Combined benefits of cooling with heat recovery for electrical cable tunnels in cities

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Abstract

Electrical power in cities is typically distributed by means of underground cable tunnels. The cables generate significant heat, and tunnel temperature is generally controlled via ventilation shafts with circulation to prevent overheating. If active cooling of the inlet air is provided, then temperatures can be lowered and electrical distribution losses reduced. This novel study, the first looking at cable tunnels with District Heating, investigates the effect and impact of heat recovery. The work combines technical and economic modelling together with measured data from a case study and shows significant benefits with wide-scale replication potential.

A finite element (FE) model, for heat dissipation in a section of cable tunnel together with a spreadsheet model has shown that up to 460 kW of heat can be delivered to the local heating network for a single cooling point. The study indicates savings of 570 kg CO_2e and 4000 kWh (of combined heat and electrical energy) per metre of tunnel per annum with reduced operating

costs. Given the widespread network of cable and other tunnels in major cities, close to numerous heat users, the application of these techniques has major financial and low-carbon benefits for the UK and globally.

Keywords Waste heat; cable tunnels; heat networks; sustainability; energy, revenue and carbon savings

Nomenclature

Symbol / Acronym	Description	Unit
ASHP	Air source heat pump	-
CEF	Carbon emission factor	kg CO_2e/kWh
CDE	Carbon dioxide equivalent	kg
COP	Coefficient of performance	-
CLHR	Cold led heat recovery	-
DH	District heating	-
E	Energy	kWh
GHG	Greenhouse gas	-
HEX	Heat exchanger	-
HLHR	Heat led heat recovery	-
HPM	Hours per month	-
I	Electrical current	A
N	Number	-
P	Power loss	W
Q	Heat	kW
R	Resistance	Ohm
RHI	Renewable Heat Incentive	-

T	Temperature	°C
α	Temperature coefficient of resistance	K^{-1}
ΔT	Temperature difference	K
η	Efficiency	-

Subscript	Description	Subscript	Description
0	Reference	evap	Evaporator
11	11kV cable	fin	Final
132	132kV cable	g	Gas
air	Air	gen	Generation
Al	Aluminium	h	Heating
av	Average	hp	Heat pump
b	Gas boiler	in	Input
cab	Cable	out	Outlet
co	Carbon offset	rec	Recovered
Cu	Copper	sHR	Savings due to heat recovery
del	Delivered	sLR	Savings due to loss reduction
e	Electricity	sT	Savings total
em	Emissions	sup	Supply

Assumptions

Parameter	Value	Unit	Reference
HPM	744	hours	-
RHI for ASHP 19/20 tariff	0.0275	£/kWh	(Ofgem, 2019)
$Price_g$	0.04	£/kWh	-
$Price_e$	0.10	£/kWh	-
$Price_{co}$.	95	£/tonne	(Greater London Authority, 2018a)

CEF_b	0.18	$kgCO_2e/kWh$	(Hill et al., 2018)
η_b (A+++ SEDBUK 2005 rating)	90%	-	(British Gas, 2019)
$CEF_{e,gen}$	0.28307	$kgCO_2e/kWh$	(Hill et al., 2018)
α_{Cu}	0.00390	K^{-1}	(Nave, 1998b)
α_{Al}	0.00429	K^{-1}	(Nave, 1998b)

1.0 Introduction

Over the past few years, the United Kingdom has achieved significant reduction of Greenhouse Gas (GHG) emissions (BEIS, 2020). The Climate Change Act (2008), which initially established a target to reduce carbon emissions by 80% of its 1990 baseline level by 2050, now amended to net-zero, was a driving force for these changes (CCC, 2019).

The heating and cooling sector accounts for approximately one third of carbon emissions and around half of the energy consumption in the UK (BEIS, 2018). Despite having considerable influence on how energy is consumed in Britain, currently very little heating and cooling is produced from renewable / low carbon energy sources. When compared to other European Union countries, the UK (benefitting from local hydrocarbon resources) has amongst the lowest share of renewable sources providing heating/cooling, at 7.5% of all the energy sources that are used (European Environment Agency, 2018).

The vast impact of human activity on the climate has now been thoroughly documented and understood. The mass deforestation and dependency on fossil fuels for transport, heating, and power generation, are some of the examples of causes of the drastic rise of Earth's surface temperatures since the Industrial Revolution. It has been proven and commonly recognised as a fact that the historically high levels of GHG emissions resulting from human activity are directly responsible for the extreme weather conditions, and rising sea levels posing a direct short-term threat to the human civisation (Carbon Brief, 2017; Stocker et al., 2013).

Currently around 57% of UK's new bulding stock incorporates heating systems utilising fossil fuels. As new regulations push towards acceleration of the transition to sustainable energy, the number is decreasing, however the observed reduction by 3% in the last decade is not enough to reach the net zero goal in time (CCC, 2020). In London, legislation has been introduced to promote the better use of energy in buildings, both for domestic and industrial/commercial use. The London Plan (Mayor of London, 2004), puts the focus on securing a low carbon energy supply for London and sets a target of achieving 25% of London's heat energy supply from decentralized or district energy schemes, by 2025. A particular advantage of district energy schemes is that they enable the use of highly efficient centralised plant for supplying low carbon heat at scale (Buffa et al., 2019). They also facilitate the capture and reuse of waste heat (Davies et al., 2017). A number of authors have investigated heat recovery from a range of waste heat sources including utility tunnel systems, e.g. geothermal utility tunnels (Yang et al., 2019), sewers (Fang et al, 2016), London Underground (Davies et al, 2019a) and subways and railways (Nicholson et al, 2014).

A number of opportunities for waste heat recovery and reuse are considered in Table 1, and the potential for using heat from underground cable tunnels is highlighted.

Table 1 - Potential waste heat sources in London (Adapted from Davies et al., 2017)

Waste Heat Source	Extent of infrastructure	Total Heat Output of Sector MW	Waste Heat Temperature °C	Potential as a Waste Heat Source?

Electricity cable tunnels	62.7 km *(32.5 more planned)*	57.7* (87.6 in 2026)	<44	High temperatures, medium to large quantity
Sewers	>1770 km	N/A	10-22	Low temperatures, unknown quantity / likely large
Underground railways	136 km of deep tube tunnels	15	17-28	Moderate temperatures, medium quantity
Data centres	75 co-location data centres (+ large number of enterprise data centres) in London	86	25-35	Moderate temperatures, medium quantity
Food manufacture and chemical processing	N/A	11.4	35-70	High temperatures, medium quantity
Power stations	5-10	945	>35	High temperatures, large quantity
Electricity substations	Hundreds	>30	50	High temperatures, medium quantity
Building air conditioning	Throughout London	924	28	Moderate temperatures, large quantity

(offices and retail)				

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

Electrical network operators often transmit electrical power through cables, which for cities, are housed in networks of tunnels. In London, many cable tunnels are large enough, around 2.5 m in diameter, to permit human access for maintenance and repairs. The cables produce significant quantities of heat, particularly at high electrical power loadings, and cooling is required, for example by forced ventilation of the tunnels using outside air. Temperatures increase along the length of the cable tunnels from that of the outside air at the point of introduction e.g. through an air supply ventilation shaft, to the point at which it leaves the tunnel e.g. through an exhaust ventilation shaft. The air flow rate and electrical power loadings used are selected on the basis of limiting the exhaust tunnel air temperature to a maximum of around 44°C (designated by UK Power Networks (UKPN) as the limit for human access to the tunnel). If network operators could reduce the air temperatures in their cable tunnels (and cables) further e.g. by introducing additional cooling, the electrical losses from the cables would be reduced. In addition, the heat generated in cable tunnels represents a significant heat resource, which the operator could recover and potentially sell for reuse.

Two heat recovery methods were investigated for cable tunnels by Davies et al. (2019b), namely: a combined cooling and heat recovery system, which has been termed a “cold led heat recovery system” (CLHR) as shown in Figure 2 and a heat recovery only system, which has been termed a “heat led heat recovery system” (HLHR) presented in Figure 2.

The study considered heat recovery from the cable tunnel to a heat pump which then provided heat to a local building. It showed significant benefits in terms of heat recovery potential.

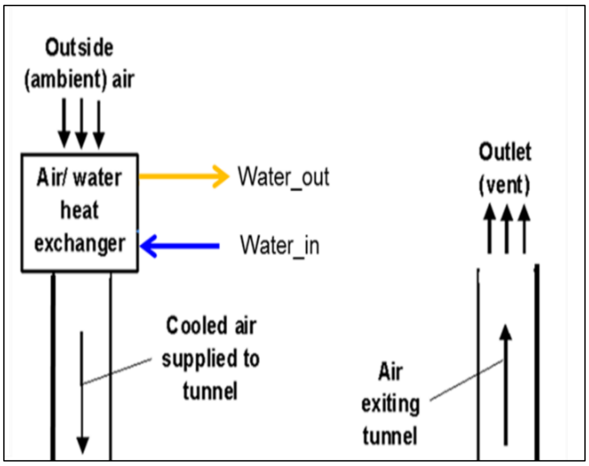

Figure 1 - CLHR diagram (Davies et al., 2019. Reprinted with permission.)

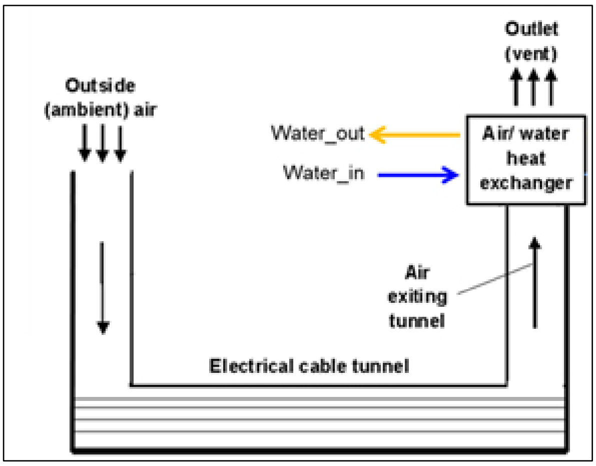

Figure 2 - HLHR diagram (Davies et al., 2019. Reprinted with permission.)

The objective of the present study is to understand the combined benefits of cooling on the power cable losses and heat recovery from the tunnel.

The paper describes the proposed technology and method of application, and investigates the technical, environmental and economic advantages of these systems.

2.0 Methodology and Analysis

The current work on the CLHR system considers specifically the benefits of cable tunnel cooling as well as secondary heat recovery. The system, as shown in Figure 3, combines cooling with heat recovery from a cable tunnel, with the recovered heat subsequently upgraded using a heat pump and transferred to a district heating (DH) network for distribution and reuse for domestic space heating and hot water heating. The heat exchanger (HEX) is installed in the head house at the supply end of the tunnel. This enables heat to be recovered from the ambient air entering the tunnel for cooling the cables within. The HEX is connected to a heat pump which upgrades the recovered heat which is then delivered to nearby buildings. Due to the tube and fin construction of the HEX, it is prone to fouling with air-borne particulates. Appropriate filters could be introduced to mitigate this. (This is not included in the model).

The HEX is used in place of a gas fired boiler therefore minimising the use of fossil fuel energy for heating. Tunnel cooling delivers additional benefits as the cable temperature decreases and the power losses due to Joule heating are reduced.

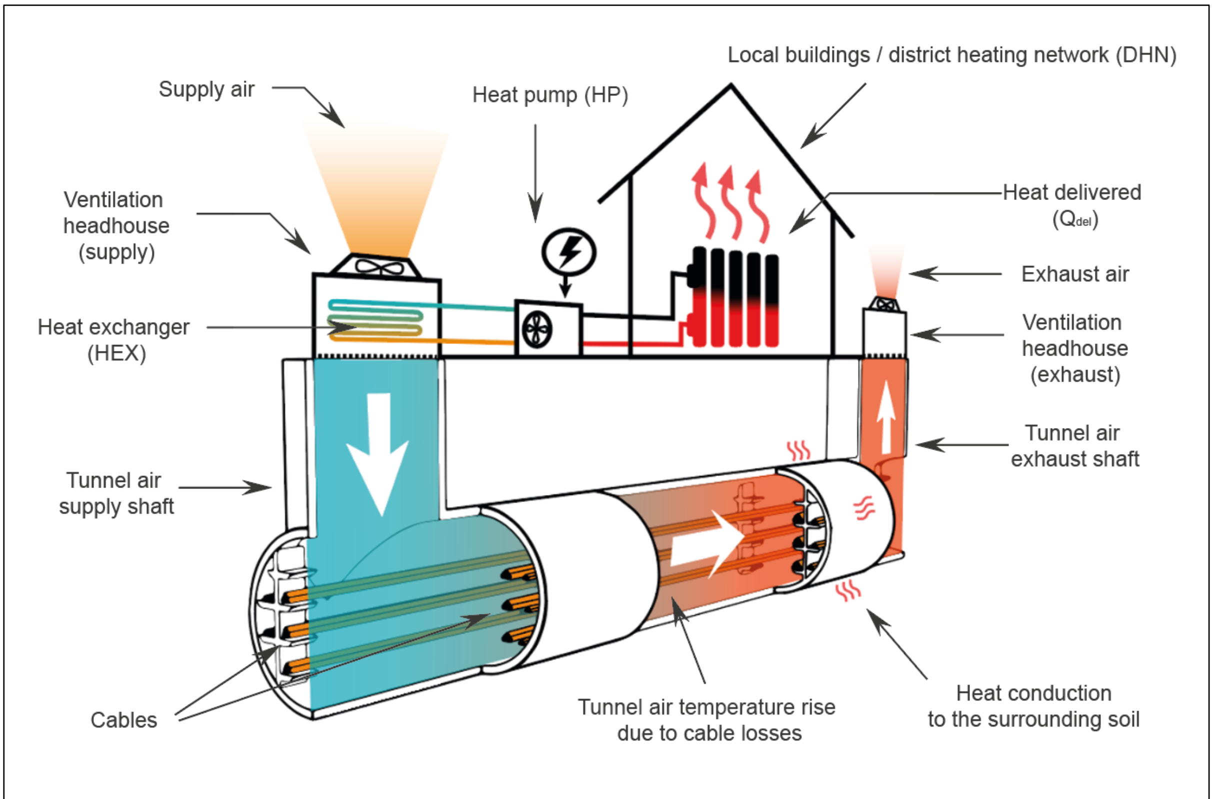

Figure 3 – Diagram of the CLHR system

The subject of the investigation was a 500 m long cable tunnel section, in central London. The tunnel had an internal diameter of 2.5 m and concrete wall thickness of 0.1 m. The lengths of the cables were assumed to be the same as the tunnel. The surrounding ground material is London Clay Formation.

A cross section of the simulated tunnel is presented in Figure 4. A number of power cables of differing capacity are shown, namely:

- 18 x 132 kV and
- 21 x 11 kV

The 11 kV cables operate much closer to their maximum current-carrying capacity, and consequently are responsible for a large proportion of the heat generation. Distribution network operator (DNO) data was used to determine the specifications of the cables, including the information about the conductor core material, which has been identified as copper (132 kV) and aluminium (11kV). Manufacturer data was also used to establish the cable resistance in Ohms/km at a reference temperature (T_0) of 20°C. The current load values were estimated using data for this particular section of the tunnel.

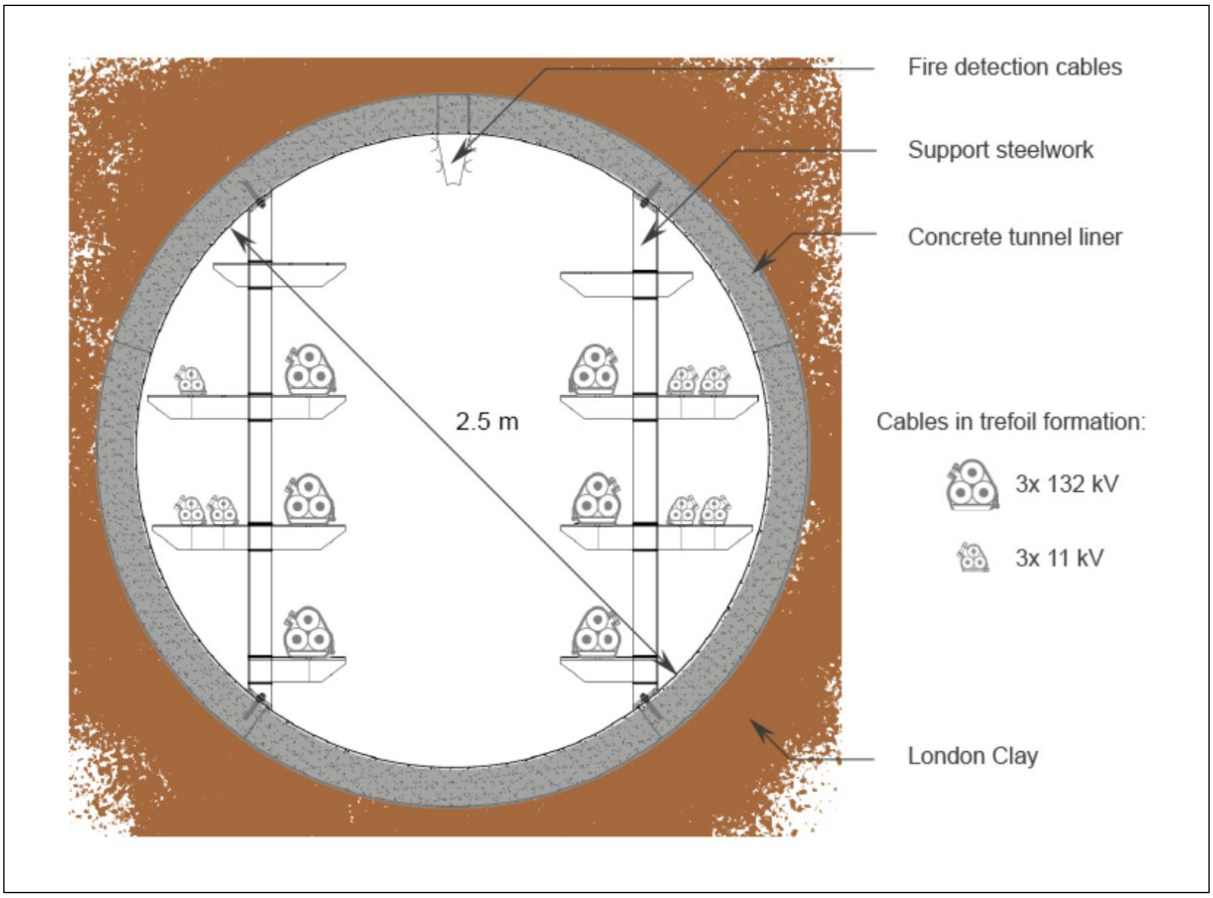

Figure 4 - Section drawing showing the number and capacity ratings of cables in the investigated tunnel

The methodology used to investigate the impact of heat recovery from air entering the tunnel involves both a numerical steady-state finite element (FE) model and two spreadsheet models as summarised in Figure 5.

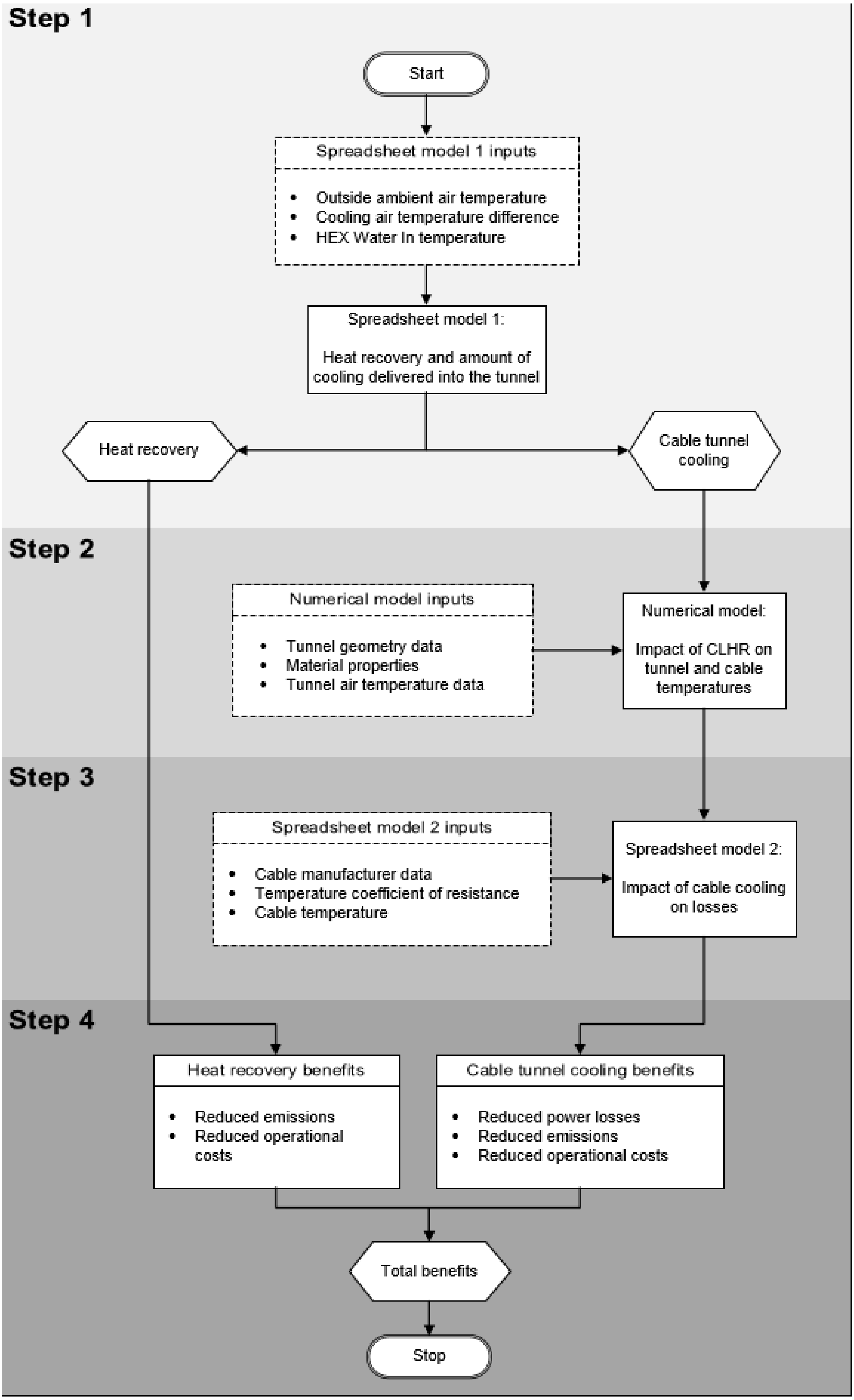

Figure 5 - Investigation approach summary workflow

2.1 Calculation of heat recovery and amount of cooling delivered into the tunnel

The heat recovery benefits associated with displacing gas used in the heating of local buildings (district heating network) as well as the benefit of cooling the tunnel air and lowering the cable temperature were calculated using a number of assumptions, in a spreadsheet model (1). Spreadsheet model 1, which was focussed on the CLHR system, consisted of input data in the form of monthly averaged temperatures for the air entering a fin and tube heat exchanger (HEX), an assumed approach temperature between the air side and water side of the HEX of 2 K, a temperature gain on the water side of 5 K, and a delivery temperature for the heat pump of 65°C.

A summary of the assumptions used in spreadsheet model 1 are listed in Table 2,

Table 2 – Summary of key assumptions (Adapted from Davies et al., 2019)

Configuration, supply temperature, cost and carbon	Heat was recovered using a fan coil HEX located at the head of the air supply shaft.
	The heated water was transported through pipes to the heat pump.
	The water temperature was then upgraded using the heat pump for delivery at 65°C.
	The degree of cooling of the outside air prior to supply to the tunnels (ΔT) depends on the outside air temperature.
	The ΔT was selected to ensure that the heat pump operated with a COP > 3.
	The cost for delivery of 1 MWh of heat, for recovered heat (with and without RHI), was compared to that for a gas boiler.
	RHI was applied to recovered heat at a tariff of £0.0269 per kWh.
	% carbon saving for recovered heat compared to that for a gas boiler was also calculated.

For the air to water fan coil HEX	An approach temperature (air side to water side) of 2K.
	Water side temperatures of less than 0˚C can be achieved using a water/glycol mixture.
	A temperature gain on the water side of 5K in each case.
	A pressure drop on the air side of the HEX of 0.3 bar.
	The outside air temperatures based on UK meteorological data for London, averaged for each month during the year.
For the cable tunnel	An average air velocity through the tunnel of 4 m/s.

The equations listed below were used to identify the energy and cost savings resulting from applying the CLHR.

Details of the application of spreadsheet model 1 to the CLHR method are provided in Davies et al (2019b). The results can be summarized as: (i) the quantity of heat recovered (Q_{rec}) from outside air varied from 64.1 to 310.8 kW during the year, and that heat recovery was lowest in winter and highest in summer; (ii) in each case, a heat pump COP of > 3 was achieved for delivery of the upgraded heat (Q_{del}) at 65°C; (iii) the cost for delivery of 1 MWh of recovered heat was significantly less (i.e. 40-50%) than that for a gas boiler when RHI was included; and (iv) carbon savings of 52-57% for the heat recovery system compared with gas boiler heating were identified.

The monthly energy savings for the heat pump system combined with heat recovery, E_{sHR}, were calculated as follows,

$$E_{sHR} = (E_{in,b} - E_{in,hp}) \tag{1}$$

Where $E_{in,hp}$ is the monthly energy input to the heat pump for the waste heat recovery system:

$$E_{in,hp} = \left(\frac{Q_{rec}}{COP_h - 1}\right) \times \mathrm{HPM} \tag{2}$$

Where Q_{rec} is the heat recovered by the fan coil heat exchanger, COP_h is the coefficient of performance for heating, and HPM is hours per month. $E_{in,b}$ is the energy input for a gas boiler to deliver the same amount of heat as the heat pump:

$$E_{in,b} = \frac{Q_{del}}{\eta_{\mathrm{b}}} \times \mathrm{HPM} \tag{3}$$

where Q_{del} is the heat delivered and η_b is the gas boiler efficiency

Monthly values were also calculated for: energy cost savings due to heat recovery ($\mathrm{Cost_{sHR}}$), reduction in carbon emissions due to application of heat recovery ($\mathrm{CDE_{sHR}}$), and cost savings related to reduced emissions ($\mathrm{Cost_{em,sHR}}$). These were calculated as follows:

$$Cost_{sHR} = \left(\left(E_{in,b} \times \mathrm{Price_g}\right) - \left(E_{in,hp} \times \mathrm{Price_e}\right)\right) \times \mathrm{HPM} \tag{4}$$

where $\mathrm{Price_g}$ and $\mathrm{Price_e}$ are respectively the price of gas and electricity in £/kWh;

$$CDE_{sHR} = \left(\left(Q_{del} \times \frac{\mathrm{CEF_b}}{\eta_{\mathrm{b}}}\right) - \left(E_{in,hp} \times \mathrm{CEF_{e,gen}}\right)\right) \times \mathrm{HPM} \tag{5}$$

where CEF_b and $CEF_{e,gen}$ represent associated carbon emissions factors for natural gas and for electricity supplied to the grid (plus imports) in $kgCO_2e/kWh$; and

$$Cost_{em,sHR} = CDE_{sHR} \times 1000 \times \mathrm{Price}_{co} \tag{6}$$

where Price_{co} is the carbon offset price.

The monthly benefits resulting from adaptation of CLHR in the air intake of a 500 m long cable tunnel section are presented in Figure 6 and Figure 7. Totalling the cost savings for the heat recovery system in Figure 6 shows that there is potential for over £30k of annual savings compared to a gas boiler. Totalling the carbon dioxide equivalent savings in Figure 7 shows that nearly 270 tonnes of CO_2e with a value of over £25k can be saved every year through use of heat recovery.

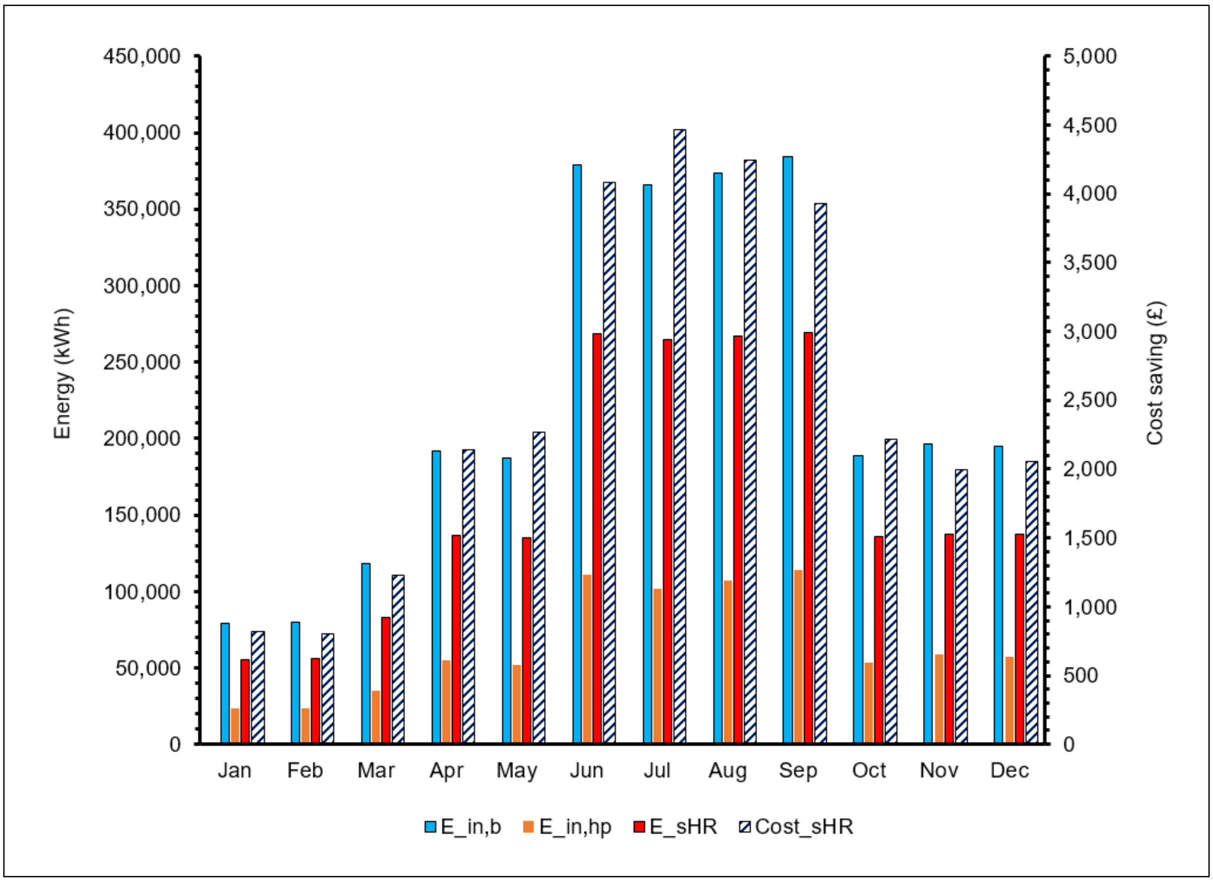

Figure 6 - Monthly energy savings resulting from waste heat recovery

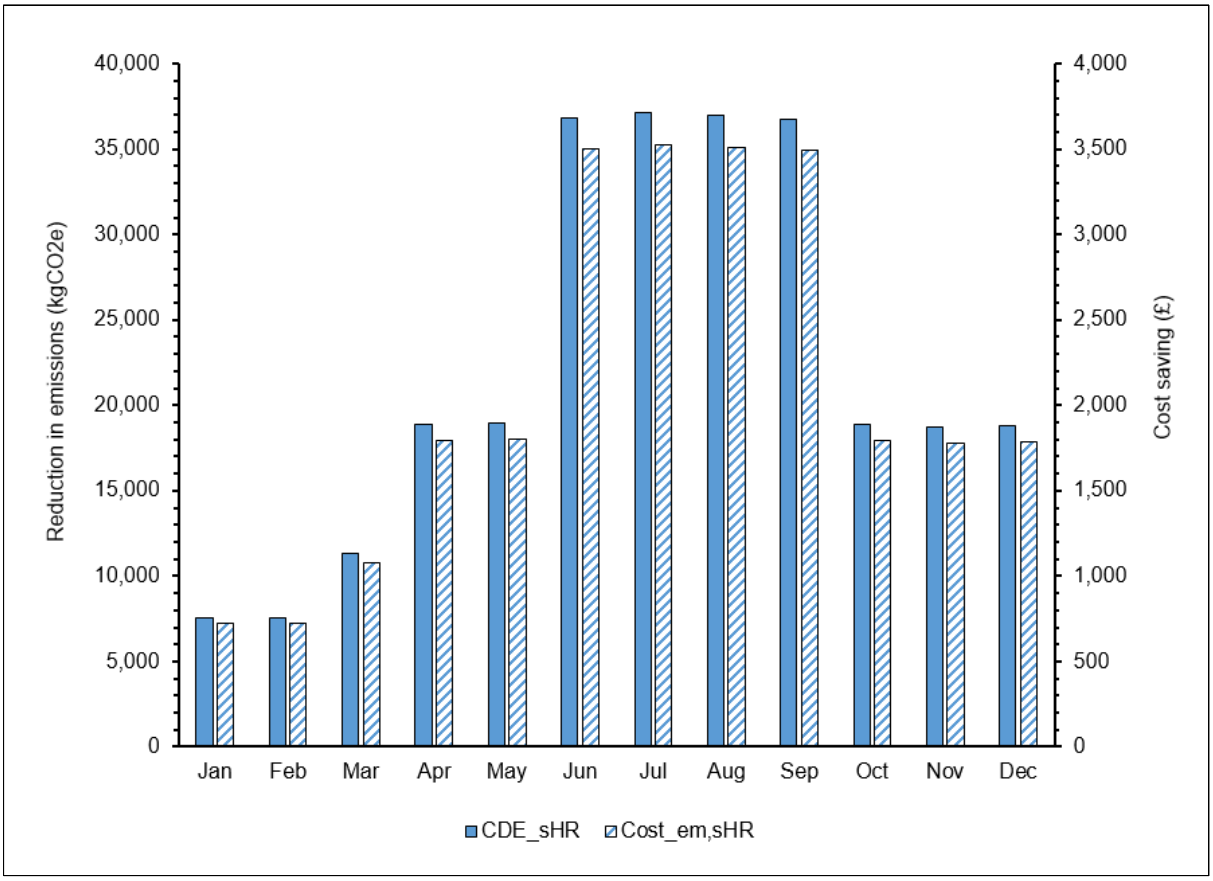

Figure 7 - Monthly carbon emissions savings resulting from waste heat recovery

2.2 Numerical modelling of the impact of CLHR on tunnel and cable temperatures

A steady state finite element (FE) model was built with the software package COMSOL Multiphysics. This enabled the investigation of the impact of heat recovery at the supply end ventilation shaft on tunnel air and cable temperatures. The model was built in 3 dimensions (3-D). The geometrical parameters, material properties, initial conditions and boundary conditions implemented within the model were based on typical operating conditions for an urban cable tunnel.

The numerical model was configured to represent a single cable tunnel section with 6 stacks of 3 cables, combining the heat generation potential of 132 kV and 11 kV assets. A cross section of the tunnel indicating the tunnel air, cables and concrete liner is shown in Figure 8 (a). The overall model geometry is shown in Figure 8 (b).

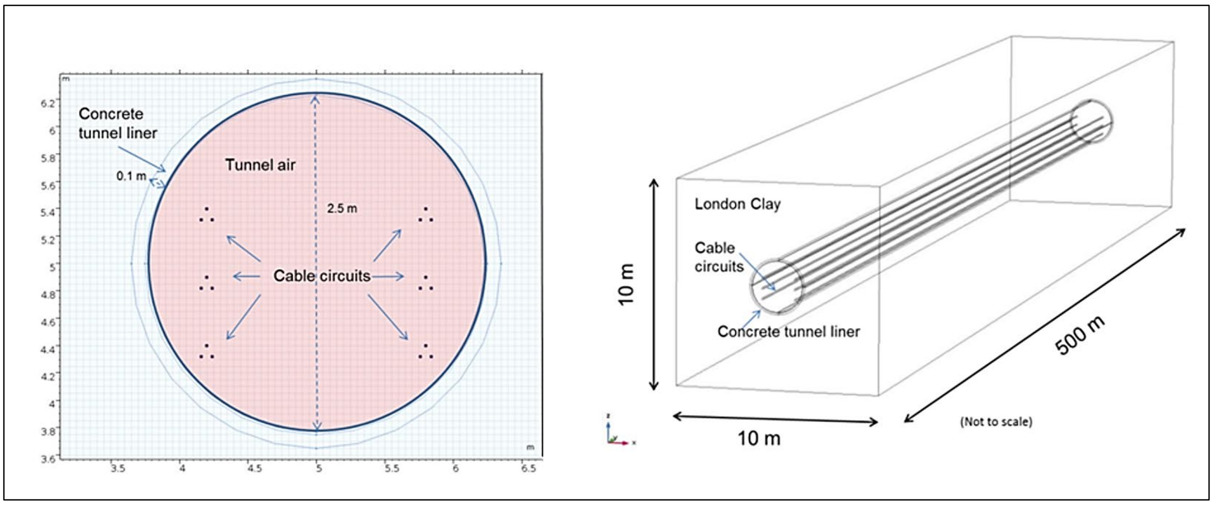

Figure 8 - (a) Cable tunnel cross section and (b) 3D model geometry (b) (Davies et al., 2019b. Reprinted with permission.)

First a benchmark model was created in order to represent typical operating conditions within the cable tunnel. This was achieved by using measured temperature data provided by an electrical network operator for the period between June and November 2017. In particular, tunnel air temperatures for the selected section, which ran between two ventilation shafts, were used to establish an average temperature difference. This temperature difference implies an average heat transfer rate i.e. heat generation rate of 31 W/m, for each cable (this has been validated using network operator's current load data).

The benchmark model was first used to simulate the tunnel environment without any cooling applied to the supply air. Simulation results for the standard operation for the selected months are presented in Figure 9. The outlet temperature ($T_{air,out}$) values output from the model are comparable to those from field measurements. The simulations were then repeated for the same months in order to investigate the effect of applying the CLHR scheme on the tunnel environment. Consequently, the main input parameter varied for the model was the air supply temperature to the cable tunnel ($T_{air,sup}$). For each simulation, an average air velocity of 4 m/s was assumed throughout the length of the cable tunnel, based on data supplied by UKPN. During the simulations the following parameters were investigated:

i. average air temperature along the length of the tunnel ($T_{air,av}$);
ii. temperature of the air exiting the tunnel ($T_{air,out}$);
iii. average temperature of the cables throughout their length (T_{cab}).

Due to the low supply air temperatures in October and November the heat removal rate was reduced to prevent tunnel air temperatures falling below the dew point.

Figure 9 and Figure 10 combine the results of Table A1 and Table A2 (please see Appendix A. Tables), and illustrate the impact of supplying air to the tunnels at lower temperatures on the average tunnel air and cable temperatures respectively (Davies et al., 2019b).

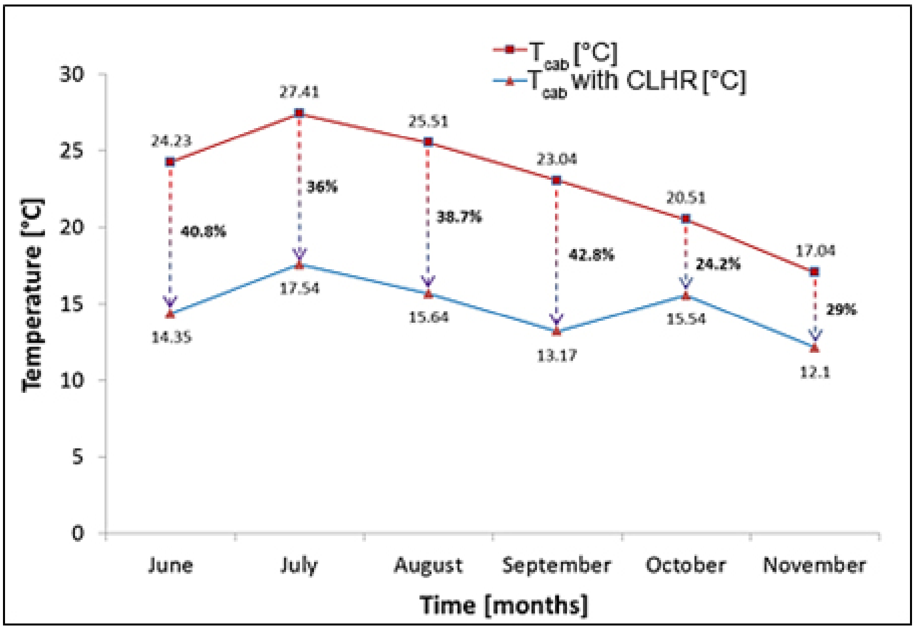

Figure 9 - Summary of numerical simulation results for cable temperatures with and without CLHR (Davies et al., 2019b. Reprinted with permission.)

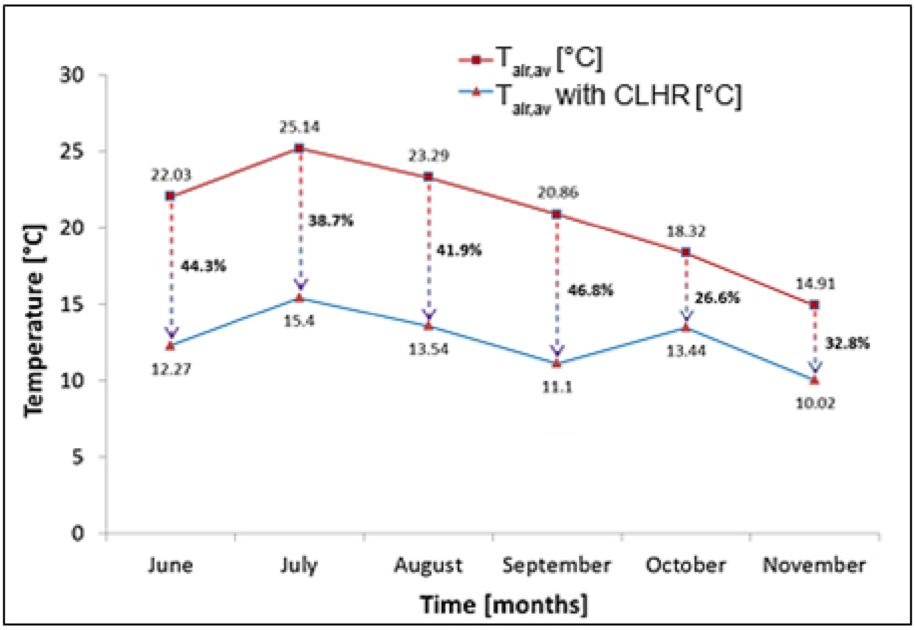

Figure 10 - Summary of numerical simulation results for tunnel air temperatures with and without CLHR (Davies et al., 2019b. Reprinted with permission.)

It is seen in the figures that reducing supply temperatures through heat recovery can significantly reduce average air and cable temperatures along the length of the tunnel. Both average air and cable temperatures have been reduced by approximately 8°C. This can result in many benefits for electrical cable tunnel operators, for example: revenues from the sale of waste heat; more efficient operation of cable tunnels by cooling the supply air; reduced operational costs through reduced ventilation; increased loading of cables,

2.3 Impact of cable cooling on losses

The relationship between cable temperature and its resistance has been investigated. The cable benefit is calculated in terms of reduction of carbon emissions and power losses.

A second spreadsheet model (spreadsheet model 2) has been developed to relate the tunnel air and cable temperatures to the power losses from cables and the savings in power losses, carbon emissions and costs due to cooling with CLHR system.

Temperature values for tunnel inlet and outlet air, average tunnel air, and cables input to the model was provided by the operator for June to November. For the remaining months the values were derived from a comparable average.

Heat generation rate (P) from power cables was calculated using the rearranged general power equation (7).

$$P = I^2 \times R \tag{7}$$

The change in cable temperature due to tunnel cooling has a positive influence on the conductor resistance (R) and therefore on the amount of power losses. The effect can be calculated using Equation (8), expressing resistor temperature dependence (Nave, 1998b).

$$R = \mathrm{R}_0 \times \left(1 + \alpha \times (\mathrm{T}_0 - T)\right) \tag{8}$$

The electrical resistance values of the 132 kV and 11 kV cables with and without CLHR were calculated using Equations (9) and (10) respectively.

$$R_{132} = \mathrm{R}_{132,0} \times \left(1 + \alpha_{\mathrm{Cu}} \times (20 - T_{132})\right) \tag{9}$$

$$R_{11} = \mathrm{R}_{11,0} \times \left(1 + \alpha_{\mathrm{Al}} \times (20 - T_{11})\right) \tag{10}$$

Equation (11) was then used to determine the value of loss reduction in all cables combined, according to their type.

$$P = I^2 \times (\mathrm{R}_0 - R) \times \mathrm{N}_{\mathrm{cab}} \times 1000 \tag{11}$$

Monthly values were calculated for: (i) Electricity saving (E_{sLR}), kWh; (ii) Cost saving, ($Cost_{sLR}$) £; (iii) Carbon emissions reduction,(CDE_{sLR}) kg; (iv) revenue value of reduced carbon emissions ($Cost_{em,sHR}$) (£).

$$E_{sLR} = (P_{132} + P_{11}) \times \mathrm{HPM} \tag{12}$$

$$Cost_{sLR} = E_{sLR} \times \mathrm{Price_e} \tag{13}$$

$$CDE_{sLR} = E_{sLR} \times \mathrm{CEF_{egen}} \tag{14}$$

$$Cost_{em,sHR} = CDE_{sHR} \times 1000 \times \mathrm{Price_{co}} \tag{15}$$

The impact of cable tunnel cooling on power cable losses, derived from spreadsheet model 2, is summarised in Figure 11 and Figure 12. The Figures present the data listed in Table A3, which shows that nearly £8k can be saved by cooling the cables alone as a combined revenue benefit of energy savings totalling 60 MWh/year from reduced cable resistance, and operation emissions.

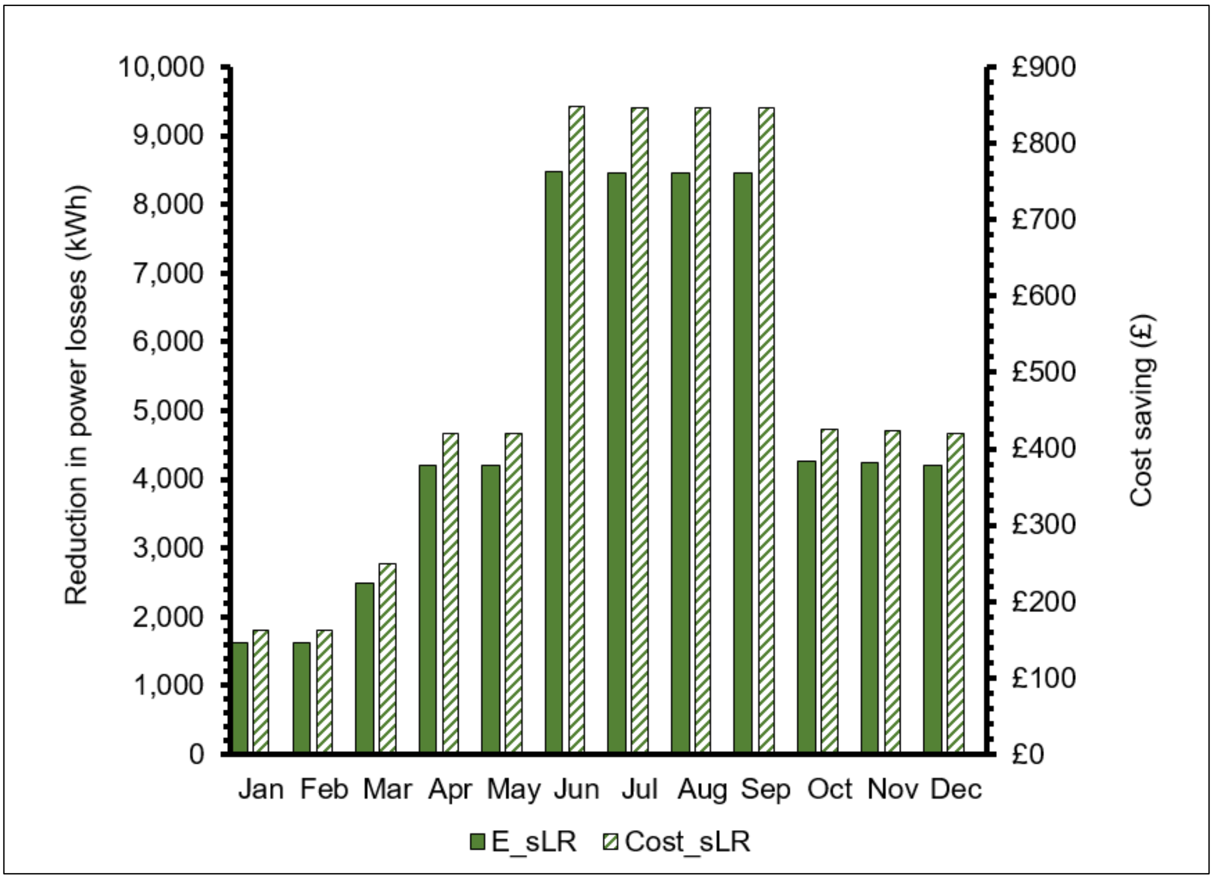

Figure 11 - Estimated monthly energy savings resulting from cable tunnel cooling

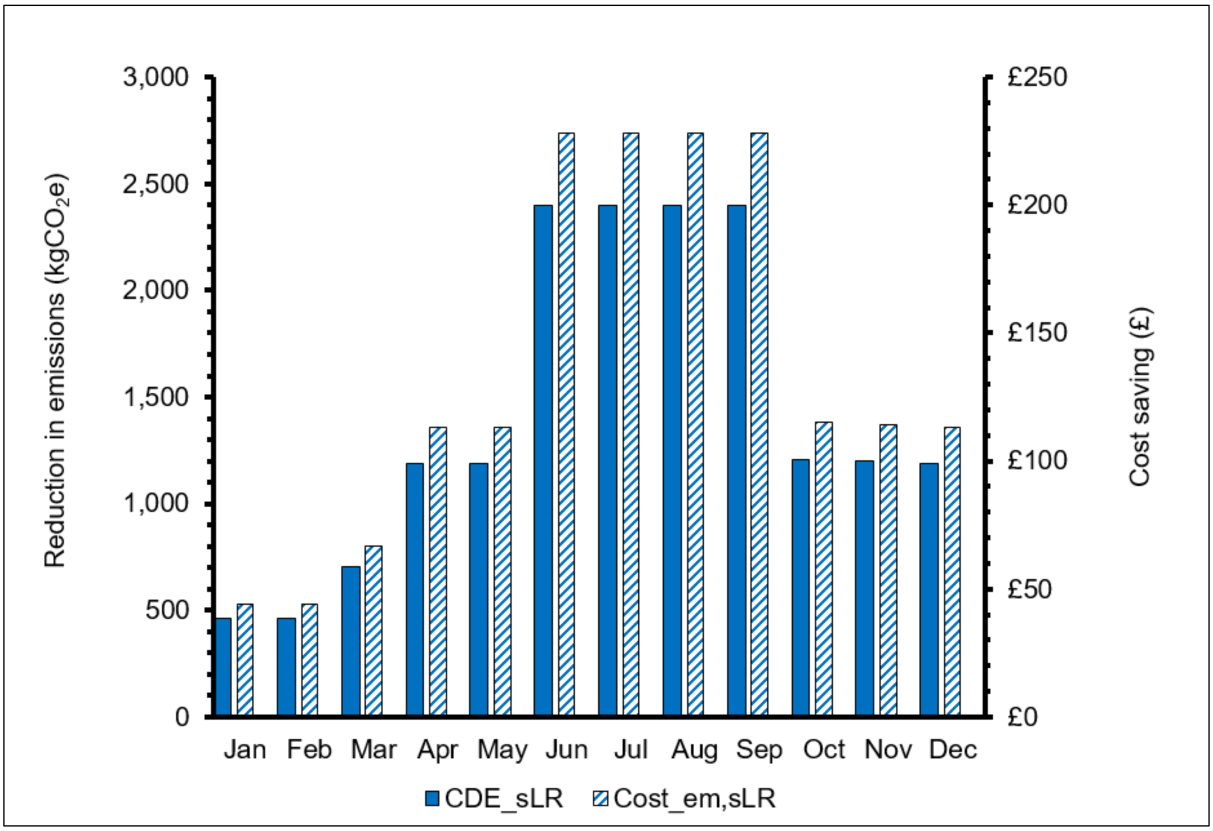

Figure 12 - Estimated monthly emissions savings resulting from cable tunnel cooling

2.4 Combined / Total Benefits

This section brings together the combined benefits associated with heat recovery (Workflow Step 1), replacing a gas boiler and cable cooling (Steps 2 & 3)

The combined monthly energy savings (16), carbon emissions reduction (17) and cost savings (18) due to heat recovery and tunnel cooling (E_{sT}) were calculated as follows:

$$\mathrm{E_{sT}} = E_{sHR} + E_{sLR} \tag{16}$$

$$CDE_{sT} = CDE_{sHR} + CDE_{sLR} \tag{17}$$

$$Cost_{sT} = Cost_{sHR} + Cost_{em,sHR} + Cost_{sLR} + Cost_{em,sLR} \tag{18}$$

Figure 13 (Table A4) shows the combined monthly benefits of heat recovery and power cable cooling for a 500 m tunnel section. The study demonstrates that a total of over 2 GWh of energy, 285 tonnes of CO_2, and £63,000 can be saved annually through:

- replacing the gas boiler with a heat pump, and
- moving the heat from tunnel intake air to the district heating network, thereby lowering the power cable losses.

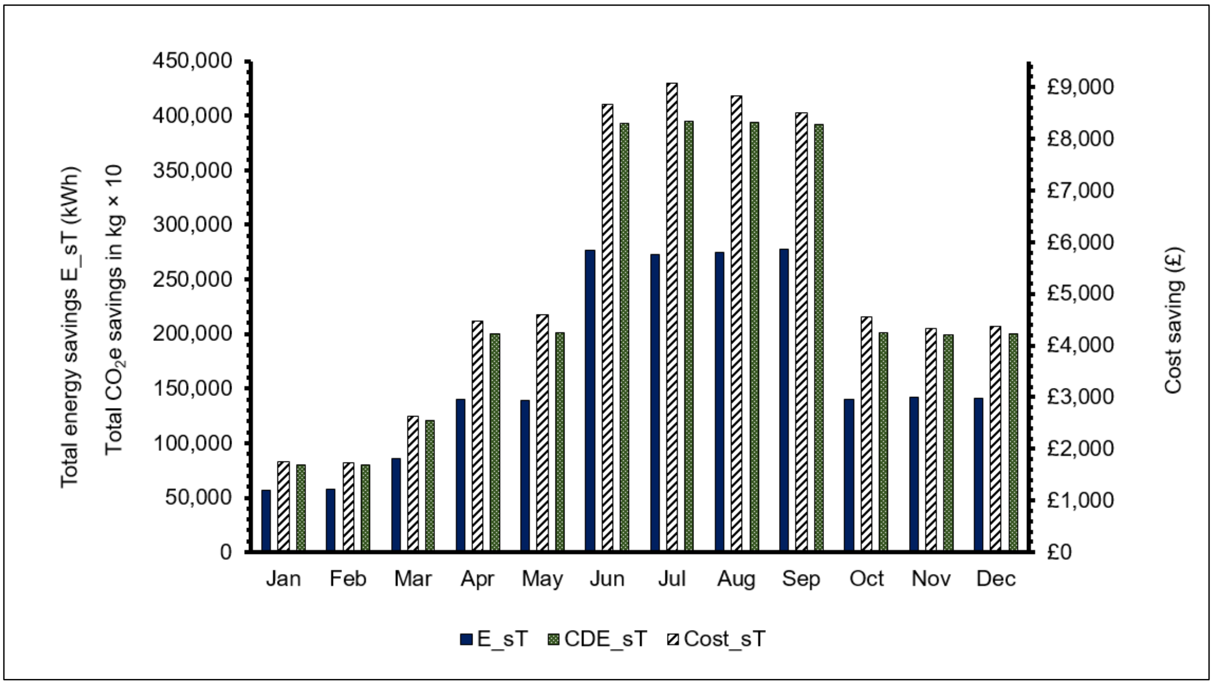

Figure 13 - Combined monthly benefits of heat recovery and power cable cooling

3.0 Discussion

This section describes benefits, barriers, and suggests future work in order to realise the potential of heat recovery from cable tunnels.

Benefits

This cable tunnel study shows that a combined cooling and heat recovery solution can deliver a wide range of benefits. These can be summarised as saving 4,000 kWh of combined heat and electrical energy, reducing carbon emissions by 600 kg CO_2e and reducing operating costs by over £100, all per metre of tunnel per annum. The total annual benefits of the modelled system, compared against the conventional gas boiler are presented schematically in Figure 11. The bars represent the emissions, kgCO_2e/year, with and without the gas boiler and the operating cost saved (including RHI) through heat recovery and cable cooling with its effect on the electric power transmission losses. The annual reduction in losses from the lowered cable resistance is 120 kWh per meter of tunnel (over 60 MWh/year for a 500 m long tunnel section). Together the combined savings associated with carbon emissions for cable losses and heat recovered are significant, offering a meaningful step towards fulfilling the United Kingdom's commitment to bring all greenhouse gas emissions to net zero by 2050 (CCC, 2020).

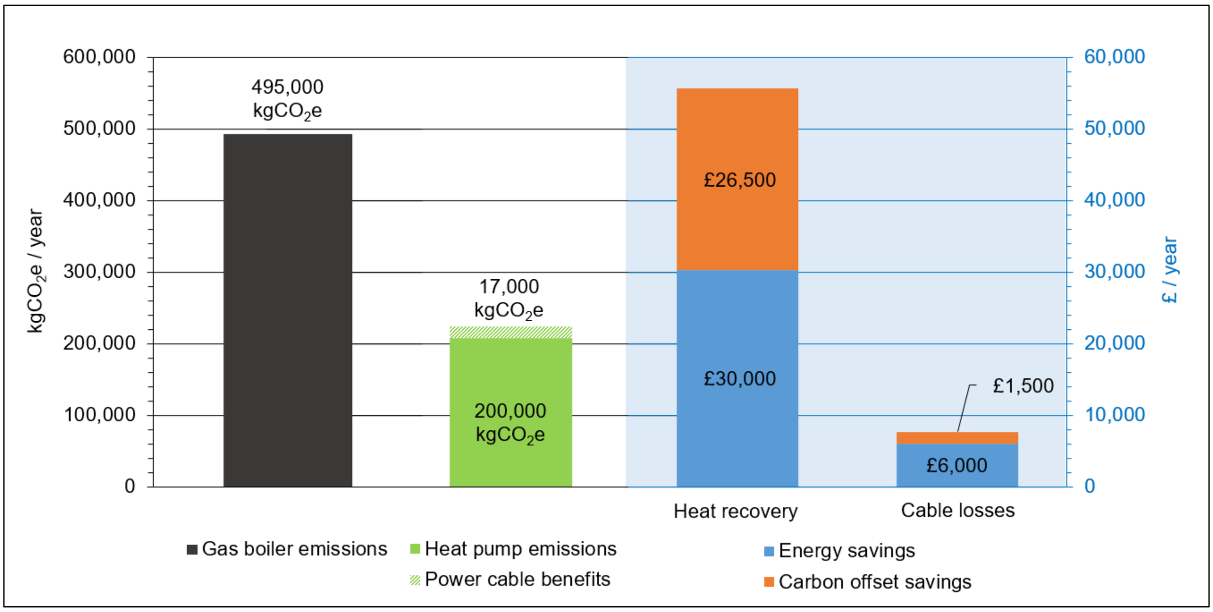

Figure 14 - Annual carbon emissions savings and revenue benefits for the 500 m cable tunnel study

Cable operators could potentially recover revenue through sale of recovered heat, for example to neighbouring buildings or greenhouses, or swimming pools. The potentially reduced ventilation loads would lead directly to cost savings and provide the additional benefit of cleaner air within the tunnel due to the air being filtered. Preventative maintenance, i.e. periodical filter replacement / cleaning would be necessary. Introducing air filtration to the system might increase the electrical load on the fan and further investigation is recommended.

As well as these direct benefits, the potential city-wide savings may be magnified considerably from this small-scale study given the 62.7 kilometres of cable tunnels in London, with another 32.5 km planned for completion in 2026 (National Grid plc, 2018). The London Plan (Mayor of London, 2004), focusing on securing a low carbon energy supply with a target of achieving 25% of London's heat energy supply from decentralized or district energy schemes by 2025, has recently been revised to zero net carbon by 2050 (Greater London Authority, 2018b).

The key benefit of using a DH system is its versatility as the heat can be derived from a range of different sources, coupled with thermal stores, renewable energy sources, battery storage, and AI-driven control technology. This way the harnessed thermal and electrical energy can be conserved and distributed autonomously according to the demand, despite the often intermittent nature of its source. Integration of waste heat sources in to such combined framework is defined in Lund et al. (2014) and Revesz et al. (2020), and the barriers and enablers were investigated in numerous studies, including: Dvorak et al. (2020), Lagoeiro et al. (2019), Marques et al. (2020), as well as for the case of district cooling in Inayat and Raza (2019). Therefore, while there may be some limitations, there is considerable potential to develop the cable tunnel concept shown here, to move progressively towards a zero-carbon future, considering the full range of tunnels identified. The opportunity is set to expand with the electrification of existing cities and developing urbanisation worldwide.

Additional potential in UK cities may be derived from the wide range of other cable-based applications including rail / road / communication tunnels, and cables in conduits directly laid in the ground. Country-wide, the carbon emissions savings become highly significant towards delivering low carbon sustainable development. A method used to investigate the availability of energy in city-wide situations was described by Paiho et al. (2019) and this could be adapted to understand the potential.

Barriers

The practicalities of implementation are important. Because of the large variation in heat output across the year it is likely that this scheme would need to form part of a hybrid scheme with supplementary heating from other sources being used when required, to make up any shortfall. Also the capital cost (e.g. of the HEX, HP, and other equipment.) may impact on deployment – and is likely to be one of the main barriers. Other associated costs include extracting or upgrading the heat from the waste heat source, and installing the pipework within the ground (usually DH pipes are run under roads alongside other utilities) and connecting into individual buildings. Typically, the cost of running DH pipework in an urban area can be estimated at about £1,000/m, with a typical additional connection cost to a two-bedroom flat of approximately £1,000 (Matson, 2018). The key to realising a successful DH scheme is to minimise the capital cost but maximise the number of customers connecting to the network.

One additional potential challenge is presented by noise generated by the heat pump, dependent on the type of the equipment, its location and design. The impacts can be split up into three categories: a) noise impact on the local environment; b) noise impact on adjacent properties; c) noise impact on the residential unit itself. Such equipment noise can be mitigated with use of solutions such as acoustic screening (Lefevre, 2018). Additionally, is it important to consider the amount of space required for the plant and the feasibility of locating the heat pump in near proximity to the heat source and demand (Mattoni et al., 2019).

Limitations of the study and Further work

While this study already presents significant savings, there is scope for further improvement. One area that could be investigated is additional heat recovery at the discharge air shaft, similar to the heat lead heat recovery system reported by Davies et al. (2019b) delivering a constant 400 kW throughout the year. Also, the model required a number of assumptions, which depend on the specific location and existing infrastructure. It assumes that the cables in the tunnel are under constant load conditions at all times while in reality, the load on the energy transmission network varies throughout the day and night. It would be useful to test these assumptions elsewhere. Dedicated investigations are recommended for every installation. This is important for evaluating the HR system performance and the capital investment required. In addition, further work to evaluate other secondary heat sources e.g. data centres, sewers and underground railway tunnels, is underway and will expand the number of opportunities.

4.0 Conclusions

This paper provides a first known investigation into the opportunities of recovering heat from cable tunnels. Cable tunnels are being used in cities to distribute electrical power, often over many kilometres. This paper investigates a novel system for capturing of significant amount of heat generated in the tunnel from the cables and its use in buildings for heating and hot water and lowering the tunnel temperature. The scheme proposed is a "cold led heat recovery" system whereby air entering the tunnel is actively cooled, the temperature of this heat is then raised using a heat pump and this can be then utilised in nearby buildings. Because the proposed heating system uses a heat pump, which is more efficient than conventional gas boilers, significant energy and carbon savings can be achieved. However, there are also secondary energy and carbon benefits since the tunnel inlet air is actively cooled and the temperatures can be lowered further with the effect of reducing electrical distribution losses from the cables themselves.

This study investigates the savings that can be achieved using this system employing a mix of real measured data from a cable tunnel in London, combined with a steady state finite element (FE) model and a bespoke techno-carbon-economic model for the system including heat pump, cables, heat exchanger and the tunnels themselves. In each case, the tunnel air and cable temperatures predicted by the models are based on relatng spot measured values to specific operating conditions. These are subsequently interpolated by the models using standard physical properties of materials and heat transfer characteristics to predict tunnel air and cable temperatures under a range of operating conditions. Therefore, the results are partially validated and plausible. The energy, carbon and cost savings are consequent to the tunnel air and cable temperatures predicted.

The paper identifies significant savings in terms of carbon, energy and operating cost. For this example, the savings are 570 kg CO_2e and 4000 kWh of combined electrical and heat energy, and £127 cost saving per meter of cable tunnel and it is likely that the use of cable tunnels in cities will expand with further decarbonisation and urbanisation. Another significant additional benefit is the potential for reducing particulates from using this approach. However, potential challenges include space and acoustics, which are both big issues in cities. The novel approach proposed is not, however, restricted to cable tunnels. Further work is underway to develop this approach to consider the benefits associated with heat recovery from cables in the ground, as well as other types of tunnels such as underground and overground rail, motorways, and sewers, of which there is a vast global network..

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Competing Interests

The authors have no competing interests to declare.

References

British Gas. (2019). How efficient is my boiler? Retrieved from https://www.britishgas.co.uk/home-services/boilers-and-heating/guides/boiler-efficiency.html

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) Retrieved from https://doi.org/10.1016/j.rser.2018.12.059

Carbon Brief. (2017). Analysis: Why scientists think 100% of global warming is due to humans. Retrieved from https://www.carbonbrief.org/analysis-why-scientists-think-100-of-global-warming-is-due-to-humans

Climate Action Tracker. (2020). United Kingdom - Country Assessment Graph. Retrieved from https://climateactiontracker.org/countries/uk/

Committee on Climate Change (CCC). (2019). Net zero: The UK's contribution to stopping global warming. Retrieved from https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

Committee on Climate Change (CCC). (2020). Reducing UK emissions: 2020 Progress Report to Parliament. Retrieved from https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament/

Davies, G., Boot-Handford, N., Grice, J., Dennis, W., Ajileye, A., Revesz, A., & Maidment,

G. (2017). Heat Recovery Potential from Urban Underground Infrastructures. Presented at the ASHRAE Winter Conference., Chicago. August 22, 2017. Retrieved from https://openresearch.lsbu.ac.uk/item/86w29

Davies, G., Boot-Handford, N., Curry, D., Dennis, W., Ajileye, A., Revesz, A., & Maidment, G. (2019a). Combining cooling of underground railways with heat recovery and reuse. Sustainable Cities and Society, 45, 543–552. https://doi.org/10.1016/j.scs.2018.11.045

Davies, G., Revesz, A., Maidment, G., Davenport, A., & Yazadzhiyan, B. (2019b). Cooling with heat recovery for electrical cable tunnels in cities. Presented at the CIBSE Technical Symposium, Sheffield, UK. April 7, 2019. Retrieved from https://openresearch.lsbu.ac.uk/item/866ww

Department for Business, Energy & Industrial Strategy (BEIS). (2018). Clean Growth – Transforming Heating Overview of Current Evidence December 2018. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/766109/decarbonising-heating.pdf

Department for Business, Energy & Industrial Strategy (BEIS). (2020). Final UK greenhouse gas emissions national statistics: 1990 to 2018. Retrieved from https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2018

Dvorak, V., Zavrel, V., Torrens Galdiz, J. I., & Hensen, J. L. M. (2020). Simulation-based assessment of data center waste heat utilization using aquifer thermal energy storage of a university campus. Building Simulation, 13(4), 823-836. doi:10.1007/s12273-020-0629-y

European Environment Agency. (2018). EEA Report No 20/2018: Renewable energy in Europe 2018 — Recent growth and knock-on effects. In European Environment

Agency. Retrieved from https://www.eea.europa.eu//publications/renewable-energy-in-europe-2018

Evans, S. (2019). In-depth Q&A: The UK becomes first major economy to set net-zero climate goal. Retrieved from https://www.carbonbrief.org/in-depth-qa-the-uk-becomes-first-major-economy-to-set-net-zero-climate-goal

Fang, L. L., Valverde-Pérez, B., Damgaard, A., Plósz, B. G., & Rygaard, M. (2016). Life cycle assessment as development and decision support tool for wastewater resource recovery technology. Water Research (Oxford), 88, 538-549. doi:10.1016/j.watres.2015.10.016

Greater London Authority. (2018a). Carbon offset funds - Greater London authority guidance for London's local planning authorities on establishing carbon offset funds. Retrieved from https://www.london.gov.uk/sites/default/files/carbon_offsett_funds_guidance_2018.pdf

Greater London Authority. (2018b). London environment strategy. Retrieved from https://www.london.gov.uk/sites/default/files/london_environment_strategy_0.pdf

Hill, N., Bonifazi, E., Bramwell, R., Karagianni, E., & Harris, B. (2018). 2018 GOVERNMENT GHG CONVERSION FACTORS FOR COMPANY REPORTING methodology paper for emission factors: Final report. Department for Business Energy & Industrial Strategy. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/726911/2018_methodology_paper_FINAL_v01-00.pdf

Inayat, A., & Raza, M. (2019). District cooling system via renewable energy sources: A review. Renewable & Sustainable Energy Reviews, 107, 360-373. doi:10.1016/j.rser.2019.03.023

Lagoeiro, H., Revesz, A., Davies, G., Maidment, G., Curry, D., Faulks, G., & Murawa, M. (2019). Opportunities for integrating underground railways into low carbon urban energy networks: A review. Applied Sciences, 9(16), 3332. doi:10.3390/app9163332

Lefevre, T. (2018). Low carbon heat: heat pumps in London. Greater London Authority website: https://www.london.gov.uk/sites/default/files/low_carbon_heat_-_heat_pumps_in_london_.pdf

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th generation district heating (4GDH). Energy (Oxford), 68, 1-11. doi:10.1016/j.energy.2014.02.089

Marques, C., Tozer, R., Revesz, A., Dunham, C., Jones, P., Matabuena, R., . . . Maidment, G. (2020). GreenSCIES – green smart community integrated energy systems – integration with data centres. Retrieved from https://openresearch.lsbu.ac.uk/download/bb33833df8ac69dd6a09e58cd4f487a6ef5781fda13d0eee786129bf4071f72d/1180142/2020_April_2_Catarina_Marques_final.pdf

Matson, C. (2018, February 7). Why district heating is becoming more popular across the UK. Retrieved from http://www.recyclingwasteworld.co.uk/in-depth-article/district-heating-can-help-bring-financial-savings-and-low-carbon-energy-to-the-uk/168366/

Mattoni, B., Nardecchia, F., & Bisegna, F. (2019). Towards the development of a smart district: The application of a holistic planning approach. Sustainable Cities and Society, 48, 101570. doi:10.1016/j.scs.2019.101570

Mayor of London. (2004). The London Plan. Spatial Development Strategy for London. Retrieved from https://www.london.gov.uk/sites/default/files/the_london_plan_2004.pdf.

National Grid plc. (2018). London power tunnels 2. Retrieved from https://www.nationalgridet.com/news/london-power-tunnels-2

Nave, C. R. (1998a). Resistivity and Temperature Coefficient at 20 C. Retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/rstiv.html

Nave, C. R. (1998b). Temperature Coefficient of Resistance. Retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/electric/restmp.html

Nicholson, D. P., Chen, Q., de Silva, M., Winter, A., & Winterling, R. (2014). The design of thermal tunnel energy segments for crossrail, UK. Proceedings of the Institution of Civil Engineers. Engineering Sustainability, 167(3), 118-134. doi:10.1680/ensu.13.00014

Ofgem. (2019). Non-domestic RHI tariff table. Retrieved from https://www.ofgem.gov.uk/publications-and-updates/non-domestic-rhi-tariff-table

Paiho, S., Ketomäki, J., Kannari, L., Häkkinen, T., & Shemeikka, J. (2019). A new procedure for assessing the energy-efficient refurbishment of buildings on district scale. Sustainable Cities and Society, (46) https://doi.org/10.1016/j.scs.2019.101454

Revesz, A., Jones, P., Dunham, C., Davies, G., Marques, C., Matabuena, R., . . . Maidment, G. (2020). Developing novel 5th generation district energy networks. Energy (Oxford), 201, 117389. doi:10.1016/j.energy.2020.117389

Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley. (2013). IPCC, 2013: Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Retrieved from https://www.ipcc.ch/report/ar5/wg1/

Yang, C., Peng, F., Xu, K., & Zheng, L. (2019). Feasibility study on the geothermal utility tunnel system. Sustainable Cities and Society, (46) https://doi.org/10.1016/j.scs.2019.101445

Appendix A. Tables

Table A1 - Summary of numerical simulation results for tunnel air and cable temperatures without heat recovery

Month of year	Input parameter	Simulated parameters		
	$T_{air,sup}$ [˚C]	$T_{air,av}$ [˚C]	$T_{air,out}$ [˚C]	T_{cab} [˚C]
Jun	16.3	22.03	27.54	24.23
Jul	19.5	25.14	30.57	27.41
Aug	17.6	23.29	28.77	25.51
Sep	15.1	20.86	26.41	23.04
Oct	12.5	18.32	23.94	20.51
Nov	9.0	14.91	20.61	17.04

Table A2 - Summary of numerical simulation results for tunnel air and cable temperatures with CLHR

Month of year	Input parameter	Simulated parameters		
	$T_{air,sup}$ [˚C]	$T_{air,av}$ [˚C]	$T_{air,out}$ [˚C]	T_{cab} [˚C]
Jun	6.3	12.27	18.04	14.35
Jul	9.5	15.4	21.09	17.54
Aug	7.6	13.54	19.28	15.64
Sep	5.1	11.1	16.9	13.17
Oct	7.5	13.44	19.19	15.54
Nov	4	10.02	15.85	12.1

Table A3 - Impact of cable tunnel cooling on power cable losses

Month of year	Reduction in power losses		Reduction in emissions	
	E_{sLR}	$Cost_{sLR}$	CDE_{sLR}	$Cost_{em,sLR}$
	[kWh]	[£]	[kg]	[£]
Jan	1630	163	461	44
Feb	1630	163	461	44
Mar	2488	249	704	67
Apr	4204	420	1190	113
May	4204	420	1190	113
Jun	8477	848	2400	228
Jul	8469	847	2397	228
Aug	8469	847	2397	228
Sep	8469	847	2397	228
Oct	4264	426	1207	115
Nov	4239	424	1200	114
Dec	4204	420	1190	113
Annual Total	**60750**	**6075**	**17196**	**1634**

Table A4 - Combined benefits of heat recovery and cable tunnel cooling

Month of year	E_{sT}	CDE_{sT}	$Cost_{sT}$
	[kWh]	[kg]	[£]
Jan	57247	8053	1744
Feb	57402	8043	1727
Mar	85539	12055	2621
Apr	140578	20044	4465
May	139292	20121	4601

Jun	276675	39258	8659
Jul	272877	39500	9069
Aug	275116	39356	8826
Sep	278123	39153	8494
Oct	139839	20109	4557
Nov	141993	19962	4318
Dec	141453	19987	4370
Annual Total	**2006132**	**285640**	**63452**
Annual Total per meter of tunnel	**4012**	**571**	**127**

Note: cost figure includes RHI.