Paper ID: 1183

Large scale cooling systems using mains water

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Abstract
A novel method for the cooling of large scale heat generating processes in cities has been identified, namely the use of mains water. Applications include data centres, underground railways, supermarkets, hospitals and large buildings. Two applications for this method are the cooling of London Underground (LU) stations and data centres, and these are the subject of this publication.

Mains water is distributed across London through a network of pipes, and varies in temperature between 5 and 20°C during the year. For much of the year, there is potential to raise the water temperature by a few degrees, while maintaining the mains water temperature within its current maximum limit. To increase the temperature of the entire mains supply of London by 1°C requires heat input of the order of 100 MW. Consequently, mains water provides a large cooling resource, which could be used to replace mechanically cooled chilled water for many applications. In London alone mains water could deliver continuous cooling of more than 500MW (for at least 8 months of the year). LU stations and data centres typically have cooling loads ranging from 0.5 to 5 MW, and a large number of them could have a substantial proportion of their cooling needs met by this method. The results of calculations for potential energy, carbon and cost savings by using mains water for cooling for these applications are presented. A number of other applications to which this cooling method could be applied have also been identified.

Key words: mains water cooling, London Underground, data centres

1. Introduction
Refrigeration and air conditioning (RAC) is responsible for about 10% of all greenhouse emissions on a worldwide basis [Birmingham Cold Commission, 2015]. Much of this is due to indirect emissions through energy use, since it is estimated that RAC is responsible for 19% of all electricity used. Low cost, low carbon methods of cooling are therefore important in meeting future targets for reductions in carbon emissions and fossil fuel use. This paper describes a low cost way of utilising the mains water loop as a cooling source, as proposed by Maidment and Paurine [2015]. Specifically the paper describes the availability of mains water and the benefits of using it for cooling, and considers a range of applications and their suitability for mains water cooling. It identifies two good candidates and investigates their proximity to the mains water supply as well as the potential relative savings associated with its use. This is compared to conventional methods of cooling. Finally, secondary savings resulting from preheating of mains water, prior to its use for generating domestic hot water are identified.

2. Mains water in London
Figure 1 shows a schematic diagram of the system initially constructed by Thames Water (TW) between 1988 and 1993. The tunnelling network connects the major reservoir systems at Teddington to the West of London with those on the River Lea to the East. It is built mainly as a loop with a short branch in the East and links with twelve vertical shafts which take water from the Ring Main and feed it into the local distribution systems beneath the streets. The tunnel is 2.5 m in diameter and is over 80 km long. At an average depth of 40 m, it is also deeper than most London Underground (LU) tube lines and was bored through the London clay. The surface shafts are topped by large pumping stations to bring the water to the surface, the majority of which are hidden away on TW land. The London ring main supplies over 1300 million litres of water a day to customers [Thames Water, 2014]. Trunk mains distribute water across London from the ring to the point of use, and have diameters between 610 and 1220 mm (i.e. 24” or 24 inches, and 48”) and distribute water for both commercial and domestic purposes. Trunk main diameters in the range 610 to 914 mm (i.e. 24” to 36”) are closest to the surface and most accessible.

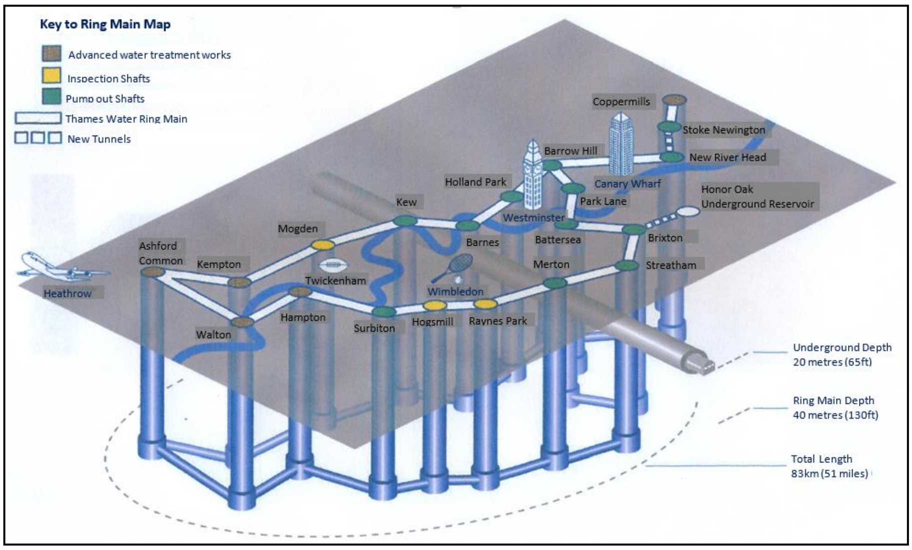

Figure 1 The London Ring Main

2.1 Using mains water for cooling

The use of mains water for cooling was first reported by Maidment and Paurine [2015]. Its capacity for cooling relies on mains water being at a relatively low temperature throughout the year as shown in Figure 2. Because of the volume of water involved, increasing London's mains water temperature by only 1°C would produce 100 MW of cooling, and it is realistic to add 5°C in temperature, for water temperatures up to 15°C (i.e. for 8 months of the year) which is equivalent to 500 MW of cooling. If this could be utilised, this is equivalent to meeting around 1/3 of the total UK building cooling load [Day et al, 2009].

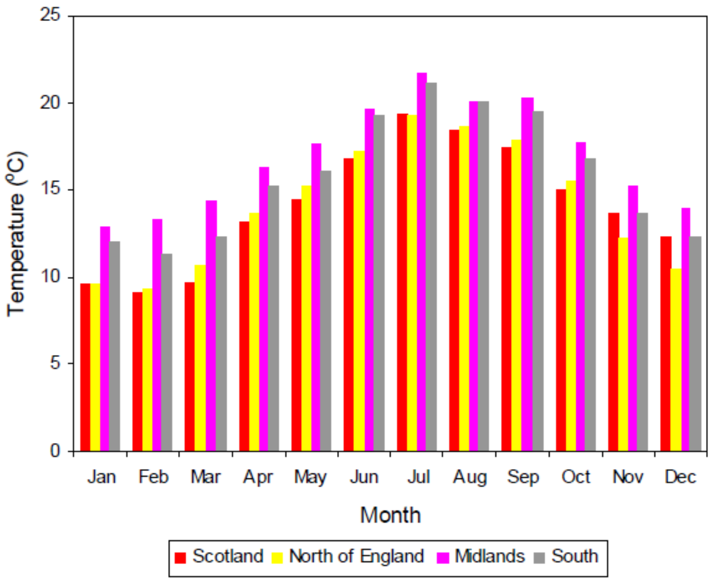

Figure 2 Regional variation in cold water supply temperature [Energy Saving Trust, 2008]

Mains water cooling could be employed to replace mechanical chillers for a substantial proportion of the year, for a range of applications e.g. for LU stations, large buildings, data centres, high density power installations, etc. However, one restriction in its application is that it is undesirable to increase water temperatures above 20°C, therefore heat could be added (to increase the temperature by up to 5°C) for mains water temperatures up to 15°C (i.e. for 8 months of the year). This would restrict its use to outside of the peak summer months. During the summer months, cooling would need to be supplemented e.g. by using a chiller operated in series. One example of a configuration for a mains water cooling system in a LU application, incorporating a secondary water cooling loop and back-up chiller, is shown in Figure 3. When the system is operating without the chiller only minimal power input is required to deliver cooling, and therefore very high efficiency can be achieved.

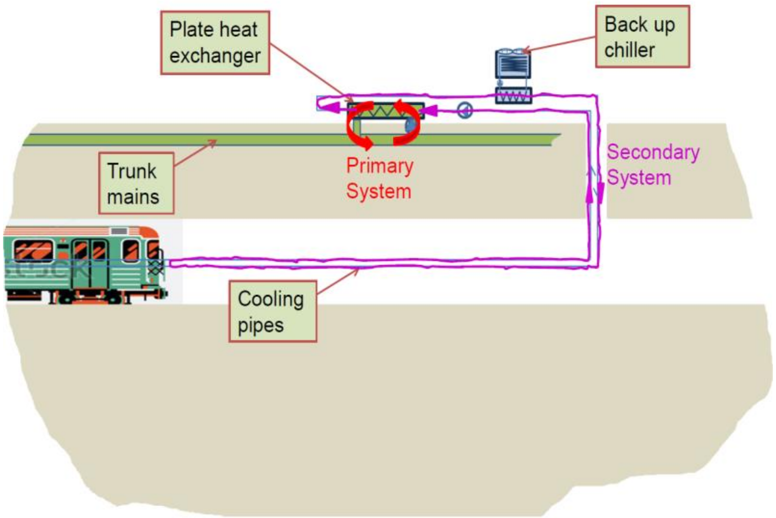

Figure 3 Potential configuration for mains water cooling system employed on an underground railway system

As well as potential energy, carbon and cost savings compared to conventional cooling methods, there are a number of other benefits of using mains water for cooling/heat recovery. These include reduced water leakage by avoiding pipe contraction through raising the trunk mains water temperature. The relationship between mains water temperature and reduced leakage is shown in Figure 4. The average reduction in leakage rate over the temperature range 5 to 15°C is 0.4% of flow per 1°C rise in mains water temperature. Reduced leakage results in both direct revenue and capital cost savings for the utility provider. It also results in reduced road maintenance and consequently less disruption for road users. An additional benefit for the UK in general is that higher mains water temperature will reduce the energy input requirement for domestic hot water (DHW) and associated carbons emissions and will therefore contribute to meeting overall emissions reduction targets. This paper investigates the benefits associated with the use of mains water for cooling.

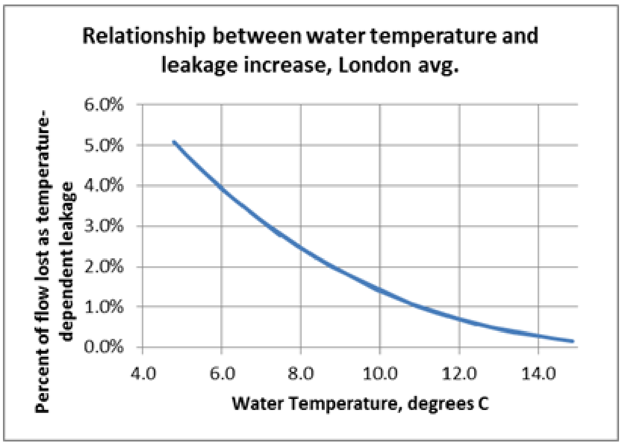

Figure 4 Influence of mains water temperature on leakage

3. Methodology

The investigation involved 4 elements:

1. Considering a range of applications and assessing their suitability for mains water cooling.
2. Identification of promising applications and determination of their proximity to the mains water supply.
3. Evaluation of the relative savings in energy, carbon emissions and costs in using this cooling method as compared to conventional cooling methods.
4. Calculation of secondary savings due to preheating of mains water for domestic hot water.

3.1 Investigating the use of mains water in different applications

Table 1 shows a comparison of a number of applications in relation to some key criteria. These include the proximity of the cooling application to mains water availability, the scale i.e. size, of the cooling requirement, how the application would cope during the peak summer months when adding heat to mains water was undesirable, and finally the benefits that might be accrued. From this mainly qualitative assessment, two promising applications identified were LU stations and data centres. These are subject to further investigation in sections 3.2 and 3.3 below.

Table 1 Investigation of the use of mains water in a range of applications

Type of heat source	Specific application	Presence in the London area	Individual cooling demand (or waste heat output) (MW)	Total waste heat output of sector (MW)	Waste heat temperatures?	How suitable for cooling are the TW water temperatures?	When is cooling required? Seasonal?	What are the benefits?
Infrastructure	London Underground	Yes	2MW/ station	25 MW (own estimate)	25-30°C	Varied. Only available for part of the cooling season.	Cooling required by LU in summer,while mains water requires heat (and can provide most cooling) in winter	Reduced mains water leakage, LU reduced energy consumption for cooling.
	UKPN substation	Yes	1.63MW/ transformer	N/A	N/A	N/A		
	National Grid electrical infrastructure	Yes	6.8 MW/ transformer	40 MW	55°C	N/A		
	Hospitals	Yes	N/A	N/A				
Building air conditioning	Offices	Yes	N/A	308 MW	28°C	Depends on application.	More cooling required during summer months	Reduced mains water leakage/ reduced energy use and cost of operating mechanical chiller.
	Retail	Yes	N/A	616 MW	28°C	Depends on application.	More cooling required during summer months	Reduced mains water leakage/ reduced energy use and cost of operating mechanical chiller.
Commercial refrigeration	Supermarkets	Yes	0.5-1 MW/ Large supermarket	32 MW	32°C	Suitable for rejection of refrigeration system heat, so potentially	Cooling required year round	Reduced mains water leakage, reduced refrigeration system energy and running cost
	Data centres	Yes	3.5 MW /data centre	86 MW	25-35°C	Suitable for rejection of refrigeration system heat	Cooling required year round	TW leakage reduction, free cooling of data centre for 8 months of year.
Industrial processes	Food manufacturing and chemical processing	Yes		11.4 MW	35-70°C (varies depending on process)			
Power generation	Power stations	Yes		945 MW	35°C +		Cooling required year round	
	CHP	Yes	0.7 MW/ CHP plant	10.3 MW	45°C		More heat rejected in winter	

3.2. Mapping of location of applications with mains water

TW provided a map of trunk main locations for London (personal communication). The trunk mains closest to the surface are the most suitable for use in cooling applications. These water mains pipes have diameters ranging from 24" (610 mm), to 36" (914 mm). The map was overlaid with the coordinate locations of every LU station throughout London. Only the underground lines were plotted, since they are the only ones that might need cooling; therefore London Overground, Transport for London (TfL) Rail and Docklands Light Railway (DLR) lines were excluded. In fact, some stations that are part of the underground network are actually above the surface, so do not require cooling. Most of the stations on the outskirts of London are above ground, while most of the stations in central London are below ground level.

In addition, a list of postcodes and coordinates for data centres across London and their heat outputs was compiled. The data centre locations were also overlaid on the map. The map showed that many stations could be provided with cooling from the trunk mains, and many of the data centres also have a location match with the trunk mains. This indicates the viability of this project in terms of geographic position, which may lead to considerably reduced installation costs. Some stations and data centres are not close to any of the trunk mains, making them less feasible to cool. The cooling requirements/heat outputs of both the stations and the data centres that are most suitable i.e. closest to a trunk main, were used to obtain the overall heat output, and then used to calculate the energy, carbon and financial savings available for this cooling method, which is described in the next section.

3.3. Investigation of benefits of mains water cooling

An investigation of the potential for cooling that can be provided by water from the trunk mains has been carried out, together with a comparison between the cooling requirements (and heat outputs) for each of the selected applications. This involved calculation of the energy, carbon and cost savings resulting from use of the water cooling system, as compared to conventional air conditioning for these applications. In addition, an estimate has been made of the potential cost savings resulting from the reduction in water wasted due to leakage. This provides additional savings through reduced maintenance costs and the need to replace existing mains water pipes. As mentioned previously, there is a relationship between the rise in temperature and decrease in leakage volume. According to TW this amounts, on average, to a 0.4% reduction in leakage for each degree Celsius increase in water temperature for any trunk main. By assuming this reduction rate, the trunk water flows have been calculated in order to find the overall reduction of leakage.

In order to transfer the waste heat (from the application requiring cooling) to the trunk mains water, it is planned to use heat exchangers. For example, in the case of cooling of underground tunnels, a secondary water loop is used for cooling the tunnels and a plate heat exchanger system used to transfer heat to the mains water, as shown in Figure 3. However, it is not practical to pass the full volumetric flow of water in the trunk mains through the heat exchanger, so a proportion of the water only is used. The temperature of the extracted water in the branch pipe is raised as a result of passing through the heat exchanger, as heat is absorbed. The extracted water is then returned to the trunk main, mixing with the remaining water, resulting in an overall rise in the trunk main water temperature. Examples of the cooling requirements/heat outputs $\dot{Q}$ for a range of LU stations (S1 to S4) are shown in Table 2 below.

Table 2 Examples of typical LU station cooling requirements

Stations	LU station cooling requirement $\dot{Q}$ (kW)		
	Minimum	Maximum	Average
S1	1	500	250
S2	501	1000	750
S3	1001	1500	1250
S4	2001	2500	2250

Data for the cooling requirements for a large number of LU stations which are close to i.e. within 10 m of, the trunk main, have been obtained. The underground station cooling requirements (and heat outputs) range in size from a minimum of 0.25 MW to a maximum of 2.5 MW, with an average of 1.5 MW per station. Together, all of the suitable stations identified to date could provide a total of 24.5 MW of heat. The cooling requirement (and heat output) ($\dot{Q}$) for LU stations will vary with e.g. the season of the year, and the time of day, however the average value reported represents the potential mean rate of heat transfer to the trunk mains water. It should be noted that LU trains operate for (and generate heat) for only 18 hours per day. However, cooling can be carried out continuously i.e. over 24 hours, while the mains water temperature is below 15°C, due to the thermal mass of the underground system. During the 6 hours when the LU system is not operating and adding heat, the tunnel air temperature will remain effectively the same, due to the re-absorption of heat stored in the tunnel walls and surrounding ground. It is therefore beneficial to continue cooling during this period.

Examples of the cooling requirements (and heat outputs) for a range of data centres (A to D) in central London, which are located close to i.e. within 10 m of, the trunk main are shown in Table 3.

Table 3 Examples of typical data centre cooling requirements

Partial postcode	Data centre identification code	Estimated data centre cooling requirement $\dot{Q}$ (kW)
EC2A	A	300
E1	B	2900
E14	C	10100
E14	D	28100

A large number of additional data centres which are located within 10 m of a trunk main were identified. Data centre cooling requirements (and heat outputs) ranged in size from a minimum of 0.25 MW to a maximum of 28.1 MW, with an average of 2.8 MW per data centre. Together, all of the suitable data centres identified could provide a total of 70 MW of heat. The overall heat availability for raising the trunk main water temperature from LU stations and data centres identified to date is therefore 95 MW.

The volumetric flow rates $\dot{V}$ and mass flow rates $\dot{m}$ through the trunk main pipes are shown in Table 4. Data provided by TW suggest indicative volumetric flow rates $\dot{V}$ of 0.3 m^3/s for 24" trunk mains and 0.6 m^3/s for 36" trunk mains. The total daily volumetric flow rate through a 24" trunk main is 25,920 m^3/day, while for a 36" trunk main, it is 51,840 m^3/day.

Table 4 Calculation of mass flow rates $\dot{m}$ in pipes

Pipe type	Pipe diameters		Cross sectional area A (m^2)	Velocities in pipes u (m/s)	Volumetric flow rate $\dot{V} = u \times A$ (m^3/s)	Mass flow rate $\dot{m}$ (kg/s)
	inches	metres				
24" Trunk (initial)	24	0.610	0.292	1.028	0.3	300
36" Trunk (initial)	36	0.914	0.657	0.914	0.6	600

Using the data for heat transfer rates $\dot{Q}$ in Tables 2 and 3, the mass flow rates $\dot{m}$ in Table 4, and assuming a specific heat capacity value for water c_p of 4.18 kJ/kg °C, the resulting temperature increases Δ**T** in the trunk mains were calculated. These increases were calculated on the basis of a single LU station or data centre, for minimum, maximum and average cooling requirements/heat outputs. The results are shown in Table 5 below. Although the calculations shown here are on the basis of the whole of the trunk main flow, in practice, a series of branch pipes and heat exchangers would need to be used to collect the heat from the LU station or data centre, and this water would then be returned to the trunk main.

Table 5 Effects of heat absorbed on trunk main water temperature increase ΔT

Pipe diameter (inches)	Mass flow rate $\dot{m}$ (kg/s)	Heat sources	LU stations			Data centres		
			Minimum	Maximum	Average	Minimum	Maximum	Average
		Heat outputs $\dot{Q}$ (MW)	**0.25**	**2.5**	**1.5**	**0.25**	**28.10**	**2.80**
24"	**300**	**Temperature increase ΔT (°C)**	0.20	1.99	1.19	0.20	22.37	2.23
36"	**600**	**Temperature increase ΔT (°C)**	0.10	1.00	0.60	0.10	11.18	1.11

It is seen from Table 5 that for some the highest heat outputs e.g. the maximum data centre values, the increase in temperature in the trunk main is quite high. In order to prevent overheating of the water in the trunk main, in some cases it might be necessary to limit the temperature rise ΔT e.g. to 5°C. This could be achieved by adjusting the mass flow rate for the cooling water and/or the size and number of plate heat exchangers.

The resulting energy, carbon and cost savings for a single LU station and data centre over the course of a year are shown in Table 6 below. It is assumed that cooling for LU stations and data centres would otherwise be provided by air conditioning systems operating at an average coefficient of performance (COP) of 2. The cost of pumping water through the heat exchanger has been assumed to be negligible compared to the cost of operating an air conditioning system to carry out cooling at the rate required. It is also assumed that while LU stations generate heat for only 18 hours per day, cooling can be beneficially applied for 24 hours (as discussed earlier). Data centres require 24 hour cooling. In each case, mains water cooling resulting in a temperature increase of 5°C in the trunk main, can be used for 8 months of the year. Further assumptions include an electricity cost of £0.10/kWh and a carbon factor of 0.46219 kg CO_2e/kWh [DEFRA, 2015].

Table 6 Potential energy, carbon and cost savings from cooling

	LU stations			Data centres		
	Minimum	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
Cooling rate/ heat output (MW)	**0.25**	**2.50**	**1.50**	**0.25**	**28.09**	**2.80**
Operating hours per annum (h)	8,760	8,760	8,760	8,760	8,760	8,760
Total cooling required per annum (MWh)	2,190	21,900	13,140	2,190	246,111	24,528
Electricity use per annum for conventional cooling (MWh)	1,095	10,950	6,750	1,095	123,056	12,264
Energy savings per annum for mains water cooling (MWh)	730	7,304	4,502	730	82,078	8,180
Carbon savings per annum (tonnes CO_2e)	338	3,376	2,081	338	37,936	3,781
Electricity cost savings per annum (£)	£73,040	£730,400	£450,200	£73,040	£8,207,800	£818,000

Table 6 shows that there are very significant savings from using mains water for cooling of underground stations and data centres, as compared with conventional cooling. It is assumed in Table 6 that cooling can be provided by mains water for 8 months of the year, since as noted earlier, heat is not needed to raise the trunk main temperatures during the peak summer season i.e. at water temperatures of >15°C, so the cooling system would need to be supplemented by a chiller during this period. Therefore, the use of mains water cooling for 8 months of the year would reduce the annual electricity per year by 2/3, resulting in substantial overall savings in energy, carbon and costs. In addition to the savings in electrical energy as compared with operating air conditioning systems for cooling LU stations and data centres, there are additional savings in terms of reduced leakage of water from the trunk mains. These have been calculated on the basis of an average reduction in leakage of 0.4% per 1°C rise in the trunk main water temperature, while the mains water temperature is 10°C or less i.e. for 4 months of the year (or 120 days). At temperatures above 15°C, temperature driven seasonal leakage is assumed to be negligible (see Figure 4). It is assumed that the cost of the leaked water is £0.32 per m^3, based on TW data (personal communication). This accounts for both the cost of the leaked water and the cost of avoiding leakage detection and repair. The results for these calculations are shown in Table 7.

Table 7 Reduction in water leakage and cost savings from raising the trunk mains temperature

Trunk diameter (inches)		London Underground Stations			Data Centres		
		Minimum	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
	Cooling rate/heat output (MW)	**0.25**	**2.50**	**1.50**	**0.25**	**28.09**	**2.80**
24"	**ΔT (°C) (for trunk main)**	0.20	1.99	1.19	0.20	22.37	2.23
	Water volume saved (%)	0.08%	0.8%	0.48%	0.08%	8.95%	0.89%
	Daily water volume saved (m^3)	21	207	124	21	2,320	231
	Annual water volume saved (m^3)	2,484	24,876	14,928	2,484	278,400	27,672
	Daily financial saving (₤)	£7	£66	£40	£7	£742	£74
	Annual financial saving (£)	£795	£7,960	£4,777	£795	£89,088	£8,855
36"	**ΔT (°C) (for trunk main)**	0.10	1.02	0.61	0.10	11.51	1.15
	Water volume saved (%)	0.04%	0.4%	0.24%	0.04%	4.6%	0.5%
	Daily water volume saved (m^3)	21	207	124	21	2,320	231
	Annual water volume saved (m^3)	2,484	24,876	14,928	2,484	278,400	27,672
	Daily financial saving (₤)	£7	£66	£40	£7	£742	£74
	Annual financial saving (£)	£795	£7,960	£4,777	£795	£89,088	£8,855

It is seen from Table 7 that moderate annual savings are available in terms of reduction in water leakage and costs, as a result of increasing the trunk mains water temperature, in addition to large savings on cooling e.g. for underground stations and data centres, compared with conventional cooling methods, such as air conditioning. The savings indicated in Table 7 are for single underground stations and data centres only.

However, a number of heat sources can be used for a single trunk main, permitting accumulative heat transfer and temperature increases along the pipe, providing increased water and cost savings.

3.4. Advantages in Domestic Hot Water by Preheating Mains Water

This section investigates the secondary benefit of warming mains water on DHW energy usage. According to DECC, domestic space heating and hot water in the residential sector, account for 13% of greenhouse gas emissions in the UK. Approximately 30% of the domestic heat consumption is due to hot water. Also, DHW represents 17% of the energy cost for a typical family, from a total of £1217 per year [BSUH, 2015]. By raising the water temperature by 5°C, from an average of 10 to 15°C, this reduces the energy and carbon emissions needed to heat water to 60°C by 5/(60-10) i.e. 10%, for 8 months (i.e. 2/3) of the year. Therefore, it can be shown that the total carbon emission reduction that might be achieved is 13% x 30% x 10% x 2/3 or 0.26%. The cost saving per family will be 17% x £1217 x 10% x 2/3 or £13.79 per year.

4.0. Conclusions

This paper describes the potential use of mains water as a low carbon cooling resource. It examines a range of applications and investigates the proximity and benefits associated with mains water cooling of data centres and LU stations. It shows that there is close proximity between the applications and specific cooling demand and there is significant energy and revenue cost saving associated with utilising the mains water. Furthermore, there are additional benefits with warming the water, for example, reduced leakage, fewer repairs to underground pipes and the associated disruption, as well as reduced energy input associated with preheating hot water. The next steps are to identify a trial site and establish the benefits, costs and feasibility of an installation.

Acknowledgements

The Authors acknowledge the funding of EPSRC in supporting this research under the End User Energy Demand programme and the input of colleagues from i-STUTE.

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