Manuscript ID: 495
DOI: 10.18462/iir.icr.2019.495

Waste heat recovery from urban electrical cable tunnels

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ABSTRACT

Electrical power distribution within cities is most often distributed through underground cables located just below the road surface. Due to steadily increasing electricity demands, many power suppliers are making large investments in housing these cables in underground tunnels. These urban cable tunnels often extend to many kilometres in length. Through the electrical loading of the cables a significant amount of heat is generated. Often this heat has to be removed through ventilation in order to avoid overheating the cables and to provide safe conditions for access. As opposed to rejecting the heat to the atmosphere, this low grade energy could potentially be recovered, upgraded if necessary, and distributed to nearby heat users above ground. This paper discusses possible heat recovery methods applicable for urban electricity distribution networks, i.e. transformers and cable tunnels. It also presents results from a modelling-based preliminary feasibility study which used cable tunnels in London as a case study.

Keywords: Heat recovery, Transformers, Cable tunnels, Heat networks, Urban energy systems

1. INTRODUCTION

The Climate Change Act (2008) 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 (1998). 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 (Committee on Climate Change, 2018). 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 (DECC, 2010) and The Future of Heating: Meeting the Challenge (DECC, 2013).

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 (Mayor of London, 2013). 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, are often in close proximity to areas of high heat demand and could potentially provide a year-round heat supply. It has been shown that the total heat that could be delivered from secondary sources in London is of the order of 71 TWh/ year, which is more than the city's total estimated heat demand of

66 TWh/yr in 2010 (GLA, 2013). 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, parts of electrical distribution networks such as substation transformers and 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 and University College London (UCL) is currently undertaking a research project called LUSTER (London Sub-Terrain Energy Recovery). This involves evaluating a range of secondary waste heat sources to determine their potential for recovery and reuse. As part of the LUSTER project, LSBU and UK Power Networks have undertaken a feasibility study to investigate the effects of cooling and heat recovery for electrical cable tunnels, and substation transformers in London. The paper first summarizes heat recovery potential from transformers and preliminary results from the feasibility study concerning the combined cooling and heat recovery from cable tunnels.

2. COOLING AND HEAT RECOVERY FOR ELECTRICTY DISTRIBUTION NETWORKS

If it is feasible to capture and use the heat generated by electricity distribution network losses, the overall energy efficiency of electricity distribution can be improved and this may also be economically viable in some cases. There are opportunities, particularly in urban areas, to consider the benefits from using any heat that has a commercial value. This may be implemented as a retrofit solution, or may be engineered into the overall network design when new equipment is required. This section of the paper reviews the potential for extracting heat from urban electrical distribution networks, i.e. substation transformers and cable tunnels.

2.1. Heat Recovery Potential from Electrical Substation Transformers

Transformer energy losses can be classified as: (i) no-load losses; or (ii) load losses. The former are constant for all transformer operating points and are related to core losses whilst the latter are proportional to transformer loadings and are associated with winding losses. Transformer winding losses produce heat which without effective cooling will increase transformer temperatures. In the case of very high temperatures, the insulation can be carbonised and produce gasses, and can significantly reduce the lifetime of the transformer. Therefore, effective cooling of transformers and rejection of heat is essential. The heat losses are normally dependent upon the transformer's rating, peak load, load factor and efficiency. Often these losses can be calculated for the full operation range using nominal operating loss values provided by the transformer manufacturer. Figure 1 illustrates typical heat outputs at different loading conditions for a 240 MVA transformer in London (Modern Power Systems, 2016). It can be seen in Figure 1 that the transformer heat losses increase at an accelerating rate as the loading percentage increases. The loading percentage will, of course, vary according to the fluctuation of electricity demand. It is therefore necessary to determine or estimate the transformer loading throughout the year in order to calculate the potential quantity of heat that could be recovered annually, and to size the heat recovery equipment appropriately. Waste heat from transformers could typically be captured through their cooling system. Table 1 compares commonly used transformer types based on their cooling methods and their potential for implementing a heat recovery application. It can be seen in Table 1 that there are a number of different transformer cooling systems currently in use. These systems vary in complexity and in their effectiveness of meeting the preliminary objective of cooling the transformer. The two main categories are the dry and oil-immersed types cooling methods. Dry type solutions are normally used for cooling smaller transformers rated up to 1.5 MVA. The oil immersed type cooling systems are generally used for larger units, e.g. those rated up to several hundreds of MVA. The top section of transformer tanks is normally cooled by either a water or air cooling system. In many cases, the heat captured by these coolants is dissipated into the atmosphere and wasted. However, in densely populated urban areas, this waste heat could serve a different purpose. For example, it could be supplied to a local district heating scheme. At times when there is no heat demand, freestanding cooling banks mounted on the substation roof could be used to dissipate the heat and maintain cooling of the transformer or the heat could be stored for later use.

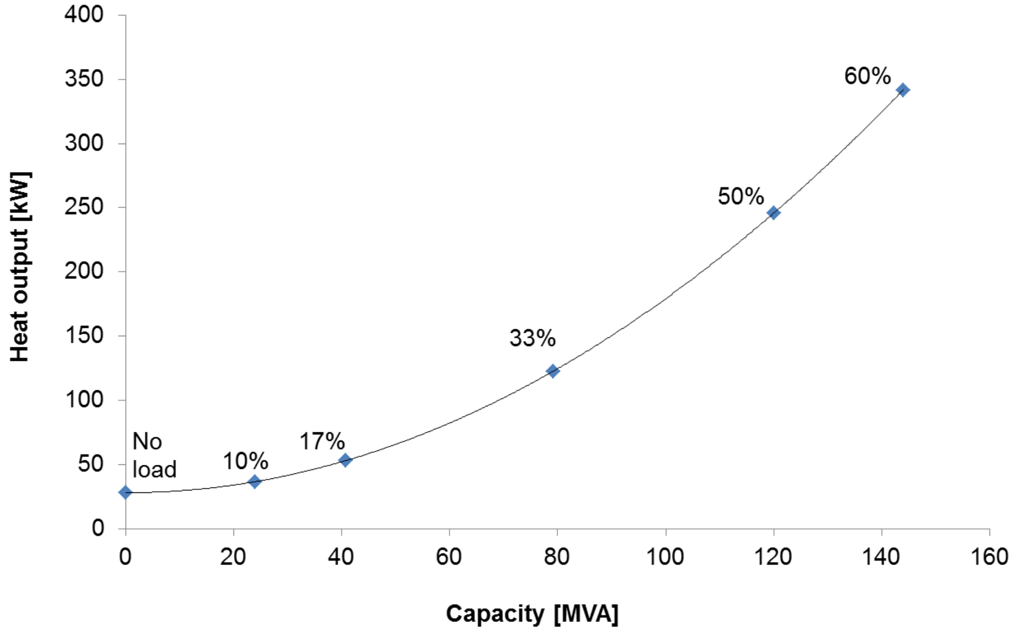


Figure 1: A typical 240 MVA transformers' heat output at different loading levels

Table 1. Summary of transformer types and their potential for heat recovery

Transformer type / cooling method		Potential for heat recovery	Comment
Dry type	Air Natural (AN): This method is used for cooling the smallest output transformers rated up to 1.5 MVA	Low (~ < 15 kW)	• Heat recovery (HR) system could be non-intrusive making it easier to retrofit • Could be cost effective for existing transformers with an adjacent heat user requirement • For natural air cooling, only low control of HR is possible • If forced air is used then medium control of HR could be achieved
	Air Forced (AF): This method is used for transformer rating up to 15MVA.	Medium (~20-60 kW)	
Oil immerse type	Oil Natural Air Natural (ONAN) This type of cooling is used for the transformer rating up to 30 MVA.	Low to Medium (~ 50-100 kW)	• It would require major intrusion into the cooling system for connecting additional heat exchangers (HEXs) • Low control of HR
	Oil Natural Air Forced (ONAF) Used for the cooling of the transformer of rating up to 60 MVA.	Medium (~80-120 kW)	• It would require major intrusion for connection of additional HEXs • Medium control of HR
	Oil Forced Air Forced (OFAF) Rating more than 60 MVA.	Medium to High (~>120 kW)	• This type of cooling system would still require major intrusion for connection of HEXs • Greater control of HR due to the forced nature of oil circulation
	Oil Forced Water Forced (OFWF) This type of method is suitable for large capacity of the transformer having rating as several hundred MVA or where banks of transformers are installed.	High (Could be more than 300 kW)	• This type of transformer currently offers the greatest opportunity for large scale HR • Generated heat is captured by the cooling water of the oil-water cooler • Permits less intrusive solutions for connecting additional HEXs • Offers a high degree of control HR

There are hundreds of primary substation transformers across the UK providing a significant quantity of excess energy and an overall heat recovery potential that is larger than 30MW in capacity (Davies *et.al.* 2018) The LUSTER project team conducting further works to investigate the potential for heat recovery from electrical substation in London.

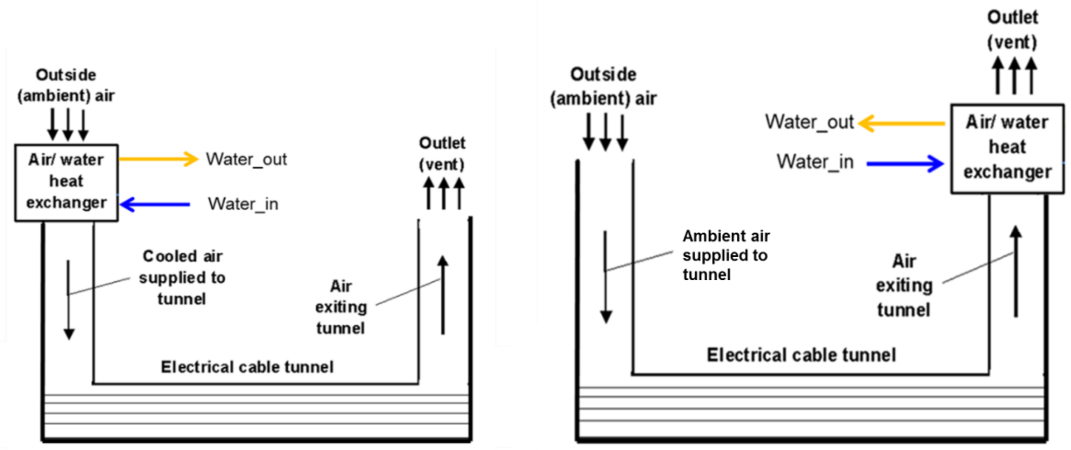
2.2. Heat Recovery Potential from Urban Electrical Cable Tunnels

Electrical network operators 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 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. Once air is supplied into the tunnels its temperature increases as it travels to the air extraction point. 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 as the limit for human access to the tunnel). If network operators could reduce the air temperatures in their cable tunnels (and cables) e.g. by introducing additional cooling, the electrical loadings on the cables could be increased. Additionally, the heat generated in cable tunnels represents a significant heat resource, which the operator could recover and potentially sell for reuse.

3. FEASIBILITY STUDY FOR COMBINED COOLING AND HEAT RECOVERY FROM CABLE TUNNELS

A typical tunnel section of length 1.8 km and 2.5 m in diameter, in central London, was selected for this study. The financial calculations included, a UK government environmental programme, the Renewable Heat Incentive (RHI), which provides financial incentives to increase the uptake of renewable heat by businesses, the public sector and non-profit organisations. Eligible installations receive quarterly payments over 20 years based on the amount of heat generated, therefore it could support the uptake of innovative energy solutions in cities and elsewhere.

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 2 (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 to any nearby end users, who are able to utilise the heat recovered. Figure 2 (b) shows the HLHR scheme, where the heat recovery heat exchanger is located at the head of the exhaust ventilation shaft.



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

Figure 2: Heat recovery options

3.1. Calculation of Heat recovery potential from electrical substation transformers

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 2.

Table 2: Summary of key assumptions

	CLHR	HLHR
Configuration, supply temperature, cost and carbon	Heat was recovered using a fan coil heat exchanger located at the head of the air supply shaft.	Heat was recovered with a fan coil heat exchanger at the head of the exhaust 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 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)
	The ΔT was selected to ensure that the heat pump operated with a COP > 3.	A constant ΔT of 10 K was used.
	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 2.69 p per kWh.	
	% carbon saving for recovered heat compared to that for a gas boiler was also calculated. Carbon factors used were 0.41 kg CO_2e per kWh for electricity and 0.18 kg CO_2e per kWh for gas (DEFRA, 2016).	
For the air to water fan coil heat exchanger	CLHR	HLHR
	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 heat exchanger of 0.3 bar.	
For the cable tunnel	CLHR	HLHR
	The outside air temperatures based on UK meteorological data for London, averaged for each month during the year.	

3.1.1. Results of CLHR method

The results obtained using the spreadsheet model applied to the CLHR method are shown in Table 3, which shows 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 also be seen in Table 3 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 3 i.e. only the heat recovery benefits have been considered. Due to 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.

Table 3: CLHR from cable tunnels

Month	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)	% CO2e saving
1	6.3	4.3	2	64.1	-2.7	3.0	31.6	95.7	£32.98	£14.95	£24.4	53.3
2	5.7	3.7	2	64.3	-3.3	3.0	32	96.3	£33.28	£15.33	£24.4	52.9
3	7.5	4.5	3	95.8	-2.5	3.0	46.9	142.7	£32.88	£14.83	£24.4	53.5
4	11.2	6.2	5	157.5	-0.8	3.1	74.2	231.8	£32.03	£13.75	£24.4	54.7
5	13.3	8.3	5	156.4	1.3	3.2	70.2	226.6	£30.99	£12.42	£24.4	56.1
6	16.3	6.3	10	309.5	-1.7	3.0	148.9	458.4	£32.48	£14.31	£24.4	54
7	19.5	9.5	10	306.2	1.5	3.2	136.8	443	£30.88	£12.29	£24.4	56.3
8	17.6	7.6	10	308.2	-0.4	3.1	143.9	452.1	£31.84	£13.50	£24.4	54.9
9	15.1	5.1	10	310.8	-2.9	3.0	153.6	464.5	£33.08	£15.08	£24.4	53.2
10	12.5	7.5	5	156.8	0.5	3.1	71.7	228.6	£31.39	£12.93	£24.4	55.6
11	9	4	5	158.8	-3	3.0	78.7	237.4	£33.13	£15.15	£24.4	53.1
12	9.8	4.8	5	158.3	-2.2	3.0	77	235.4	£32.73	£14.64	£24.4	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

3.1.2. Results of HLHR method

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 4.

The results presented in Table 4 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. 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. However, very significant cost savings for the recovered heat are possible, if RHI is available. Carbon savings of 62-65.6% were calculated for the recovered heat system compared to the carbon emissions for gas boiler heating to deliver the same quantity of heat.

Table 4: HLHR from cable tunnels

Month	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)	% CO2e saving
6	27.6	17.6	10	298	9.6	3.7	109.5	407.4	£26.87	£7.19	£24.4	62
7	28.6	18.6	10	297	10.6	3.7	106.4	403.4	£26.38	£6.57	£24.4	62.7
8	32.7	22.7	10	293	14.7	4.1	94.2	387.2	£24.33	£3.98	£24.4	65.6
9	30.7	20.7	10	294.9	12.7	3.9	99.9	394.8	£25.30	£5.20	£24.4	64.2
10	29	19	10	296.5	11	3.8	105	401.5	£26.14	£6.28	£24.4	63
11	27.6	17.6	10	298	9.6	3.7	109.6	407.6	£26.88	£7.21	£24.4	62

T_{ext} (°C) = Cable tunnel exhaust air temperature (°C)
T_{evap} (°C) = HP evaporator temperature

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
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

3.1.3. Identified benefits of a combined cooling and heat recovery solution

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) Provision of significant quantities of waste heat from a single cable tunnel ventilation shaft for delivery to low temperature energy networks: The results of the investigation showed that substantial amounts of heat can be recovered 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 through the investigation period, at approximately 400 kW.

(ii) 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.

(iii) Reduced operational costs i.e. through reduced ventilation loads: For example if the tunnel air is being cooled by implementing the CLHR method.

(iv) 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.

(v) Contributions towards low carbon sustainable development: The London Plan (Mayor of London, 2016) 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. Heat recovery from cable tunnels can contribute towards these targets. Also, a shift towards using electrical energy for space heating and hot water, it is likely to add to the need for increased distribution network capacity, thus making more waste heat available for repurposing.

4. CONCLUSIONS

A preliminary investigation was carried out to investigate heat recovery potential from electricity conversion and distribution networks. The paper first summarised energy recovery potential from the losses of substation transformers. It was described that the oil immersed type transformer cooling systems which are generally used for larger units, have the highest heat recovery potential. It was shown that more than 300 kW of waste heat can be captured from these types of transformers. The paper then described a more detailed study of the combined cooling and heat recovery potential for the air supplied to cable tunnels. 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 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. Therefore, both substation transformers and 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. Further work, within the LUSTER project, will investigate the matching of the local heat demand to the heat available from cable tunnels, using demand modelling and geospatial techniques. This will be covered in future publications.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the support by Engineering and Physical Science Research Council (EPSRC) and LUSTER - London Urban Sub-Terrain Energy Recovery project [EP/R001294/1]. Thanks also go to the Innovation team at UK Power Networks, for general support and the provision of data.

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