University College London
Research Paper

Title: What are the prospects for net-zero district heating in large estates or university campuses?

Word count: 6704

Author: Bipash Paul
Supervisor: Dr Nick Hughes
The Bartlett Faculty of the Built Environment

Abstract

Climate change caused by the increasing global temperatures could be the world's next catastrophe. The lack of a low carbon sustainable heat source has led cities such as London to produce high levels of carbon emission from the heating sector. To reduce carbon emissions, organisations have made use of the district heating network (DHN) to supply heat to households. However, although these networks cut carbon emissions, they use fossil fuels such as natural gas as the heat source. This restricts the network from being a carbon-neutral source and thus for net-zero to be achieved by 2050, alternatives must be thought of.

This report investigates two different scenarios to achieve net-zero district heating for an estate like University College London. Scenario 1 looked at recovering the waste heat from the London Underground (LU) ventilation shaft. The model developed was similar to the Bunhill 2 project led by TfL and Islington Council. This solution made use of a series of heat exchangers and a heat pump to provide space heating and domestic hot water. Scenario 2 looked at adapting to a 5th generation district heating and cooling (5GDHC) system. It made use of geothermal heat and also allowed buildings to exchange their thermal energy to balance the overall heating demand. Each building had a bi-directional heat pump which would also allow cooling and lower energy consumption.

The main objectives and constraints were considered during the research for the potential solutions. The theoretical carbon savings from using the waste heat from the London Underground was analysed and quantified. The paper further details the working of the 5GDHC and lists its advantages and disadvantages. However, the projected carbon savings from this network could not be quantified due to the complexity of the model and the required data.

The two solutions had a common requirement which was the need for a thermal store in the network. This concludes that for a net-zero district heating system, there is a need to integrate a thermal store that is missing in UCL's existing network. This would further help in enabling demand-side response and allow the institution to lower its expenditure on energy. The paper also provides recommendations for the future by integrating the two scenarios to form a new DHN. This would increase the resilience of the system and allow the network to function efficiently during different seasons.

Table of Contents

Chapter 1. Introduction

1.1 Problem definition

The combustion of commonly used energy sources leads to the emission of greenhouse gasses that have raised global temperatures. This has acted as one of the main causes for climate change which will be the world's next biggest problem to think about. The UK government has now recognised this problem, making an obligation of reducing the CO_2 emission by 80% of the 1990's levels by 2050 (HM Government, 2009).The heating sector in particular accounts for one-third of carbon emissions in the UK. The lack of sustainable heating has led cities such as London to make use of gas-boilers that make significant contributions to the carbon footprint and air pollution. Only 4.5% of heating in buildings in 2017 came from sustainable heating such as low-carbon sources (Committee on Climate Change, 2018). The Committee on Climate Change has stated that the UK won't be able to achieve its net-zero without focusing on decarbonising the heating sector. Hence, decarbonising the heating sector has a decisive role to play for the UK to achieve its future goals.

The development of heat networks such as the district heating network has proved to be a solution for cost-effective low-carbon heating. A district heating network (DHN) is a comprehensive system that provides space heating and domestic hot water (DHW) to a series of buildings via an established pipe network. The heat is generated at a source and then distributed to the connected buildings via pipes. The network replaces the conventional style of buildings having gas boilers to meet their heat demand. Conventional DHN use a Combined Heat and Power (CHP) system fired by natural gas to act as the main heat source. However, this system proves to be inefficient due to the high-water temperature in the pipe that losses thermal energy to the ground. The excess heat produced in the summer months also goes to waste as the demand for heating is low. More importantly, this fossil fuel-fired engine causes significant carbon emissions and hence, an alternative must be thought of. This can be through making use of waste heat, geothermal heat, adopting a new heat network or lastly changing the fuel type of the engine to biomass. The paper details a few of the possible solutions below.

1.2 Literature Review

The research began at understanding the heating requirements of a large estate such as of University College London (UCL). According to the data provided, 31% of UCL's energy consumption is used in the heating sector (Sustainable UCL (2021) "Delivering a zero carbon UCL by 2030). This is met by individual gas-boiler located throughout campus and the established district heating networks. The heat demand from the DHN of UCL is met by two local heat networks:

1. Gower Street District Heating Network (UCL owned) which accounts for nearly 28% of UCL's carbon emissions

2. Bloomsbury Heat and Power Network (UCL partially owned in a consortium) that accounts for 3.5% of UCL's carbon emissions.

Note: This paper only studies the Gower Street District Heating Network. The Bloomsbury Heat and Power Network was neglected from the study as it provided heating to several other colleges and its data wasn't readily available.

The DHN owned by University College London is located at Gower Street and was studied to determine the prospects of net-zero district heating systems. It is comprised of a $3MW_e$ natural gas-fired CHP engine with an additional $1.5MW_e$ capacity to manage demand during peak hours (Burohappold Engineering, 2015). The heat produced from the engine was used as the heat source for the network. The energy distribution of the CHP system is shown below:

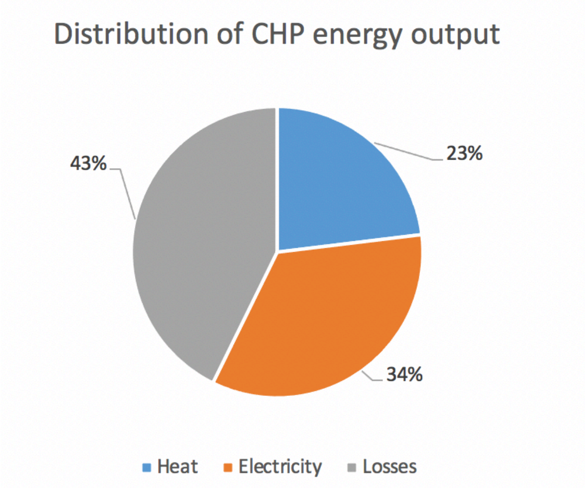

Figure 1: Distribution of CHP energy output. (Refer Appendix A)

This network is capable of handling an annual head load of 9600MWh (Sustainable UCL (2021) “Delivering a zero carbon UCL by 2030) but is currently serving a load of 6540MWh on an annual basis (Burohappold Engineering, 2015). This could be due to the requirements that UCL has imposed on buildings to connect to this network. Another possible reason for this could be to increase the life span of the CHP engine and reduce maintenance costs. This reduces the efficiency of the system which is 57% compared to typical CHP engines which are 60-80% efficient (United States Environmental Protection Agency. n.d). However, although this network aims to reduce carbon emissions, the fuel source tends to have a significant effect on the carbon footprint of UCL. Data suggests that the district heating network is responsible for 28% of UCL’s carbon emissions summing to roughly 15,000 tonnes of CO_2 on an annual basis (Sustainable UCL (2021) “Delivering a zero carbon UCL by 2030). The remaining heat load is met by conventional gas boilers that are responsible for roughly 9520 tonnes of CO_2 on an annual basis. (Refer Appendix B)

UCL as an organisation aims to become a net-zero carbon institution by 2030 and this would be done by:

- Purchasing renewable electricity and green gas by 2024 to achieve net-zero energy from buildings.
- Achieve absolute zero carbon emissions from energy use by 2030 by generating their own renewable electricity and more importantly displacing fossil fuels to renewable alternatives

External drivers such as the requirements by the Greater London Authority (GLA) and the Camden Council towards achieving net-zero reflects its importance. There is also a forecasted financial benefit from this transition as organisations would avoid paying high carbon tax. The Department for Business, Energy and Industrial Strategy forecasts to increase the carbon tax from £30/tonne to £80/tonne by 2030 (Giles, 2020).

1.3 Aims and Objectives

The overarching aim of this research project was to determine the prospects of net-zero district heating systems in large estates such as universities. The process began by performing an energy balance on UCL’s energy consumption to quantify the heating requirements for such an estate. A range of alternatives to the existing technology was then researched and its feasibility studied. The main objective throughout the research was to reduce the existing networks carbon emissions and potentially upgrade its capacity.

Chapter 2. Methodology

2.1 Overview and functions

It was vital to look at the entirety of UCL's heat consumption to understand the emissions from the different heat supplies. The gas boilers installed in most buildings delivered a majority of UCL's heat demand. Hence, a possible synergy would be to ultimately increase the DHN's capacity and reduce the load from these boilers. This would further lower the institution's carbon footprint and maintain its position in the carbon league.

2.2 Objectives

The objectives that the proposed solution must fulfil are:

- <u>Minimise carbon emissions</u>: This aligns with the main objective of the research project. For UCL to achieve its zero-carbon energy target, focusing on decarbonising the heating sector is vital.
- <u>Supply space heating and domestic hot water</u>: The current network serves the campus with space heating and domestic hot water. Hence, the proposed solution must be able to deliver these services.
- <u>Avoid the use of fossil fuels</u>: UCL has set a goal to substitute fossil fuels such as natural gas to renewable alternatives by 2030 (Sustainable UCL (2021) "Delivering a zero carbon UCL by 2030). Furthermore, the government has banned the installation of gas or oil fed boilers in new buildings from 2025 to achieve their net-zero target (McGrath, 2021).
- <u>Minimise energy consumption</u>: The existing CHP unit is only 57% efficient with the remaining energy being lost. There are certain amounts of carbon emissions produced by kWh of energy consumed that undergoes a carbon tax. Carbon emissions have fallen in recent years as the majority of the electricity consumed is from renewables. However, electricity prices have been steadily increasing (by 33%) since 2010 (Department for Business, Energy and Industrial Strategy, 2021). Hence, minimising energy input was an important aspect to minimise cost.
- <u>Upgrade heat capacity</u>: The requirements for new buildings and major refurbishments to connect to district heating schemes makes upgrading the networks capacity vital.

- Maximise efficiency: The existing network had a water flow and return temperature of 95°C and 65°C (UCL Estates, 2017). These high temperatures led to thermal losses that can reach a upto 30% because of the high retention time of water in the pipelines especially during summer. Thus, aiming to reduce the operating temperatures to maximise the efficiency was an important objective.

2.3 Constraints

The constraints imposed on the proposed solutions are:

- The solution must have lower carbon emissions compared to natural gas-fired CHP system to be acceptable
- The solution must be able to match the existing annual heat load of 6540 MWh from the Gower Street Network
- The location of the network in Central London possesses a constraint on the acceptable pollution level. The Greater London Authority and the Camden Council have strong requirements for reducing air pollution from the heating sector.

2.4 Limitations of the investigation

The short nature of this research project only permitted the analysis of the UCL owned DHN. However, it is vital to look at the Bloomsbury Heat and Power Network that also acts as a source of district heating. Furthermore, to reduce carbon emissions on a larger scale, a study must be conducted on the existing gas boilers. However, this is an area of future work.

Chapter 3. Potential Solutions

Scenario 1

To meet the net-zero target by 2050, the UK has to adapt to sustainable heating alternatives. In a city like London, this presents itself by making use of excess or waste heat sources. A great opportunity to harvest this waste heat is from the London Underground Network. The Underground has been known for its record-breaking temperatures that causes major discomfort to the passengers onboard. The heat sink present in the network was the tunnel walls that absorbed majority of the thermal energy. However, due to the increase of the surrounding clay's temperature, the heat can no longer flow towards to wall (Mansfield, 2017). Hence, Transport for London has made it its priority to cool down this large, comprehensive network.

However, cooling down such a large network is rather complicated due to the age of the tunnels and the tight kinematic envelope present. Hence, TfL has begun to use the in-built mid-tunnel ventilation shafts to extract the warm air from the tunnels. The Bunhill 2 Energy Centre is a recent accomplishment of TfL and the Islington council's ability to recover this heat for the use in district heating (Celsius, 2020).

To promote sustainable heating, TfL recovered waste heat from a large thermal mass which is the underground train tunnels. A bi-directional fan was installed in the mid-tunnel ventilation shaft which extracted the warm air from the tunnel. This warm air then passed through a series of air-to-water heat exchangers that recovers nearly 780kW of heat. However, this heat is low-grade and hence, is sent to a heat pump which upgrades the energy by adding 260kW of heat. This heat energy is then ultimately supplied to the established district heating network with a flow temperature of 75°C and return temperature of 55°C. The expected annual heat demand is closely 11,358MWh providing heating to 455 dwellings and to a primary school (Henrique Lagoeiro, et al., 2019). The heat pump is powered by the electricity generated by the two CHP units on-site and the excess heat also adds resilience to the system. Lastly, the system also has a 77.5 m^3 thermal store to manage peak demand (Henrique Lagoeiro, et al., 2019). The schematic of this system is presented in Figure 2:

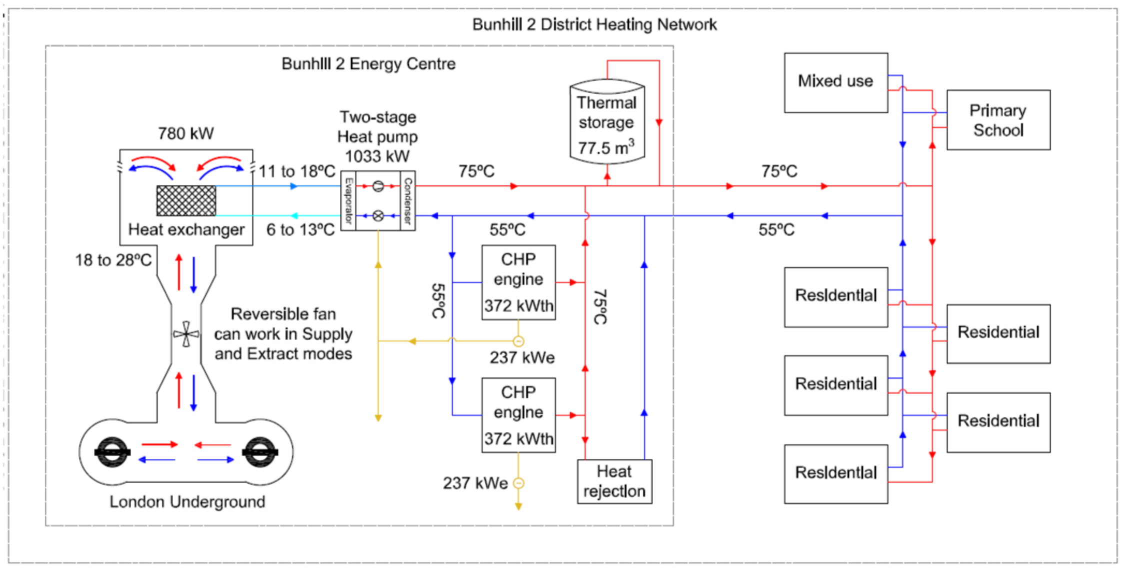

Figure 2: Schematic of the Bunhill 2 waste heat district heating network (Lagoeiro & Revesz, 2019).

The warm air from the tunnels has a temperature ranging from 18-28°C and can heat the water in the exchangers to about 11-18°C. The total recovered heat energy from this process is averaged to be 780kW and the rest is supplemented with the energy supplied by the heat pump as explained earlier.

A two-stage water to water heat pump with ammonia (R717) as the refrigerant is used in the system. The advantage of such a heat pump is that is allows intercooling and thus reduces the work input to the compressors of the heat pump (Ohkyung, et al., n.d.). This makes the system seem more feasible by increasing the Coefficient of Performance (COP). The COP of a heat pump is defined as the ratio of the heat produced per unit of electricity consumed by the compressor of the heat pump. The design parameters of the heat pump used in the Bunhill 2 Energy Centre is shown in Table 1:

Design Parameters	Operating Condition
Water in heat exchanger flow temperature (°C)	13
Water in heat exchanger return temperature (°C)	8
Cooling duty (kW)	780
Heat Pump compressor efficiency (assumed)	92%
Shaft power for the compressor (kW)	253
Estimated electrical consumption (kW)	275

Heating Duty (kW)	1033
Heating COP	3.76

Table 1: Design parameters of the heat pump installed at Bunhill 2 Energy Centre.

The presence of a thermal store in the system would also help with managing peak loads and enable an effective demand side response. This is also a method to reduce electricity costs as the electricity charges vary throughout the day and night in a city like London. As electricity prices have steadily increased since 2017, making intensive use of the system when electricity is at its cheapest could be the ideal way to maximise profitability. The thermal store also increases the design life of the heat pumps by avoiding short cycling. If the heat pump is frequently switched on/off, its efficiency can be harmed and there will be a need for regular maintenance. However, with a thermal store this problem is avoided and the heat pump can store excess heat when demand is low. The system also contains two CHP units which are a way to increase the resilience of the network and generate power. The CHP engines power the heat pumps while simultaneously using the wasted heat within the network. If there is any excess heat, it can be stored in the thermal store or can be released to the environment. However, if there is excess electricity, this can be returned to the grid or sold to generate revenue.

Furthermore, the benefits of this network are that:

i. It significantly reduces carbon emissions by approximately 500 tonnes a year (Colloide , n.d.).
ii. Reduces heating costs by decreasing dependency on fossil fuels and electricity grid. It was estimated that the tenants connected to this network saved 10% of their bills when compared to other heating systems (Building Design & Construction , 2020).
iii. Makes use of the excess heat present in the London Underground which inherently reduces its temperatures and solves TfL's problem
iv. Significant energy input savings due to high Coefficient of Performance of the heat pumps

It is interesting to note that this system can be replicated and used as a substitute to the existing heat source in UCL's district heating network. This is possible due to UCL's close proximity to the nearest mid-tunnel ventilation shaft in Euston. The shaft is located on Stephenson Way, a small street behind Euston road and on the site of a former UCL building, Wolfson House (The Construction Index, 2019). The shaft is linked to the Northern line tunnel beneath it from where the excess heat can be extracted. High Speed Services were appointed to redesign the ventilation shaft in 2019 and the proposed design can be seen in Figure 3:

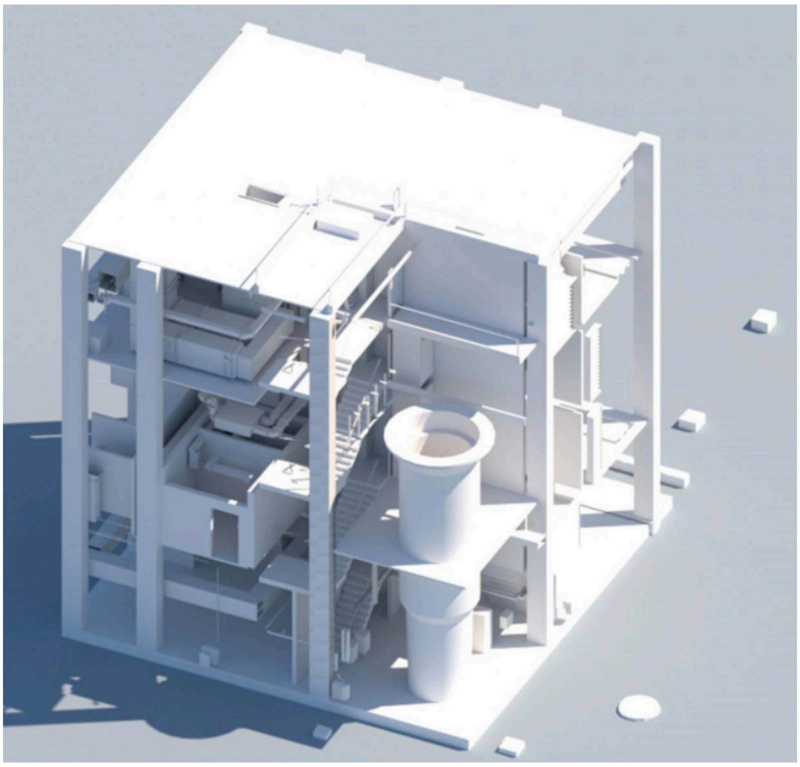

Figure 3: Euston ventilation shaft linked to the northern line (WestonWilliamson+Partners, n.d.).

The above designed building will contain a substation for the London Underground as well as the ventilation shaft for the Northern Line. The shaft conventionally releases the warm air into the environment where it goes to waste. However, instead of this, the heat from the air can be recovered and used as a source for heating the Bloomsbury campus of UCL. The same design parameters can be replicated for the Euston road ventilation shaft. UCL has already conducted feasibility studies to provide zero carbon district energy by 2030. An aspect of this study included making use of waste heat sources and UCL had considered purchasing a ventilation shaft from TfL. Hence, the characteristic features of this solution align with UCL's vision.

The Bunhill 2 Energy Centre was a joint collaboration between the Islington Council, Transport for London and the Mayor of London (Wilson, 2020). It was funded by the Islington Council who own and run this heat network but received numerous grants from the European Union's CELCIUS projects (Islington Council, n.d.). According to the Islington Council, TfL is conducting further research to identify areas where this network can be replicated. Furthermore, the Camden Council has launched the Green Action for Climate Change where they aim to severely reduce carbon emission in the borough. They have stated that they would encourage partnerships with organisations to promote low carbon energy projects (Camden Council , 2019). Hence, from the political scenario, UCL can collaborate with TfL and the Camden Council to initiate this project. The funding for this could come from various sources such as UCL, TfL, Camden Council or grants such as the Industrial Heat Recovery Support (IHRS) Programme from the UK government (Department for Business, Energy and Industrial Strategy, 2020).

As the Bunhill 2 Energy Centre is owned by the council, it would be fair to assume that this project would also be owned by the council. However, this is more of an institutional decision as there are financial and political factors involved. If UCL were to purchase this, there would be a burden on the finances as they would have to lease the ventilation shafts, install the infrastructure and handle operations. However, there are savings, given the lower energy input and carbon emissions which reduce the overall carbon tax paid by the institution.

The data given states that 31% of UCL's energy consumption is required for heating and hot water (Sustainable UCL (2021) "Delivering a zero carbon UCL by 2030). Furthermore, the literature also suggests that UCL meets its heating requirements through three methods: the Gower Street District Heating Network, Bloomsbury Heat and Power Network and gas-fired boilers. The distribution of each is presented in Figure 4:

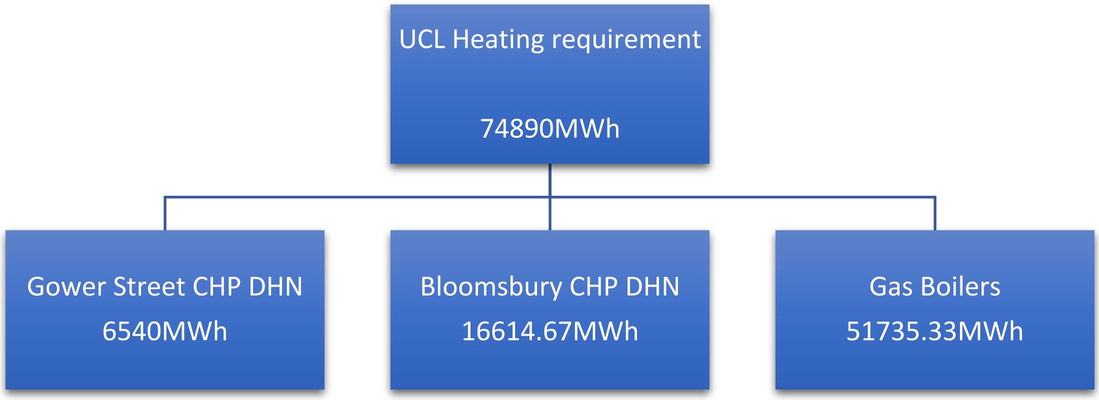

Figure 4: Distribution of UCL's heating demand. (Refer Appendix C)

However, due to the short nature of the project, only the Gower Street CHP unit is analysed. UCL aims to be a zero-carbon institute and hence, it is vital to look at the emissions currently being produced from these sources. The carbon factor for a CHP engine is typically 0.55 $kgCO_2/kWh$ (Department for Business, Energy and Industrial Strategy, 2021) while for a gas boiler is 0.18 $kgCO_2/kWh$ (DBEIS, 2021). Thus, the carbon emissions from these sources are:

Source	Energy usage (kWh)	Carbon factor ($kgCO_2/kWh$)	Total emission (tonnes)
1. Gower Street CHP	28353310.88	0.55	15594.32
2. Gas boilers	64669162.50	0.18	11640.45

Table 2: Total carbon emissions of the different heat sources of UCL.

From Table 2 it can be noted that although the CHP units used approximately a third of the energy consumed by the gas boilers, they had a larger share in the carbon emissions. The CHP engine is much more carbon intensive as it operates at a much higher temperature level. The higher the temperature of combustion, the greater would be the levels of carbon dioxide formation. This calculation is also backed with the data that suggests that 28% of UCL's carbon emissions originate from the Gower Street CHP unit that equates to around 15,283 tonnes. (Refer Appendix D)

The Bunhill 2 estimated to provide an annual heat load of 11358 MWh while the CHP was only providing a heat load of 6540 MWh. Hence, there is a scope for increasing the capacity of the entire network. This would simultaneously reduce the energy usage from the gas boilers, reducing its carbon emissions.

If the same heat load from the Bunhill 2 centre is anticipated, then there would be a 9.3% decrease in the gas usage from boilers on campus (Refer Appendix E). The assumption here would be that the energy usage for heating and hot water would be the same over the years.

Technology (Heat source)	Efficiency/COP	Heat Demand (MWh)	Annual energy usage (MWh)
Gas-fired CHP engine	0.23	11358	49382.61
Heat Pump	3.76		3020.74

Table 3: Annual energy usage of the different heat sources for the same heat load.

Table 3 also concludes that using a heat pump would significantly reduce the energy usage for the heating sector. It would inherently reduce carbon emissions, however, the source for the energy would play a role in determining the extent of the emissions. The electricity can be purchased directly from the grid or consumed from the installed CHP engine on campus. The projected carbon emissions from these sources can be seen in Table 4:

Technology	Annual Energy usage (MWh)	Carbon factor ($kgCO_2/kWh$)	Carbon emissions (tonnes)
CHP (running entire network)	49382.61	0.55	27160.44
CHP (only powering heat pump)	3020.74	0.55	1661.41
Grid	3020.74	(Year 2021) 0.15	453.11
		(Year 2030) 0.05	151.04

		(Year 2035) 0.01	30.21
		(Year 2050) 0.002	6.04

Table 4: Carbon emissions of different technologies to meet the upgraded networks capacity.

Note: The carbon factor or intensity for the grid is projected to decrease from 220gCO_2/kWh in 2019 to around 50gCO_2/kWh in 2030 and finally to 2gCO_2/kWh in 2050 (Committee on Climate Change, 2020). This decreasing trend can be seen from Figure 5:

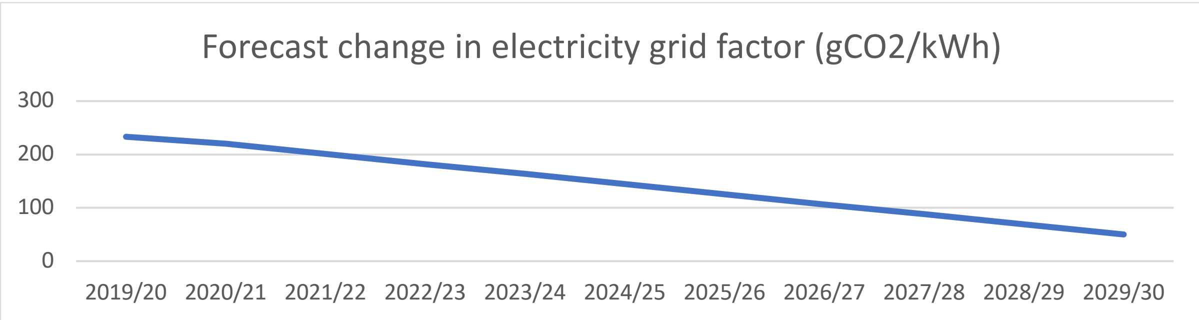

Figure 5: Projected decrease in carbon factor from electricity grid.

Scenario 2

The next potential solution to decarbonise the district heating network could be by adapting to the 5th Generation District Heating and Cooling (5GDHC) network. It is a system that combines the heat network to deliver heating and cooling by exchanging thermal energy between buildings with different heat demands. The network consists of two pipes, a warm pipe and a cold pipe which are connected to the buildings on the network. The heat is derived primarily from geothermal sources and is extracted or rejected through a borehole. Each building has a heat pump installed within them and generates the required temperature at the point of demand (Interreg North West Europe, 2021). These heat pumps are bi-directional and can thus deliver both heating and cooling power.

If a building on the network requires heating, it will draw water from the warm pipe, extract the heat and return it to the cold pipe. There reverse happens if the building needs cooling. Thus, through this, the network also accounts for cooling which takes a significant amount of energy during summer months. According to the data provided, UCL uses 31% of its entire energy usage is directed towards cooling and ventilation 2030 (Sustainable UCL (2021) "Delivering a zero carbon UCL by 2030). Hence, the synergy from this network would reduce UCL's energy consumption and carbon emissions. Furthermore, this network also consists of a borehole and water thermal energy store that manage peak load and add resilience to the entire network. This stores excess heat during summer for use in winter months and counterbalances mismatches between the heating and cooling demands of the system (Buffa, et al., 2019). With this the network can also take advantage of the cheaper electricity prices during off peak hour to run majority of its operation.

London South Bank University (LSBU) has recently adopted this method to provide heating and cooling for two of its buildings. The network is called the Balanced Energy Network (BEN) and was partially funded by the Department for Business, Energy and Industrial Strategy through the Innovate UK programme. It draws water from the London Aquifer through two 110m boreholes. The groundwater has temperatures ranging from 13°C-15°C with its heat extracted via a heat pump. Through this method, the BEN combines the heat network with smart-grid technology to minimise costs and carbon emissions (Song, et al., 2019). The simultaneous heating and cooling with a thermal store eliminate the need for individual gas boilers that reduces costs.

The fundamental principle that this system works on is to reject heat to the network from a building that needs cooling and recover it for those buildings that need heating. In winter when all the buildings on the network require heating, the network makes use of the buildings thermal inertia to balance the heating requirements. A buildings thermal inertia is its ability to retain thermal energy and is defined as the degree of slowness with which its temperature reaches that of the environment (Lizarraga & Picallo-Perez, 2020). Different buildings on the network would have different thermal masses with some being well insulated while others being poorly insulated. A well-insulated building with a large thermal mass could be seen as a thermal store as it would release heat to the building when there is no external heating. It would also capture and release solar energy thereby reducing the overall energy consumption. The Balanced Energy Network also makes use of a thermal energy store such as the one shown in Figure 6 to balance the heat demand. It can also use the excess electricity to store heat as hot water for later use in the stores (CIBSE Journal, 2019).

Figure 6: Thermal storage tank located at London South Bank University (Balanced Energy Networks, n.d.).

This network proves to be highly efficient as it works on low operating temperatures . The low water temperatures restrict thermal losses and limits the thermo-mechanical stress experienced by the pipeline (Buffa, et al., 2019). The network also permits the recovery of excess heat available in buildings that have different heating/cooling demands. The 5GDHC network can be integrated with the current district heating network to create a multi-level district heating (MLDH) network. However, this idea needs further research as the pipelines would be operating at different temperatures. The operating temperatures of this network can be raised with the heat rejection that in-turn lowers the work done by the heat pumps.

UCL's new policy for heating, cooling and ventilation spaces aims to heat spaces across campuses at temperatures between 19-21°C during winter, spring and autumn (UCL Estates, 2016). Hence, it is evident that there is no need to operate the DHN at their existing high temperatures. Furthermore, due to UCL's historic estate with some building's refurbishment such as the Bartlett, there are spaces that are too hot while some that are too cold. Due to this, UCL can successfully manage the heating/cooling demand and adopt this new network.

The heat pump used in the network is modelled to operate at 50% of the Carnot efficiency which is its maximum efficiency. The Coefficient of Performance is then determined using the below relationship (Ally, et al., n.d.):

$$COP = \frac{useful\ heat\ energy}{work\ input} \times e = \frac{50}{100} \times \frac{T_{ho} + 273}{T_{ho} - T_{co}} \qquad \text{Eq. 1}$$

Where,
e is the scaled Carnot efficiency factor (i.e. 50%) (Song, et al., 2019), T_{ho} is the temperature of the heat pump warm water output and T_{co} is the temperature of the heat pump cold water output.

The Balanced Energy Network (BEN) used the following simulation to determine the COP of the Carnot heat pumps. The hot water leaving the heat pump was fixed at 70°C while the cold water ranged from 10-15°C which led the COP of to range from 2.86-3.12. This system works with an energy aggregator to avoid raising the peak electricity load. This is controlled using a set of algorithms that allows operation during off-peak hours.

Chapter 4. Results and Discussion

The paper detailed two scenarios that could be potential solutions to decarbonise the heating sector of large estates such as a university campus. These solutions aim to reduce the DHN's carbon emissions and their working is explained in the earlier section. This section aims to highlight the results of the two solutions.

A major source for sustainable heating can be through utilising the waste heat from any thermodynamic process. The London Underground consumes nearly 1.6TWh of energy on an annual basis (Mayor of London, 2020). However, large sums of thermal energy are lost during the braking process and due to other losses. As the tunnel walls can no longer absorb the lost thermal energy, TfL has focused on removing the excess heat through the vent shafts. In the process of extracting the heat, they have also managed to recover it and the Bunhill 2 Energy Centre was a prime example of this.

The literature and data provided from this project stated that the waste heat was being used for district heating with an annual load of 11,358MWh. The data provided by UCL suggests that the on-site CHP unit provides 6540MWh of heating towards the campus. However, although providing heat from a centralised source reduces overall carbon emissions, the CHP engine uses natural gas, a fossil fuel. The low thermal efficiency of the engine further causes its contribution to be marginal. This network produced 15,283 tonnes of carbon emissions on an annual basis for this heat load. Hence, thinking of an alternative was vital to meet the UK's goal of achieving net-zero by 2050.

The analysis in the previous section demonstrates the feasibility of installing heat pumps to recover and upgrade the waste heat from the LU. The high Coefficient of Performance significantly reduces the required energy input and thereby lowers cost. It drastically reduces emissions by producing 453.11 tonnes of carbon emissions at twice the existing networks capacity when powered by the grid. If the capacity was flexed then there was a 98.29% carbon emission savings which equated to approximately 15022 tonnes (Refer Appendix F). However, if the energy to power the heat pumps were derived from the CHP engine instead of purchasing it from the grid, the carbon emissions would be higher. This would result in an

93.74% carbon emission savings which equates to approximately 14326 tonnes. (Refer Appendix F)

The proposed solution came with other advantages as well such as its capability to store excess heat. This further enabled demand-side response (DSR) as the electric heat pumps could be operational during times of cheaper electricity costs. The system can also be linked to the building management system which can determine the heat usages of each building in the network. This can allow energy aggregators to manage the demand for heat and ensure excess is stored rather than wasted. However, this all comes at great costs due to the needed infrastructure and capital costs. The cost to install a fan and heat exchangers within the mid-tunnel ventilation shafts tends to be very high. The entire network would also require regular maintenance as the warm air in the tunnel has dust and other particles that cause fouling to the equipment. Lastly, the fuel powering the CHP engines produce significant carbon emissions (367% more than what is produced from the grid). It could be argued that biomass could be used as a fuel instead of natural gas. However, biomass tends to have a negative effect on air quality, which is a constraint, given the requirement by the Council.

Scenario 2

The difference in the infrastructure of the various buildings across the UCL campus leads to their different heating and cooling demands. Furthermore, some of the historic estates might not be as well insulated as the new refurbishments. Hence, some buildings might be too hot while some of them might be too cold. The 5th generation heat sharing network takes advantage of this by enabling heat to be recycled. Heat is rejected from buildings that need cooling and injected into buildings that need heating.

As seen from the Balanced Energy Network, this system seems to be advantageous as it cuts carbon emissions. It is because the entire network runs primarily on electricity and not on any fossil fuel. This network also takes into account cooling, which accounts for 31% of UCL's energy consumption. During summer, when a majority of the buildings require cooling then the heat from them can be extracted and stored in a thermal storage. The borehole thermal energy storage acts as an inter-seasonal storage system and stores this heat for the winter months. A demand-side response can also be enabled by storing heat in the thermal storage tanks when the electricity price is low. This would occur at times when there is excess

electricity and at off-peak hours. It can also make use of the buildings thermal inertia to store excess heat and later use this property to balance the heating/cooling demand.
This system is based on electrifying heat to reduce carbon emissions. The energy consuming component is the installed heat pumps in each building. Their energy consumption is dependent on the operating temperatures which determines their COP. However, as the temperature of the water exiting the heat pump is fixed at 70°C, the COP is entirely dependent on the borehole output temperature. This ranged from 10-15°C with an annual average of 13°C (Song, et al., 2019). However, if this temperature were increased, then the COP of the heat pump would increase which would reduce its energy consumption. The effect of the borehole outlet temperature can be seen in the below Figure 7 using the relationship from Equation 1.

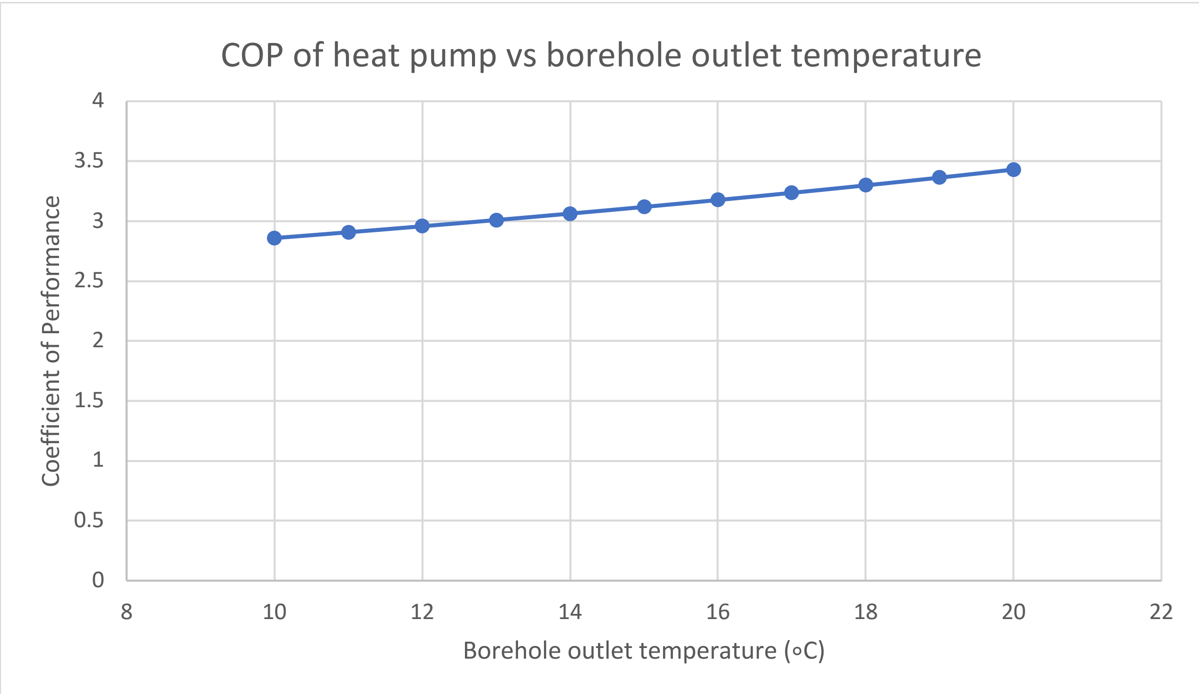

Figure 7: Coefficient of Performance of the heat pump vs borehole outlet temperature.

Furthermore, the BEN system in LSBU managed to significantly reduce carbon emissions in one of the buildings in the network. The system replaced gas-fired boilers and reduced carbon emissions by 3.62 tonnes over a period of two weeks (Song, et al., 2019). However, it was not possible to carry out an analysis on the carbon savings that this system could potentially have for UCL. This is because an investigation to balance the heating and cooling demand across the various buildings connected to the network would need to be conducted. However, this is an area of future work.

The system is also highly efficient as it operates at rather low-temperatures and hence, there are lower thermal losses within the network. It makes use of geothermal heat from the London Aquifer and circulates this energy to a network of buildings. The ability of buildings to reject heat into the network decreases the required work input of the heat pumps. This has the ability to increase the COP of the heat pumps and lowers energy usage. It also allows each building to control its heating/cooling requirement which is not possible with the existing district heating network. The presence of the bi-directional heat pumps at each building further allows them to control the desired temperature of the building. This ensures that each building receives just the right amount of heating/cooling and no energy is wasted.

The network also brings in economic benefits as it does not require large-diameter steel pipes which need to be placed underground. The system works with a small diameter flexible plastic piping which is cheaper to install as they don't need to be dug into the ground (ICAX, n.d.). The system also reduces running costs as it is cheaper to operate than a CHP engine and reduces energy consumption for cooling purposes. The network will also be eligible for the Renewable Heat Incentive (RHI) which is a government environmental programme. It aims to provide financial incentives to increase the uptake of renewable heat (Ofgem, 2021).

However, this system does pose certain risks due to its dependence on emerging technology. Furthermore, it required the installation of heat pumps at each building which increases capital costs. It needs to be installed in a location with the right mix of building types that acts as a constraint. This would also not allow the existing network to be replaced as the heating/cooling demand must balance out. However, a major disadvantage of this system is that it requires an additional booster heat pump to supply DHW. This is because of the low operating temperatures of the network that leads to the problem of Legionella (Ewing, 2020). Legionella is a bacterium that forms and multiples in water above 20°C and starts to die at 50°C while being killed instantly at 70°C and above. This bacterium can harm humans if inhaled and the disease can be fatal. The risk of legionella growth at different water temperatures is shown in Figure 8:

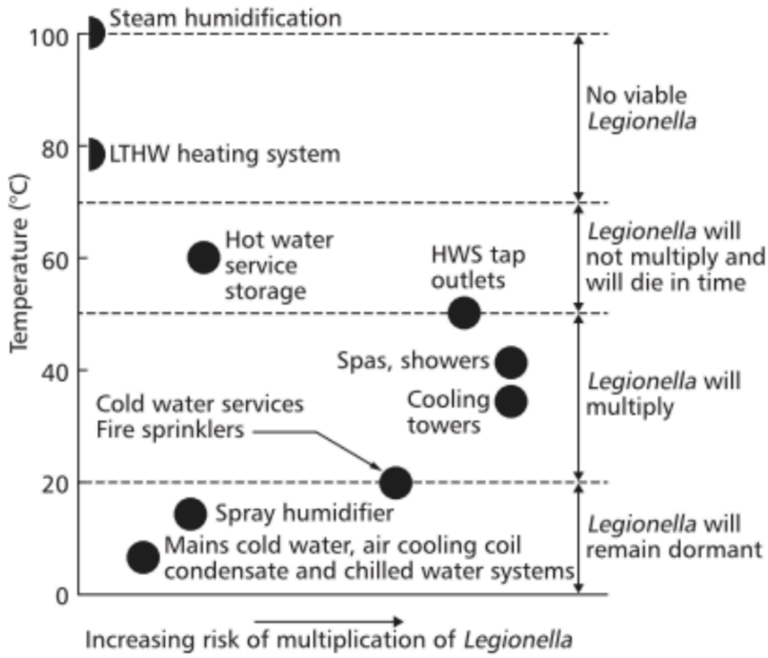

Figure 8: Risk of Legionella multiplication at different water temperatures (CIBSE (2013a)).

A suitable temperature for DHW services would be 55°C to mitigate the risk of legionella. Hence, for this system to provide DHW, an additional booster heat pump or an immersion heater would be required. This is because of the difference in the space heating water temperature and the DHW temperature. Due to this fallback, additional capital would be required that makes this less appealing to organisations.

Chapter 5. Conclusions and future work

This paper aimed to research the potential alternatives to the gas-fired district heating network of UCL. From the data and literature provided, the large sums of carbon emissions of this network demonstrate the need for its replacement. Furthermore, to reach UK's goal of achieving net-zero by 2050, a carbon-neutral heat network must be thought of. The paper detailed the working of two potential solutions: using waste heat from the London Underground and adopting the 5th generation district heating and cooling network.

Given the success of the Bunhill 2 Energy Centre, the idea can be replicated for its use to provide heating across the UCL campus. The waste heat from the tunnels can be recovered with a series of heat exchangers integrated with a heat pump. The advantage of this system is that it also uses the infrastructure that UCL has already installed. It also reduces carbon emissions but its extent depends on the source that powers the heat pumps. However, this solution comes with certain disadvantages with the need for an agreement between different stakeholders. This would be Transport for London, Mayor of London, University College London and the Camden Council. This solution also proves to be expensive and requires large sums of capital that may take more than 10+ years to recover. Lastly, this network requires a thermal store that is not present within the existing network.

The 5th generation district heating and cooling network also concluded to be a suitable alternative. The advantages of this network were higher efficiency, lower operating costs and lower carbon emissions. It also has the potential to be a zero-carbon heating network in the future, if it powers its heat pumps from green electricity. Its ability to exchange thermal energy between different buildings on the network reduces the energy input to the system. However, this system would also require a thermal store and preferably an inter-seasonal store such as a borehole thermal energy store. Although this is advantageous to the system, it is difficult and expensive to construct. It is also difficult to model this network unless all the buildings on the network balance each other's heating and cooling demand. The system also requires an array of geothermal boreholes or another heat source in situations where the demand exceeds the supply. This ultimately increases costs and makes this network less appealing.

Hence, although both the solutions can replace the existing network and reduce carbon emissions, their drawbacks make them less desirable to organisations. A common fallback for both these solutions is that they require thermal stores. As mentioned earlier, investing in a thermal store would enable demand-side response. It could allow UCL to reduce its expenditure on energy which is estimated to be £16million a year (Sustainable UCL (2021) "Delivering a zero carbon UCL by 2030). As mentioned earlier, the Camden Council is eager to form partnerships to promote low carbon projects. They are likely to partner with UCL and fund this project. Cooling the London Underground stands as TfL's biggest priority and hence, they would also be interested in removing heat from the tunnels. Furthermore, the government has launched grants such as the RHI and the IHRS to promote such projects. Enrolling for such grants would reduce the burden on the required capital for such solutions.

Future works in this field could be by exploring the potential of integrating the two solutions to design a DHN. One of the major drawbacks of the 5GDHC system is that it poses a risk if the network cannot balance the heating and cooling demand. Hence, it is integrated with an array of geothermal boreholes which can be costly and difficult to construct. However, the potential heat recoverable from the LU ventilation shaft can solve this problem. This system could also have different operational modes with waste heat being recovered only during the winter months.

References

Lizarraga, J. M. P. & Picallo-Perez, A., 2020. Exergy analysis of heat transfer in buildings. *Exergy Analysis and Thermoeconomics of Buildings.*

Ally, M. R., Munk, J. D., Baxter, V. D. & Gehl, A. C., n.d. *Exergy Analysis of a Two-Stage Ground Source Heat Pump with a Vertical Bore for Residential Space Conditioning under Simulated Occupancy,* s.l.: s.n.

Balanced Energy Networks, n.d. *Smart Hot Water Storage at LSBU.* [Online]
Available at: https://www.benuk.net/image-Mixergy-Tank.html
[Accessed 17 July 2021].

Buffa, S. et al., 2019. 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews,* Volume 104.

Building Design & Construction , 2020. *Worldwide model project: Bunhill 2 Energy Centre heats London homes with GEA heat pump technology.* [Online]
Available at: https://www.bdcmagazine.com/2020/12/worldwide-model-project-bunhill-2-energy-centre-heats-london-homes-with-gea-heat-pump-technology/ [Accessed 9 December 2021].

Burohappold Engineering, 2015. *Borough Wide Heat Demand and Heat Source Mapping: London Borough of Camden,* s.l.: s.n.

Camden Council , 2019. *Green Action for Change: Camden's Environmental Sustainability Plan (2018-2020),* London: Camden Council.

Celsius, 2020. *Heat recovery from the London Underground in Islington, United Kingdom.* [Online] [Accessed 10 July 2021].

CIBSE Journal, 2019. *Intranets for heat: Introducing BEN networks,* s.l.: s.n.

Colloide , n.d. *Bunhill 2 Energy Centre – Innovative District Heating.* [Online]
Available at: https://www.colloide.com/bunhill-2-energy-centre-innovative-district-heating/
[Accessed July 2021].

Committee on Climate Change, 2018. *Reducing UK emissions: 2018 Progress Report to Parliament,* s.l.: s.n.

Committee on Climate Change, 2020. *The Sixth Carbon Budget: The UK's path to Net Zero,* s.l.: s.n.

DBEIS, 2021. *VALUATION OF ENERGY USE AND GREENHOUSE GAS (GHG) EMISSIONS Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government,* s.l.: s.n.

Department for Business, Energy and Industrial Strategy, 2020. *INDUSTRIAL HEAT RECOVERY SUPPORT (IHRS) PROGRAMME,* s.l.: DBEIS.
Department for Business, Energy and Industrial Strategy, 2021. *Combined Heat and Power – Environmental: A detailed guide for CHP developers – Part 3,* s.l.: s.n.

Department for Business, Energy and Industrial Strategy, 2021. *Gas and electricity prices in the non-domestic sector*. [online] Available at: <https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector> [Accessed 5 August 2021].

Ewing, G., 2020. *5th Generation District Heating and Cooling Retrofit a Case study,* s.l.: The University of Strathclyde .

Giles, C., 2020. *Zero emissions goal: the mess of Britain's carbon taxes.* [Online]
Available at: https://www.ft.com/content/c4e7cf36-61f5-11ea-a6cd-df28cc3c6a68
[Accessed 15 July 2021].

Henrique Lagoeiro, Revesz, A., Davies, G. & Maidment , G., 2019. Heat from Underground Energy London. *CIBSE Technical Symposium.*

HM Government, 2009. *The UK Low Carbon Transition Plan: National strategy for climate and energy,* s.l.: s.n.

ICAX, n.d. *Fifth Generation District Heating Networks.* [Online]
Available at: https://www.icax.co.uk/Fifth_Generation_District_Heating_Networks.html
[Accessed 21 July 2021].

Interreg North West Europe, 2021. *5GDHC in short.* [Online]
Available at: https://5gdhc.eu/5gdhc-in-short/ [Accessed 30 July 2021].

Islington Council, n.d. *Bunhill 2 – Project Partners.* [Online]
Available at: https://www.energyadvice.islington.gov.uk/bunhill-heat-and-power/bunhill-2-project-partners/ [Accessed 29 July 2021].

Lagoeiro, H. & Revesz, A., 2019. Opportunities for Integrating Underground Railways into Low Carbon Urban Energy Networks: A Review. *Urban District Heating and Cooling Technologies.*

Mansfield, I., 2017. *Cooling the tube – Engineering heat out of the Underground.* [Online]
Available at: https://www.ianvisits.co.uk/blog/2017/06/10/cooling-the-tube-engineering-heat-out-of-the-underground/ [Accessed 25 July 2021].

Mayor of London, 2020. *Mayor moves forward with plans to power TfL Tube with green energy*. [online] Available at: <https://www.london.gov.uk/press-releases/mayoral/plans-to-power-tfl-network-with-green-energy> [Accessed 5 August 2021].

Ofgem, 2021. *Non-Domestic Renewable Heat Incentive (RHI).* [Online] Available at: https://www.ofgem.gov.uk/environmental-and-social-schemes/non-domestic-renewable-heat-incentive-rhi [Accessed 27 July 2021].

Ohkyung, K., Dongan, C. & Chasik, P., n.d. Performance evaluation of a two-stage compression heat pump system for district heating using waste energy. *Korean Journal of Air-Conditioning and Refrigeration Engineering.*

Pearson, A., 2020. *Tunnel Vision: The Challenge Of Cooling The London Underground*. [online] CIBSE Journal. Available at: <https://www.cibsejournal.com/technical/londons-tunnel-vision/> [Accessed 17 July 2021]

Song, W. H. et al., 2019. Modelling development and analysis on the Balanced Energy Networks (BEN) in London. *Applied Energy,* Volume 233-234, pp. 114-125.

Sustainable UCL (2021) "Delivering a zero carbon UCL by 2030

The Construction Index, 2019. *HS2 reveals Euston vent shaft designs.* [Online] Available at: https://www.theconstructionindex.co.uk/news/view/hs2-reveals-designs-for-euston-vent-shaft[Accessed 28 July 2021].

The Bartlett (2021) Procurement data shared with [Nick Hughes], xx July

UCL Estates, 2016. *UCL Heating, Cooling and Ventilation Policy,* s.l.: UCL.

UCL Estates, 2017. *Design Requirements for Connections to the UCL District Heating Network.* [Online] Available at: https://www.ucl.ac.uk/estates/sites/estates/files/17_07_06_ucl_district_energy_design_guidance.pdf [Accessed July 2021].

United States Environmental Protection Agency. n.d. *CHP Benefits | US EPA*. [online] Available at: https://www.epa.gov/chp/chp-benefits [Accessed 5 August 2021].

WestonWilliamson+Partners, n.d. *Euston vent shaft.* [Online] Available at: https://www.westonwilliamson.com/projects/euston-vent-shaft [Accessed 28 July 2021].

Wilson, R., 2020. *Cullinan Studio-designed Bunhill 2 Energy Centre completed in Islington.* s.l.:Architects Journal .

Appendix

Note:
Source for all the data: The Bartlett (2021) Procurement data shared with [Nick Hughes], xx July

Appendix A: Distribution of CHP energy output

Amount of natural gas used as input for a CHP engine: 28353310.88 kWh

Heat consumed from onsite CHP: 6542015.083 kWh

Electricity consumed from onsite CHP: 9695033 kWh

$$Losses = Input - Heat\ consumed - Electricity\ consumed$$

$$Losses = 28353310.88 - 6542015.083 - 9695033$$

$$Losses = 12116262.8 \text{ kWh}$$

Hence:

Heat proportion: 23%

Electricity proportion: 34%

Loss proportion: 43%

Appendix B: Carbon emissions from gas boilers

UCL's annual energy consumption: 241572.0617 MWh

Heating and hot water energy usage: 31% of UCL's energy consumption

$$E_{Heating} = 0.31 \times 241572.0617 \cong 74890 \text{ MWh}$$

The different sources for heating and hot water are the Gower Street CHP, Bloomsbury CHP and Gas Boilers

Natural gas used as input for the CHP engine (Gower Street): 28353.31088 MWh

Heat consumed from CHP: (approximately) 6540 MWh

Data suggested that UCL's gas boilers consumed 47% of the total natural gas consumption.

UCL's total gas consumption: $109240.6725 + 28353.331088 = 137594.0036$ MWh

However, it is assumed that these boilers are only 80% efficient. Hence the total energy consumed from the boilers are:

$$E_{gas\ boilers} = 0.80 \times 0.47 \times 137594.0036 = 51735.33 \text{ MWh}$$

The carbon factor of the gas boiler is estimated to be: 0.184 $kgCO_2/kWh$

Hence,

$$Carbon\ emissions: 0.184 \times 51735.33 \approx 9520 \text{ tonnes of } CO_2$$

Appendix C: Distribution of UCL's heating demand

$$E_{Gower\ CHP} = 6540 \text{ MWh}$$

$$E_{gas\ boilers} = 51735.33 \text{ MWh (from Appendix B)}$$

$$\therefore E_{Bloomsbury\ CHP} = E_{Total} - E_{Gower\ CHP} - E_{gas\ boilers}$$

$$E_{Bloomsbury\ CHP} = 137594.0036 - 6540 - 51735.33 = 16614.67 \text{ MWh}$$

Appendix D: UCL District Heating Network carbon emissions

UCL's total carbon emissions for the year 2018-19: 54580.59 tonnes of CO_2

Share of carbon emissions from DHN: 28%

Hence,

$$Carbon\ emissions = 0.28 \times 54580.59 \approx 15283 \text{ tonnes of } CO_2$$

Appendix E: Change in carbon emissions from proposed new heat load of DHN

New Heat loads:

Total heat load: 74890 MWh

Gower Street CHP engine: 11358 MWh

Bloomsbury CHP engine: 16614.67 MWh

Gas boilers: x MWh

Thus, to match the total heat load, the load required by the boiler can be calculated:

$$11358 + 16614.67 + x = 74890$$

$$x = 46917.33 \text{ MWh}$$

Comparing this to the previous heat load of 51735.33 MWh, there is a reduction which equates to:

$$\frac{51735.33 - 46917.33}{51735.33} = 9.3\%$$

Appendix F: Total carbon savings from proposed DHN

The total heat load from the CHP unit is: 6540 MWh

Current carbon emissions from the CHP unit: 15283 tonnes of CO_2

The estimated Coefficient of Performance of the heat pump is 3.76

The COP is defined as:

$$COP = \frac{Energy\ output}{Energy\ input}$$

$$Energy\ input = \frac{6540}{3.76}$$

$$Energy\ input = 1739.36 \text{ MWh}$$

The current carbon factor from the grid is estimated to be: 0.15 $kgCO_2/kWh$

Hence,

$$Carbon\ emissions: 0.15 \times 1739.36 \approx 261 \text{ tonnes of } CO_2$$

Hence, the total carbon savings from this:

$$Carbon\ savings = 15283 - 261 = 15022 \text{ tonnes of } CO_2$$

However, if the heat pump was powered by a CHP engine, the carbon emissions would differ. The carbon factor for the CHP unit was stated to be 0.55 $kgCO_2/kWh$

Thus the carbon emission is:

$$Carbon\ emissions: 0.55 \times 1739.36 \approx 957 \text{ tonnes of } CO_2$$

Hence, the total carbon savings from this:

$$Carbon\ savings = 15283 - 957 = 14326 \text{ tonnes of } CO_2$$