# Electrical cable tunnel cooling combined with heat recovery, in cities

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## Abstract

Within cities, electrical power is often distributed by means of underground cable tunnels, frequently extending for many kilometres. Cables can generate significant heat, with the quantity of heat being directly related to the electrical load carried. Tunnel air temperatures are generally controlled by ventilation using outside air; preventing the cables from overheating. If active cooling was provided, tunnel air temperatures could be further reduced, permitting higher electrical loadings to be used. Using an air/water heat exchanger to cool the outside air entering the ventilation shaft has been investigated. The temperature of the heat extracted (to water) was increased using a heat pump before transfer to a heat network. Benefits identified included reduction in cable temperatures, and carbon and cost savings compared to conventional heat delivery.

**Keywords** Electrical cable tunnels, cooling, heat recovery, heat networks, sustainability

## 1.0 Introduction

Electrical network operators often transmit electrical power through cables, many of which are housed in networks of tunnels, particularly in cities such as London. Many cable tunnels are large enough e.g. of the order of 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 needs to be provided, for example by forced ventilation of the tunnels using outside air. 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 44°C, based on a maximum design inlet ambient temperature of 28°C [1]. If network operators could remove heat at a greater rate from their cable tunnels e.g. by introducing additional cooling, the electrical loadings on the cables could be increased, while both the cable temperatures and air temperatures in the tunnels could be maintained within their current range. However, any heat recovered i.e. extracted, from either the ambient air, when providing cooling to the tunnels or from the heated air exiting the tunnel represents a significant heat resource, which the operator could recover and potentially sell for reuse.

The UK Climate Change Act [2] sets UK wide targets for reducing carbon emissions by 80% of its 1990 baseline level by 2050, and was established to meet the requirements of the Kyoto Protocol [3]. The carbon reduction measures adopted to date include the phasing out of coal fired power stations, the increased use of renewable energy resources, together with improvements in the efficiency of vehicles, electrical and electronic equipment and new building performance requirements. Current data suggest that these measures have ensured that the UK is on track to achieve the interim 2020 carbon reduction target [4]. However, achieving the UK's 2050 carbon emissions target is likely to be more difficult and will require significantly more radical solutions than the measures and technologies considered to date. In order to meet its emission targets, the UK government has put forward a strategy for mitigating future carbon emissions from heating and cooling, as described in, for example, the 2050 Pathways Analysis [5] and The Future of Heating: Meeting the Challenge [6].

One of the key areas for reducing carbon emissions is the implementation of low carbon heating and cooling networks, especially in cities. For example, The Mayor of London has set a target for London to generate 25% of its heat and power requirements through the use of local, decentralised energy systems by 2025 [7]. Renewable decentralised energy opportunities include the use of energy from secondary sources such as sewers, electricity cable tunnels or underground railways (URs). These urban infrastructure systems, are potent and untapped energy sources, and are often in close proximity to areas of high heat demand and could potentially provide a year-round heat supply. In the UK, it was shown that the total heat which could be delivered from secondary sources in London is of the order of 71 TWh/ year, which was more than the city's total estimated heat demand of 66 TWh/year in 2010 [8]. Some of these secondary heat sources have the limitation that their location is too far from where the heat is needed or that they are only available at a particular period of the year. However, underground cable tunnels are often in close proximity to areas of high heat demand and could potentially provide a year-round heat supply. London South Bank University's (LSBU's) Centre for Air conditioning and Refrigeration Research team are currently undertaking a research project called LUSTER (London Sub-Terrain Energy Recovery). This involves evaluating a range of secondary heat sources to determine their potential for recovery and reuse. As part of the LUSTER project, LSBU and UK Power Networks are undertaking a feasibility study to investigate the effects of cooling and heat recovery for electrical cable tunnel, in London, and the preliminary results from this study are described in this paper.

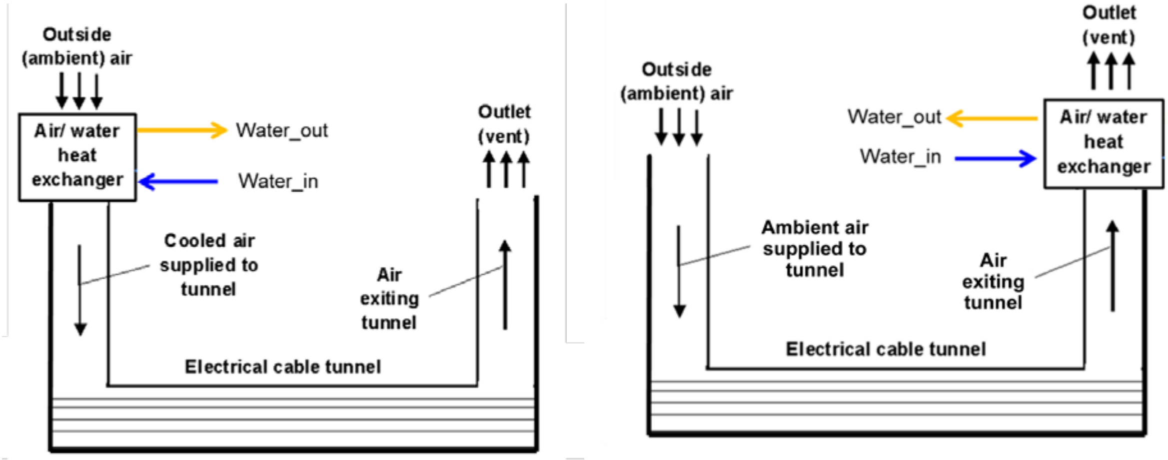
## 2.0 Cooling with heat recovery for electrical cable tunnels

The potential heat available for two heat recovery scenarios has been quantified for a typical cable tunnel section of length 1.8 km, in central London.

### *2.1. Heat recovery methods*

Two heat recovery methods were considered for the cable tunnel location selected, namely: (i) a combined cooling and heat recovery system, which has been termed a "cold led heat recovery system" (CLHR); and (ii) a heat recovery only system, which has been termed a "heat led heat recovery system" (HLHR).

For the CLHR method it is assumed that an air to water heat exchanger is installed at the supply end of the ventilation system. This configuration is illustrated in Figure 1 (a). It can be seen that the ambient air supplied is cooled by the water circuit of the heat recovery heat exchanger. This heat exchanger could provide benefits for both the electrical network operator, due to its cooling impact on the tunnel environment, and also to any nearby end users, who are able to utilise the heat recovered. Figure 1 (b) shows the HLHR scheme, where the heat recovery heat exchanger is located at the head of the exhaust ventilation shaft. It should be noted that the HLHR scheme does not provide any cooling for the electrical cables, but provides a higher temperature heat source than that for the CLHR scheme.



**(a) CLHR method** **(b) HLHR method**

**Figure 1 – Heat recovery options**

## 3.0 Calculations of heat recovery potential and associated benefits

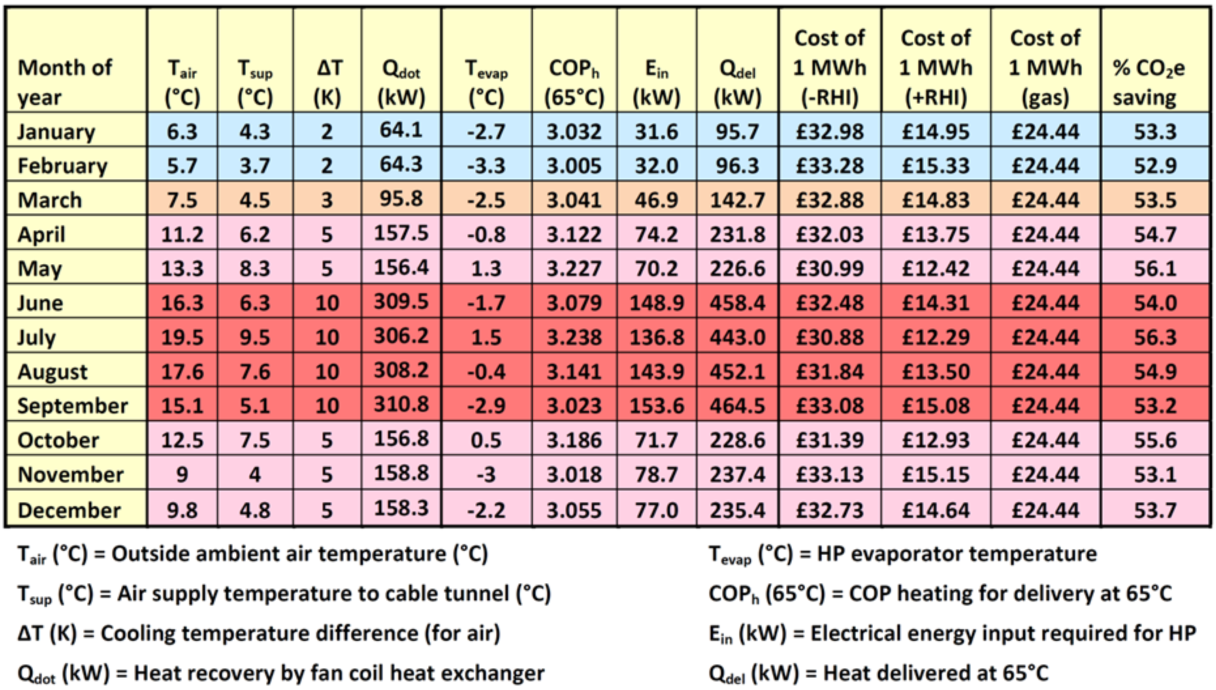
A spreadsheet based calculation has been conducted in order to estimate the heat exchanger performance with different air temperature reductions across the heat exchanger. The assumptions used during the calculations are summarised in Table 1.

<table>
<tr><td rowspan="7"><b>Configuration, supply temperature, cost and carbon</b></td><td><b>CLHR</b></td><td><b>HLHR</b></td></tr>
<tr><td>Heat was recovered using a fan coil heat exchanger located at the head of the air <b>supply</b> shaft.</td><td>Heat was recovered with a fan coil heat exchanger at the head of the <b>exhaust</b> shaft</td></tr>
<tr><td colspan="2">The heated water was transported through pipes to the heat pump.</td></tr>
<tr><td colspan="2">The water temperature was then upgraded using the heat pump for delivery at 65°C.</td></tr>
<tr><td>The degree of cooling of the outside air prior to supply to the tunnels ($\Delta T$) depends on the outside air temperature.</td><td>The tunnel exhaust air temperatures, which were based on measured data, were found to be steady (i.e. 27.6 to 32.7°C) for the period considered (June to November)</td></tr>
<tr><td>The $\Delta T$ was selected to ensure that the heat pump operated with a COP > 3.</td><td>A constant $\Delta T$ of 10 K was used.</td></tr>
<tr><td colspan="2">The cost for delivery of 1 MWh of heat, for recovered heat (with and without RHI), was compared to that for a gas boiler.</td></tr>
<tr><td></td><td colspan="2">RHI was applied to recovered heat at a tariff of 2.69 p per kWh.</td></tr>
<tr><td></td><td colspan="2">The % carbon saving for recovered heat compared to that for a gas boiler was also calculated.</td></tr>
<tr><td rowspan="5"><b>For the air to water fan coil heat exchanger</b></td><td><b>CLHR</b></td><td><b>HLHR</b></td></tr>
<tr><td colspan="2">An approach temperature (air side to water side) of 2K.</td></tr>
<tr><td colspan="2">Water side temperatures of less than 0˚C can be achieved using a water/glycol mixture.</td></tr>
<tr><td colspan="2">A temperature gain on the water side of 5K in each case.</td></tr>
<tr><td colspan="2">A pressure drop on the air side of the heat exchanger of 0.3 bar.</td></tr>
<tr><td rowspan="3"><b>For the cable tunnel</b></td><td><b>CLHR</b></td><td><b>HLHR</b></td></tr>
<tr><td colspan="2">The outside air temperatures based on UK meteorological data for London, averaged for each month during the year.</td></tr>
<tr><td colspan="2">An average air velocity through the tunnel of 4 m/s.</td></tr>
</table>

**Table 1 – Summary of key assumptions**

## *3.1. Results of CLHR methods*

The results obtained using the spreadsheet model applied to the CLHR method are shown in Table 2. It is seen from Table 2 that the quantity of heat recovered 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. A heat pump COP of > 3 was achieved for delivery of the upgraded heat at 65°C, in each case. It can be also seen in Table 2 that the cost for delivery of 1 MWh of recovered heat was much less than that for a gas boiler when RHI was included. The calculated results also showed carbon savings of > 50% for the heat recovery system compared with gas boiler heating. It should be noted that the total economic benefits of the cooling of the cable tunnel air and cables combined with simultaneous heat recovery from the outside air, have not been included in the results shown in Table 2 i.e. only the heat recovery benefits have been considered. Because of the large variation in heat output 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.



| Month of year | $T_{air}$ (°C) | $T_{sup}$ (°C) | ΔT (K) | $Q_{dot}$ (kW) | $T_{evap}$ (°C) | $COP_h$ (65°C) | $E_{in}$ (kW) | $Q_{del}$ (kW) | Cost of 1 MWh (-RHI) | Cost of 1 MWh (+RHI) | Cost of 1 MWh (gas) | % $CO_2e$ saving |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 6.3 | 4.3 | 2 | 64.1 | -2.7 | 3.032 | 31.6 | 95.7 | £32.98 | £14.95 | £24.44 | 53.3 |
| February | 5.7 | 3.7 | 2 | 64.3 | -3.3 | 3.005 | 32.0 | 96.3 | £33.28 | £15.33 | £24.44 | 52.9 |
| March | 7.5 | 4.5 | 3 | 95.8 | -2.5 | 3.041 | 46.9 | 142.7 | £32.88 | £14.83 | £24.44 | 53.5 |
| April | 11.2 | 6.2 | 5 | 157.5 | -0.8 | 3.122 | 74.2 | 231.8 | £32.03 | £13.75 | £24.44 | 54.7 |
| May | 13.3 | 8.3 | 5 | 156.4 | 1.3 | 3.227 | 70.2 | 226.6 | £30.99 | £12.42 | £24.44 | 56.1 |
| June | 16.3 | 6.3 | 10 | 309.5 | -1.7 | 3.079 | 148.9 | 458.4 | £32.48 | £14.31 | £24.44 | 54.0 |
| July | 19.5 | 9.5 | 10 | 306.2 | 1.5 | 3.238 | 136.8 | 443.0 | £30.88 | £12.29 | £24.44 | 56.3 |
| August | 17.6 | 7.6 | 10 | 308.2 | -0.4 | 3.141 | 143.9 | 452.1 | £31.84 | £13.50 | £24.44 | 54.9 |
| September | 15.1 | 5.1 | 10 | 310.8 | -2.9 | 3.023 | 153.6 | 464.5 | £33.08 | £15.08 | £24.44 | 53.2 |
| October | 12.5 | 7.5 | 5 | 156.8 | 0.5 | 3.186 | 71.7 | 228.6 | £31.39 | £12.93 | £24.44 | 55.6 |
| November | 9 | 4 | 5 | 158.8 | -3 | 3.018 | 78.7 | 237.4 | £33.13 | £15.15 | £24.44 | 53.1 |
| December | 9.8 | 4.8 | 5 | 158.3 | -2.2 | 3.055 | 77.0 | 235.4 | £32.73 | £14.64 | £24.44 | 53.7 |

$T_{air}$ (°C) = Outside ambient air temperature (°C)

$T_{sup}$ (°C) = Air supply temperature to cable tunnel (°C)

ΔT (K) = Cooling temperature difference (for air)

$Q_{dot}$ (kW) = Heat recovery by fan coil heat exchanger

$T_{evap}$ (°C) = HP evaporator temperature

$COP_h$ (65°C) = COP heating for delivery at 65°C

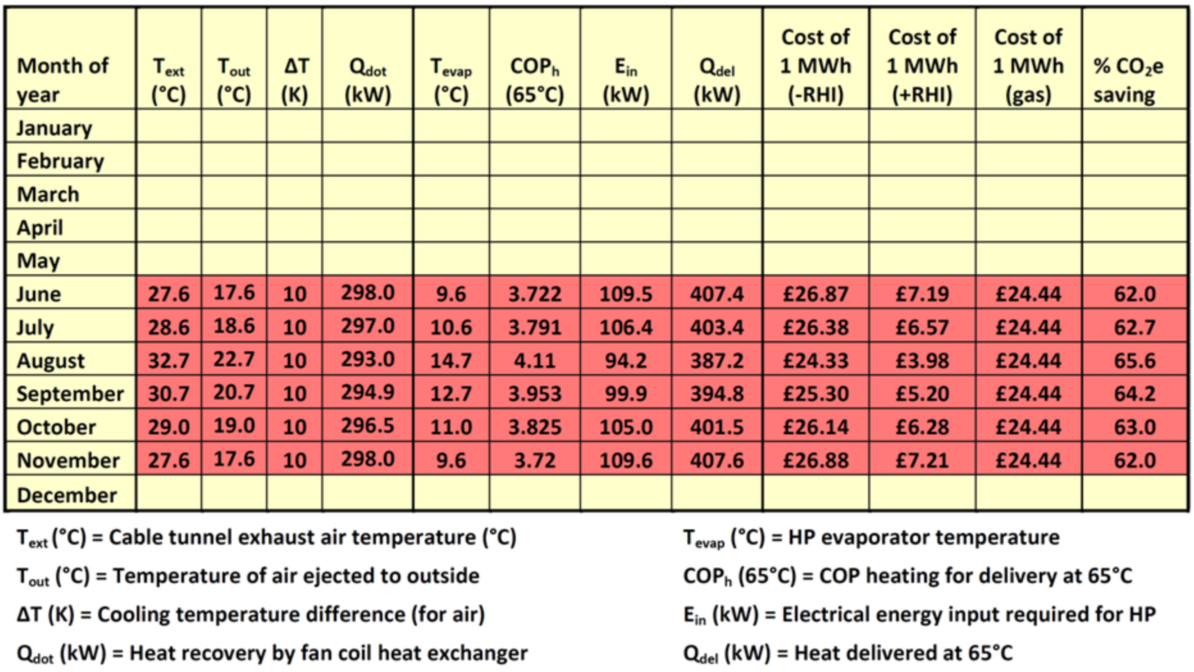
$E_{in}$ (kW) = Electrical energy input required for HP

$Q_{del}$ (kW) = Heat delivered at 65°C

**Table 2 – CLHR from cable tunnels**

## *3.2. Results of HLHR methods*

The results from the model showing the calculated quantities of heat recovered from the 1.8 km cable tunnel section and the costs for delivering this heat at 65°C are shown in Table 3.



| Month of year | $T_{ext}$ (°C) | $T_{out}$ (°C) | ΔT (K) | $Q_{dot}$ (kW) | $T_{evap}$ (°C) | $COP_h$ (65°C) | $E_{in}$ (kW) | $Q_{del}$ (kW) | Cost of 1 MWh (-RHI) | Cost of 1 MWh (+RHI) | Cost of 1 MWh (gas) | % $CO_2e$ saving |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| January | | | | | | | | | | | | |
| February | | | | | | | | | | | | |
| March | | | | | | | | | | | | |
| April | | | | | | | | | | | | |
| May | | | | | | | | | | | | |
| June | 27.6 | 17.6 | 10 | 298.0 | 9.6 | 3.722 | 109.5 | 407.4 | £26.87 | £7.19 | £24.44 | 62.0 |
| July | 28.6 | 18.6 | 10 | 297.0 | 10.6 | 3.791 | 106.4 | 403.4 | £26.38 | £6.57 | £24.44 | 62.7 |
| August | 32.7 | 22.7 | 10 | 293.0 | 14.7 | 4.11 | 94.2 | 387.2 | £24.33 | £3.98 | £24.44 | 65.6 |
| September | 30.7 | 20.7 | 10 | 294.9 | 12.7 | 3.953 | 99.9 | 394.8 | £25.30 | £5.20 | £24.44 | 64.2 |
| October | 29.0 | 19.0 | 10 | 296.5 | 11.0 | 3.825 | 105.0 | 401.5 | £26.14 | £6.28 | £24.44 | 63.0 |
| November | 27.6 | 17.6 | 10 | 298.0 | 9.6 | 3.72 | 109.6 | 407.6 | £26.88 | £7.21 | £24.44 | 62.0 |
| December | | | | | | | | | | | | |

$T_{ext}$ (°C) = Cable tunnel exhaust air temperature (°C)
$T_{out}$ (°C) = Temperature of air ejected to outside
ΔT (K) = Cooling temperature difference (for air)
$Q_{dot}$ (kW) = Heat recovery by fan coil heat exchanger
$T_{evap}$ (°C) = HP evaporator temperature
$COP_h$ (65°C) = COP heating for delivery at 65°C
$E_{in}$ (kW) = Electrical energy input required for HP
$Q_{del}$ (kW) = Heat delivered at 65°C

**Table 3 – HLHR from cable tunnels**

The results shown in Table 3 span only the months June to November, as measured temperature data for the heated air exhausted from the tunnel was only available for this period, at the time of the study. However, the results for the CLHR (Table 2) and HLHR (table 3) schemes for the selected period have been compared.

The results presented in Table 3 show that heat recovery was fairly constant (at approximately 300 kW) for the period considered i.e. June to November. It is seen that for delivery at 65°C, a heat pump COP close to 4 was achieved, in each case, as compared to a COP of approximately 3 for the CLHR scheme. The cost for delivery of 1 MWh of recovered heat is seen to be about the same as that for a gas boiler without RHI for the HLHR scheme. However, very significant cost savings for the recovered heat were possible, if RHI was available. Carbon savings of 62-65.6% were calculated for the HLHR recovered heat system compared to the carbon emissions for gas boiler heating to deliver the same quantity of heat.

## 4.0 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. The key modelling objectives were to investigate 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.

## 4.1. Model geometry

The numerical model represents a single cable tunnel section housing 6 stacks of 3 cables, with 3 stacks on each side of the tunnel. A cross section of the tunnel section indicating the tunnel air, cables and concrete liner is shown in Figure 2 (a). The overall model geometry is shown in Figure 2 (b). The length of the tunnel section was assumed to be 500 m (i.e. a representative section of the 1.8 km tunnel), and to have 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 (i.e. 500 m for the section represented by the model). The ground material surrounding the tunnel is London Clay, and appropriate properties were assumed for the model.

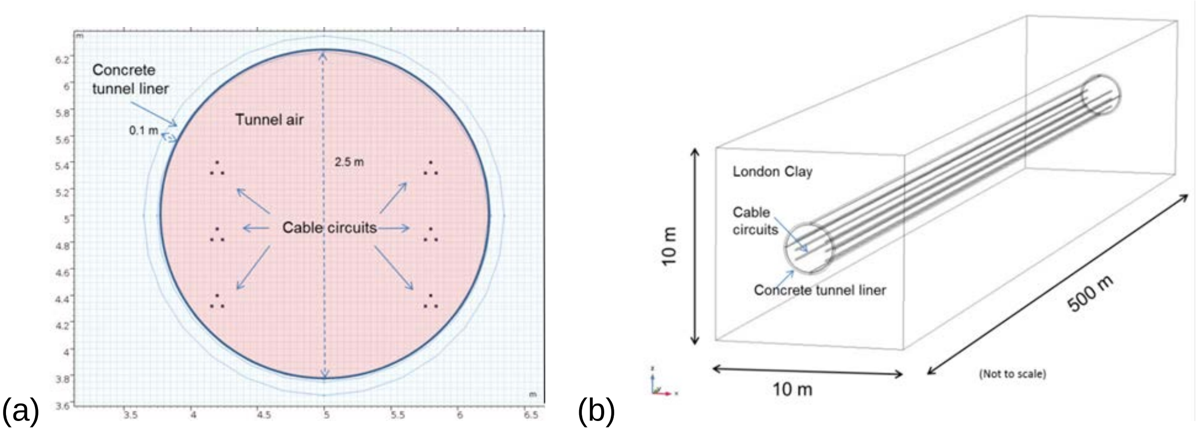


**Figure 2 – (a) Cable tunnel cross section and (b) 3D model geometry**

## 4.1. Model investigation and results

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 1.8 km section selected, 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, so this value was applied to each cable, within the model. Although the COMSOL model was only used to simulate a 500 m section of the tunnel, the results were extrapolated to predict parameter values for the whole 1.8 km tunnel length.

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 Table 4. 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 (Tair_sup). For each simulation, an average air velocity of 4 m/s was assumed throughout the length of the cable tunnel. 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_cables)

Simulation results where the CLHR method was applied are summarised in Table 5.

| | **Input parameter** | **Simulated parameters** | | |
|---|---|---|---|---|
| **Month** | **$T_{air\_sup}$ [˚C]** | **$T_{\_air\_av}$ [˚C]** | **$T_{\_air\_out}$ [˚C]** | **$T_{\_cables}$ [˚C]** |
| **June** | 16.3 | 22.03 | 27.54 | 24.23 |
| **July** | 19.5 | 25.14 | 30.57 | 27.41 |
| **August** | 17.6 | 23.29 | 28.77 | 25.51 |
| **September** | 15.1 | 20.86 | 26.41 | 23.04 |
| **October** | 12.5 | 18.32 | 23.94 | 20.51 |
| **November** | 9.0 | 14.91 | 20.61 | 17.04 |

**Table 4 – Summary of numerical simulation results without heat recovery**

| | **Input parameter** | **Simulated parameters** | | |
|---|---|---|---|---|
| **Month** | **$T_{air\_sup}$ [˚C]** | **$T_{\_air\_av}$ [˚C]** | **$T_{\_air\_out}$ [˚C]** | **$T_{\_cables}$ [˚C]** |
| **June** | 6.3 | 12.27 | 18.04 | 14.35 |
| **July** | 9.5 | 15.4 | 21.09 | 17.54 |
| **August** | 7.6 | 13.54 | 19.28 | 15.64 |
| **September** | 5.1 | 11.1 | 16.9 | 13.17 |
| **October** | 7.5 | 13.44 | 19.19 | 15.54 |
| **November** | 4 | 10.02 | 15.85 | 12.1 |

**Table 5 – Summary of numerical simulation results of CLHR impact on tunnel environment**

Figures 3 and 4 combine the results of Table 4 and 5, and illustrate the impact of supplying air to the tunnels at lower temperatures on the average tunnel air and cable temperatures respectively.

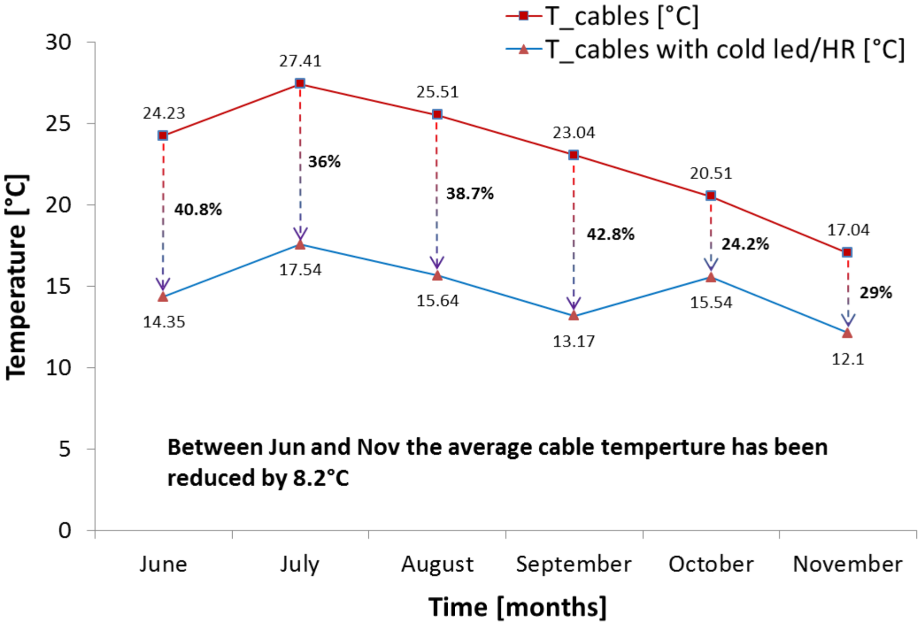


Figure 3 – Average cable temperatures with and without CLHR

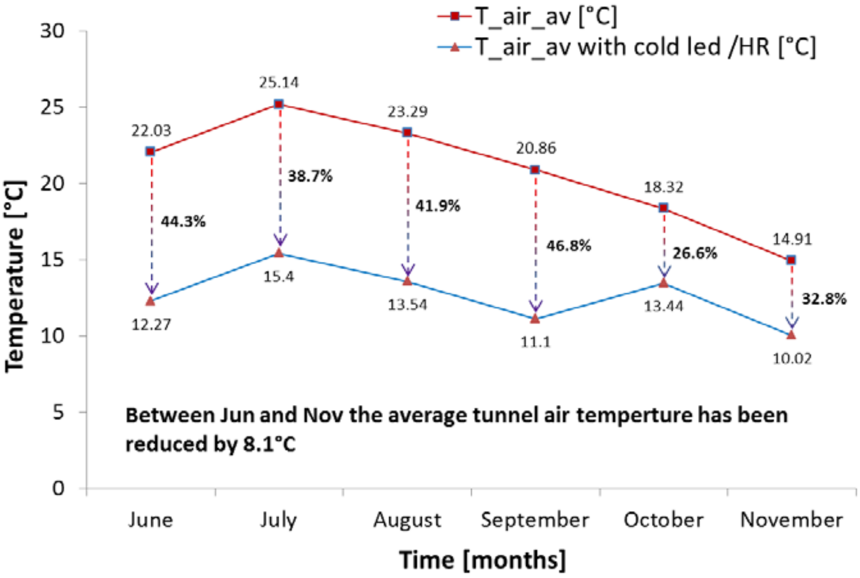


Figure 4 – Average tunnel air temperatures with and without CLHR

It can be 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. The results for October and November for both Figures 3 and 4 indicate a reduction in the degree of cooling achieved compared to the period June to September. This is due to applying a different temperature difference ΔT between the ambient air and the air supplied to the tunnel, which was 10 K for the period June to September, but was reduced to 5 K for October and November, as shown in Table 2. The reduction in ΔT was necessary to limit the decrease in water loop temperature at lower ambient air temperatures, and maintain the COP for the heat pump at a value > 3.

## 5.0 Potential benefits

The results of the study showed that a combined cooling and heat recovery solution can result in a range of benefits for electrical cable operators. These include:

(i) More efficient operation of cable tunnels by cooling the supply air: The results showed that if the CLHR method is implemented, both the tunnel air, and cable temperatures can be reduced substantially. Based on the available data and the assumptions used in the models, it was shown that the temperature of the tunnel environment (both air and cables) can be reduced by approximately 8°C if the CLHR method is applied.

(ii) Reduced operational costs i.e. through reduced ventilation loads: for example, if the tunnel air is being cooled by implementing the CLHR method, e.g. by reducing air flow rates and fan power while achieving the same cooling capacity.

(iii) Increased loading of the cables: For example, if the cables are being cooled by implementing the CLHR method. A reduction in cable temperature could also result in lower electricity distribution losses, producing additional carbon and cost savings.

(iv) Provision of significant quantities of heat for delivery to low carbon energy networks, either by cooling the outside air prior to supply to the tunnel, or by recovery of heat from the air exhausted from the tunnel, for a single cable tunnel ventilation shaft: The results of the investigation showed that substantial amounts of heat can be extracted and delivered to end users in the vicinity of the ventilation shafts. The quantity of deliverable heat would depend on the method of heat recovery. For cold led heat recovery, it was estimated that between 96 and 460 kW of heat can be delivered, depending on the season. For heat lead heat recovery, the deliverable heat values remained relatively constant throughout the investigation period, at approximately 400 kW.

(v) Revenues from the sale of the recovered waste heat: If the heat recovery system is located in an urban area, it may be possible to sell heat to neighbouring buildings such as offices, hospitals, hotels or leisure centres. Recovered heat can also be sold for use in district heating, urban farms, greenhouse heating and swimming pools.

(vi) Contributions towards low carbon sustainable development: The London Plan [9] focuses 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. Recovery of the heat extracted during cooling the air supplied to cable tunnels can contribute towards these targets.

## 6.0 Conclusions

A preliminary investigation was carried out to investigate the combined cooling and heat recovery potential for the air supplied to cable tunnels, and its impact on the tunnel environment. Two heat extraction/recovery methods were considered for the cable tunnel location selected, namely: (i) a combined cooling and heat recovery system, which has been termed a CLHR system; and (ii) a heat recovery only system, which has been termed a HLHR system. In each case, an air to water heat exchanger was utilised. Results from a spreadsheet based calculation showed that between 60 and 300 kW of heat can be recovered this way, depending on the ambient air temperature supplied to the shaft (which varies seasonally) and the applied temperature difference ΔT used within the heat exchanger. Using a heat pump, the recovered heat could be upgraded, transported and distributed to nearby heat users. Simulation results from a steady state numerical model showed that cooling the supply air through heat recovery will have an impact on the tunnel environment and will reduce the average tunnel air and cable temperatures significantly. Therefore, cable tunnels offer the opportunity of a useful heat source, which is comparable to (and in some cases superior to) many other waste heat sources being considered for LSBU's EPSRC sponsored LUSTER project e.g. sewers, canals, data centres and underground railway tunnels.

## References

(1) Garcia, J. (2018) Cable tunnel design manual. Engineering Design standard EDS 02-0041 UK Power Networks. Online at: https://library.ukpowernetworks.co.uk/library/en/g81/Design_and_Planning/Cables/EDS+02-0041+Cable+Tunnel+Design+Manual.pdf Accessed 4-12-18

(2) Climate Change Act 2008: Elizabeth II. (2008) London, Stationery Office.

(3) Kyoto Protocol (1998) Kyoto Protocol to the United Nations Framework Convention on Climate Change 2303 UNTS 148/[2008] ATS 2/37 ILM 22 (1998)

(4) Committee on Climate Change (2018) Reducing carbon emissions: How the UK is progressing. Online at: https://www.theccc.org.uk/tackling-climate-change/reducing-carbon-emissions/how-the-uk-is-progressing/ Accessed 15-11-18

(5) DECC (2010) 2050 Pathways Analysis, Department of Energy and Climate Change, UK

(6) DECC (2013) The Future of Heating: Meeting the Challenge, Department of Energy and Climate Change, UK.

(7) Mayor of London (2013) London's Zero Carbon Energy Resource: Secondary Heat. Mayor of London Report. Online at: https://www.london.gov.uk/sites/default/files/gla_migrate_files_destination/031250%20GLA%20Secondary%20Heat%20-%20Summary%20Report_0.pdf Accessed 4-12-18

(8) The Greater London Authority, Buro Happold, London's zero carbon energy resource, Online at: http://www.london.gov.uk/sites/default/files/031250%20GLA%20Secondary%20Heat%20-%20Summary%20Report.pdf Accessed 12-11-2018], 2018.

(9) London Plan, Mayor of London, The London Plan, Spatial Development Strategy for London, Greater London Authority, London, UK, 2004.

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