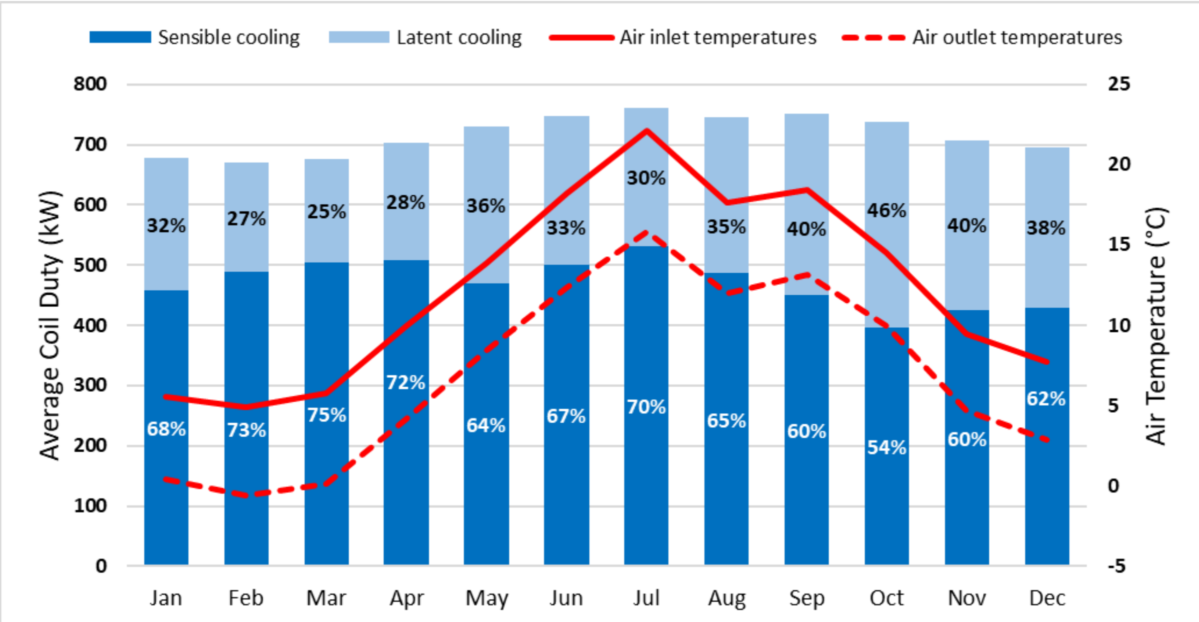


Figure 9 – Monthly average coil duties for sensible and latent cooling, as well as air inlet and outlet temperatures calculated by the WHR model in supply mode.

The results show how the scenarios involving cooling provision would lead to significant reductions in platform temperatures as opposed to year-round extract mode operation, particularly for the stations adjacent to the ventilation shaft (Angel and Old Street), as negligible reductions were observed at King's Cross and Moorgate. The highest reductions were estimated for scenario 5, where the year-round supply of cooling could potentially reduce peak temperatures by 7.2°C at Angel and 6.3°C at Old Street. For scenarios 2, 3 and 4, which involve a combination of extract and supply modes, the average ΔTs, considering both adjacent stations, were of 1.1, 2.6 and

4.5°C, respectively, highlighting how the cooling benefit can be increased if the system operates for longer periods in supply mode. These temperature reductions might lead to several tangible benefits for LU, such as increasing the wellbeing of passengers and staff [23], reducing risk of train delays caused by high temperatures [7], as well as unlocking potential for service frequency and ridership to be increased.

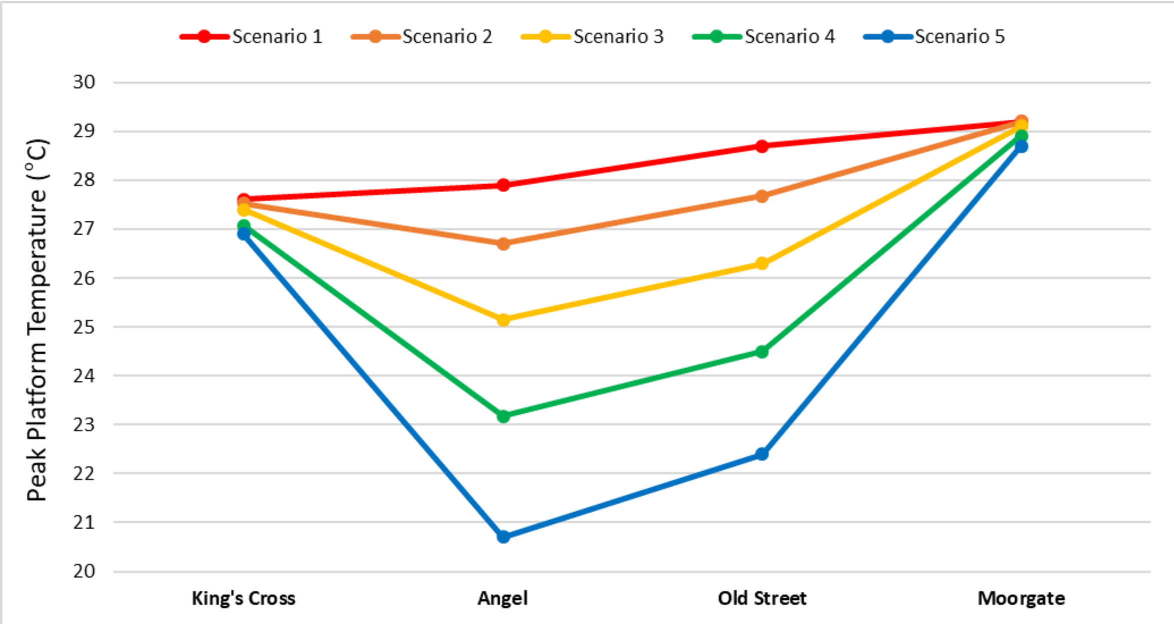


Figure 10 – Peak platform temperatures for 2030 based upon a combination of extract and supply mode SES simulations.

6. Conclusions

The results reported in this paper show how there are significant additional benefits that could be obtained by exploiting the cooling potential of a system that recovers waste heat from an underground railway network, based upon a London case study. In addition to avoiding the costs of cooling provision, the WHR system also has the potential to achieve considerable reductions in station temperatures, improving the thermal environment of the metro system and reducing the risk of issues associated with heat stress. A novel approach was developed, combining both EES and SES models, in order to estimate the impacts of cooling coils on railway tunnels with greater accuracy, considering both latent and sensible cooling effects.

One risk identified regarding supply mode operation is the reduction of system efficiency, as lower temperature air is used as the heat source. This could increase running costs for system operators, and a balance between cooling and heating benefits must be sought. In addition, the economic analysis showed how the price disparity between electricity and natural gas in the UK is a major barrier to the development of WHR systems, particularly from a heating perspective. Therefore, it is expected that future policy can provide much needed support for waste heat and heat networks, allowing them to play their role in the decarbonisation of heat, whilst also enabling secondary benefits to be exploited, thus maximising the efficiency and feasibility of such systems.

References

(1) Department for Business, Energy & Industrial Strategy, 2020. Digest of UK Energy Statistics 2020. Available online: https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2020 [Accessed 18 August 2020].

(2) Department for Business, Energy & Industrial Strategy, 2018. Heat Networks Investment Project, Introduction to the Scheme. Available online: https://www.gov.uk/government/publications/heat-networks-investment-project-hnip-scheme-overview [Accessed 21 November 2018].

(3) The Association for Decentralised Energy, 2018. Heat Networks in the UK. Available from: https://www.theade.co.uk/resources/publications/market-report-heat-networks-in-the-uk [Accessed 4 November 2018].

(4) The Committee on Climate Change, 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].

(5) The Greater London Authority, 2021. The London Plan 2021. Available online: https://www.london.gov.uk/what-we-do/planning/london-plan/new-london-plan/london-plan-2021 [Accessed 2 March 2021].

(6) Duffy, S., 2018. Opportunities to Utilise Transport for London's Secondary Heat Sources. CIBSE Technical Symposium, London, UK.

(7) Greenham, S., Ferranti, E., Quinn, A. & Drayson, K., 2020. The impact of high temperatures and extreme heat to delays on the London Underground rail network: An empirical study. Meteorological Applications 27(3).

(8) Lagoeiro, H., Revesz, A., Davies, G., Maidment, G., Curry, D., Faulks, G., Bielicki, J., 2019. Heat from Underground Energy London. CIBSE Technical Symposium, Sheffield, UK.

(9) F-Chart Software, 2019. EES Overview. Available online: http://fchartsoftware.com/ees/index.php [Accessed 15 September 2019].

(10) Milnes, M., 2010. The Mathematics of Pumping Water. AECOM Design Build & The Royal Academy of Engineering. Available online: https://www.stem.org.uk/resources/elibrary/resource/25398/mathematics-pumping-water [Accessed 3 January 2020].

(11) Heinonen, E. W., Wildin, M. W., Beall, A. N. & Tapscott, R. E., 1997. Assessment of Antifreeze Solutions for Ground-Source Heat Pump Systems. ASHRAE Transactions 103(2), 747-56.

(12) Mitchell, J. W. & Braun, J. E., 2013. Principles of Heating, Ventilation and Air Conditioning in Buildings. 1st Edition. John Wiley & Sons, USA.

(13) Nellis, G. & Klein, S., 2008. Heat Transfer. 1st Edition. Cambridge University Press, USA.

(14) Chartered Institution of Building Services Engineers. 2020. CP1 – Heat Networks Code of Practice for the UK.

(15) Energy Saving Trust, 2013. The heat is on: heat pump field trials: phase 2. Available online: https://www.energysavingtrust.org.uk/sites/default/files/reports/TheHeatisOnweb%281%29.pdf [Accessed 13 April 2021].

(16) BRE Group. Standard Assessment Procedure, version 10, 2019. Available online: https://bregroup.com/sap/sap10 [Accessed 4 April 2021].

(17) Department for Business, Energy & Industrial Strategy, 2020. Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal. Available online: https://www.gov.uk/environment/energy-and-climate-change-evidence-and-analysis [Accessed 4 April 2021].

(18) Revesz, A., Jones, P., Dunham, C., Davies, G., Marques, C., Matabuena, R., Scott, J. & Maidment, G., 2020. Developing novel 5th generation district energy networks. Energy 201, 117389.

(19) Office of Gas and Electricity Markets, 2020. Non-Domestic Renewable Heat Incentive. Available from: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi [Acessed 6 April 2021].

(20) Department for Business, Energy & Industrial Strategy, 2020. Green Heat Network Fund: proposals for the scheme design. Available online: https://www.gov.uk/government/consultations/green-heat-network-fund-proposals-for-the-scheme-design [Accessed 6 April 2021].

(21) Thompson, J.A., Maidment, G.G. & Missenden, J.F., 2006. Modelling low-energy cooling strategies for underground railways. Applied Energy 83, 1152-62.

(22) U.S. Department of Transportation, 2002. Subway Environmental Design Handbook, Volume II. Subway Environmental Simulation Computer Program, Version 4.1.

(23) Wen, Y., Leng, J., Shen, X., Han, G., Lijun, S. & Yu, F., 2020. Environmental and Health Effects of Ventilation in Subway Stations: A Literature Review. International Journal of Environmental Research and Public Health 17, 1084.

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