Integration of High Temperature Heat Networks with Low Carbon Ambient Loop Systems

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ABSTRACT

Heat networks are a key technology proposed in the UK Government's Clean Growth Strategy for delivering low carbon and low-cost energy to urban communities in the UK. Currently, around 2% of all heat in the UK is provided by heat networks compared to other countries such as Sweden/ Denmark, where they have more than 30% delivered in this way. Most of the Scandinavian systems use high temperature 3rd or 4th generation heat networks (>50-80°C) [>122-176°F] and these are often driven by fossil fuel powered Combined Heat and Power (CHP), which are carbon intensive and also impact on local pollution/ particulates. In the UK there is a drive towards 5th generation heat networks involving ambient temperature loops (13 - 25°C) [55-77°F]. These systems deliver additional benefits and savings as they are able to share heat/coolth across the network and capture waste heat from secondary heat sources like the heat from London Underground ventilation shafts and local data centres. They utilise heat pumps to deliver heat or cold from the loop to individual applications or buildings and they avoid emissions of particulates associated with CHP.

This paper investigates how existing 3rd and 4th generation networks can be connected into 5th generation systems. It uses the 3rd generation Bunhill CHP installation in the London borough of Islington as a case study to investigate the relative performance when converting a system. The paper describes the techno-economic models developed to show how the Bunhill installation might perform when connected to 5th generation, including CAPEX and engineering connection approaches.

INTRODUCTION TO 5G ENERGY NETWORKS

In 2019 the UK Government passed legislation to deliver net zero carbon emissions by 2050. The new target will require a significant reduction compared to the previous target of at least 80% reduction from 1990 levels (GOV.UK, 2019a). Heating and transport are the highest carbon emitters representing 37% and 27% of the UK total emissions respectively (GOV.UK, 2018a). Achieving the ambitious net zero carbon target will require an integrated approach to the way we use and generate energy. The UK has significantly reduced the electrical grid carbon intensity, through the generation of clean renewable electricity mainly from wind and solar renewable energy systems. Decarbonising the electricity system presents many opportunities to improve the way we heat and cool our homes and businesses, power appliances and industry, and fuel our vehicles. Electric cars are becoming widely available, and electricity is also being used to power buses, vans and taxis. Low carbon heating and cooling using heat pumps offers significant environmental benefits over conventional heating or cooling systems such as gas boilers and chillers. They also enable

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the sharing of heat between different applications or between buildings in a neighbourhood. Sharing (prosuming) of heat in this way provides the opportunity to deliver extremely efficient, ultra-low carbon, bivalent cooling and heating between buildings. In addition, heat pumps also present the opportunity to utilise heat from secondary and renewable sources such as heat from datacentres, canals, railway tunnels, industrial processes and sewage systems, which would otherwise be wasted. The London Mayor's office estimated the total waste heat from secondary sources in London is in the order of 71 TWh/year, which is greater than the City total heat demand of 66 TWh/year in 2010 (GLA, 2014).

District Heating Networks (DHNs) have traditionally used a centralised energy centre where the heat generated is supplied to multiple buildings in a neighbourhood via a network of insulated pipes carrying either steam, hot or chilled water (GOV.UK, 2018b). Figure 1 illustrates the evolution of DHNs since the 1880's and it shows that there has been a significant reduction in temperature from 100°C [212ºF] in 1st generation networks to ambient temperature (13 to 25°C) [55 to 77ºF] in 5th generation networks with a subsequent increase in system efficiency. DHNs up to the 3rd generation (60 - 90°C) [140 – 194ºF] were mainly powered by fossil fuels using Combined Heat and Power (CHP) generation with the potential to integrate heat recovery from industrial processes. 4th Generation networks operate around 45 to 55°C [113 to 131ºF] and can integrate photovoltaic (PV) electricity generation and low-grade waste heat sources. The 5th generation (5DHC) concept is a recent development and comprises decentralised energy centres with heat pumps and hubs for PV generation, Electric Vehicles (EVs) and Vehicle-to-Grid (V2G) charging/storage alongside large scale stationary batteries (Revesz et al., 2020). In V2G systems, electric vehicles with bi-directional charging can store electricity generated from renewable energy sources and discharge electricity back into the grid during peak times. The artificial intelligence system switches the flexible system assets such as the heating or cooling heat pumps and batteries in reaction to the electricity grid requirements and tariffs providing demand side response.

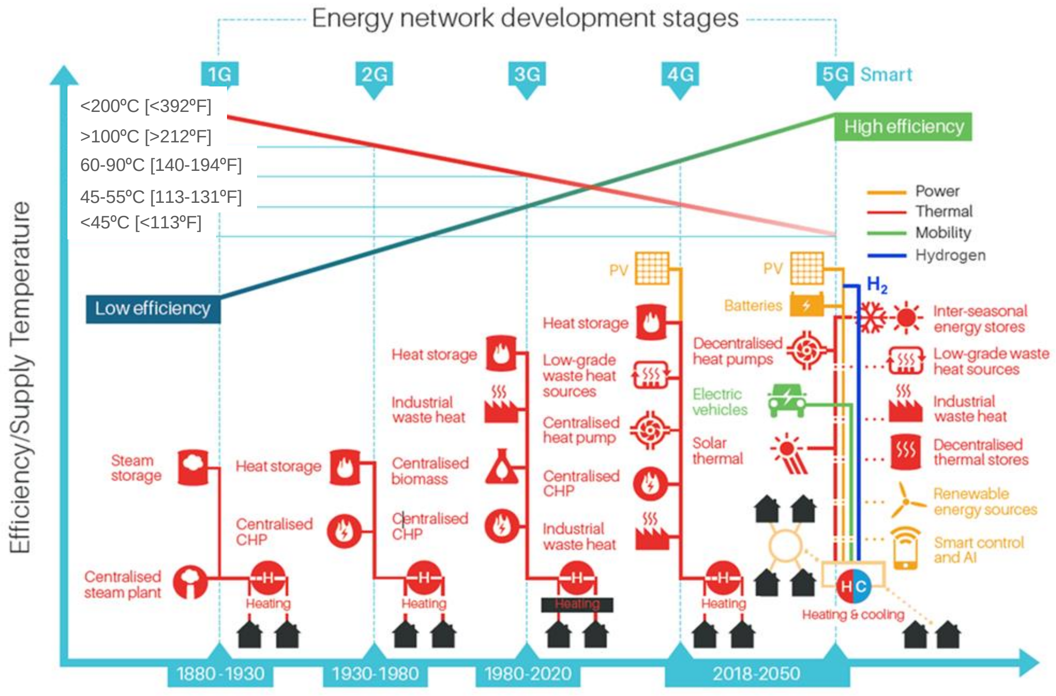

Figure 1: Energy network development stages (adapted from Lund et al., 2014 and Revesz et al., 2020)

Innovative 5th generation energy networks have great potential to become the most efficient local energy systems of the future, but there are very few 5G networks worldwide (Buffa et al., 2019) and there is limited information, innovation, knowledge and skills around them. One of the biggest advantages of 5G ultra low temperature networks is the opportunity to capture low-grade waste heat from local sources such as canals, mine water, data centres and underground railway tunnels among other sources.

Data centres are large energy users, responsible for at least 1.5% of the electricity demand for the whole of the UK (Davies et al., 2016) and worldwide they account for 1% of global electricity consumption (Masanet et al., 2020).

The fact that data centres require cooling of the Information Technology (IT) servers 24/7 makes heat recovery from this source particularly feasible due to their constant load throughout the year. In data centres with local and remote air cooling the IT load waste heat can be recovered directly from the air at 25-35ºC [77-95ºF] or from the chilled water system at 10-20ºC [50-68ºF] (Davies et al., 2016).

Undergrounds railway tunnels generate significant amounts of heat with over 80% coming from mechanical losses mainly from braking friction and resistive losses in the traction-control system, whilst the remainder can be attributed to commuters and station and tunnel systems (Botelle et al., 2010). London has the world's first metro system with a network length of 402 km [244 mi] (45% in tunnels) and 1.35 billion passengers per year (TfL, 2019). The temperature in undergrounds railways is around 17-28ºC [63-82ºF], hence this is a particularly good source for secondary heat recovery in cities.

In the UK only 2% of the overall heating demand is supplied by heat networks (GOV.UK, 2018c), London is above average with 6% of its energy demand supplied by local networks (GLA, 2018). By 2025 it is expected that 25% of the heat and power used in London will be generated through the use of localised decentralised energy systems and DHNs connecting to zero carbon and waste energy sources are key to achieve this target (GLA, 2018).

Currently most 3rd and 4th generation DHNs use gas fired combustion-based Combined Heat and Power (CHP) systems whereby reciprocating engines burn fuel to turn generators to produce electricity, heat exchangers then recover heat from the engine and deliver it to the DHN. The advantage of CHP systems is that by capturing and using heat that would otherwise be wasted, and by avoiding distribution losses, CHP can achieve efficiencies of over 80%, compared to 50% for traditional technologies (i.e., conventional large power station electricity generation and an on-site boiler) (EPA, 2020). However, CHP systems can have a major impact on air pollution as burning fuels generates oxides of Nitrogen (commonly referred as NOx) as well as smaller amounts of fine particulate matter (PM_{10} and $PM_{2.5}$) (Ricardo Energy & Environment, 2018). Catalytic convertors can mitigate this but at some significant additional CAPEX. Road transport and the built environment account for 52% and 29% of London emission sources i.e. NOx and particulates (GOV.UK, 2018d). Improving air quality has become the biggest priority for the London Greater Authority and London's ambition is to be a zero-carbon city by 2050 (GOV.UK, 2018d).

Converting 3rd and 4th generation DHNs into low carbon 5th generation decentralised energy networks is not really practical due to the significantly different pipework architecture. However, 'connecting' 3rd and 4th generation DHN to a 5th generation scheme is entirely possible, practical and can be economic in some circumstance. This can be achieved in three ways:

- Transfer of excess heat from the return water in a 4G scheme down into a 5G scheme using a Plate Heat Exchanger
- Transfer of cooling from the cool water temperatures in a 5G scheme into a traditional District Cooling Network using a Plate Heat Exchanger
- Using a heat pump to upgrade/transfer heat from a 5G scheme into a 4G scheme

Using decentralised heat pumps in 5DHC schemes is a key part of the electrification of heat (replacing CHP with heat pumps) and transport (electric vehicles), which can be powered by renewable energy sources (solar and wind). In particular, opportunities to integrate 4th and 5th generation DHN offers a transition path for older existing heat networks in the UK.

This paper investigates how existing 3rd and 4th generation networks can be connected into 5th generation systems using the final approach (heat pumps) shown above. It uses the 3rd generation Bunhill CHP installation in the London borough of Islington as a case study to investigate the relative performance when integrating a system. The paper describes the techno-economic models developed to show how the Bunhill installation might perform when connected to a 5th generation scheme, including CAPEX and engineering connection approaches.

3RD GENERATION BUNHILL HEAT AND POWER NETWORK

The Bunhill Heat and Power Network is a 3rd generation district heating network supplying 1350 homes in the London borough of Islington. It comprises two schemes: Bunhill 1, a gas fired CHP system providing heat and electricity to 850 homes and Bunhill 2, which employs a heat pump to upgrade waste heat recovered for the London underground to heat 500 homes (LBI, 2019).

Bunhill 1 was launched in 2012, the energy centre consists of a 1.9 MW$_e$/2.3 MW$_{th}$ [6.48 MBTU/h$_e$/7.85 MBTU/h$_{th}$] gas fired CHP and a 115 m^3 [4061 ft^3] thermal store. The Bunhill 2 extension was launched in 2019 and its energy centre comprises a 77.5 m^3 [2737 ft^3] thermal store, 1MW [3.4 MBTU/h] heat pump and two small CHP units each with an output of 237kW$_e$/372kW$_{th}$ [0.81 MBTU/h$_e$/1.3 MBTU/h$_{th}$] supplying heat and providing electricity to the heat pump and exporting to the grid during peak times (Lagoeiro et al, 2019). Both networks (Bunhill 1 and 2) currently operate with flow and return temperatures of 75°C [167°F] and 55°C [131°F], respectively and have a total length of 4.4 km [2.7 mi] of insulated pipework. Figure 2 shows a diagram of Bunhill heat and power network.

Bunhill 2 recovers low grade waste heat from a London Underground ventilation shaft (approx. 780kW [2.7 MBTU/h]), which has exhaust air temperatures ranging from 18°C [64°F] to 28°C [82°F]. Heat is captured through an air-to-water heat exchanger placed above the ventilation shaft and the water temperature is then upgraded with a heat pump from 11-18°C [52-64°F] to 75°C [167°F] to supply the network buildings with domestic hot water and space heating. The ventilation shaft was fitted with a variable speed reversible fan that enables the system to work both in extract and supply mode and its operation was previously investigated by Davies et al. (2017). During winter months the fan operates in extract mode, removing hot air from the underground railway tunnels and warming up the water in the heat exchanger. During summer months, when the external temperatures are higher, the fan operates in supply mode whereby the warm air from the exterior is cooled in the heat exchanger then supplied to the underground, with the heat extracted being recovered in the heat exchanger and supplied to the network. Figure 3 shows a schematic of the heat exchanger and ventilation shaft at the Bunhill 2 energy centre.

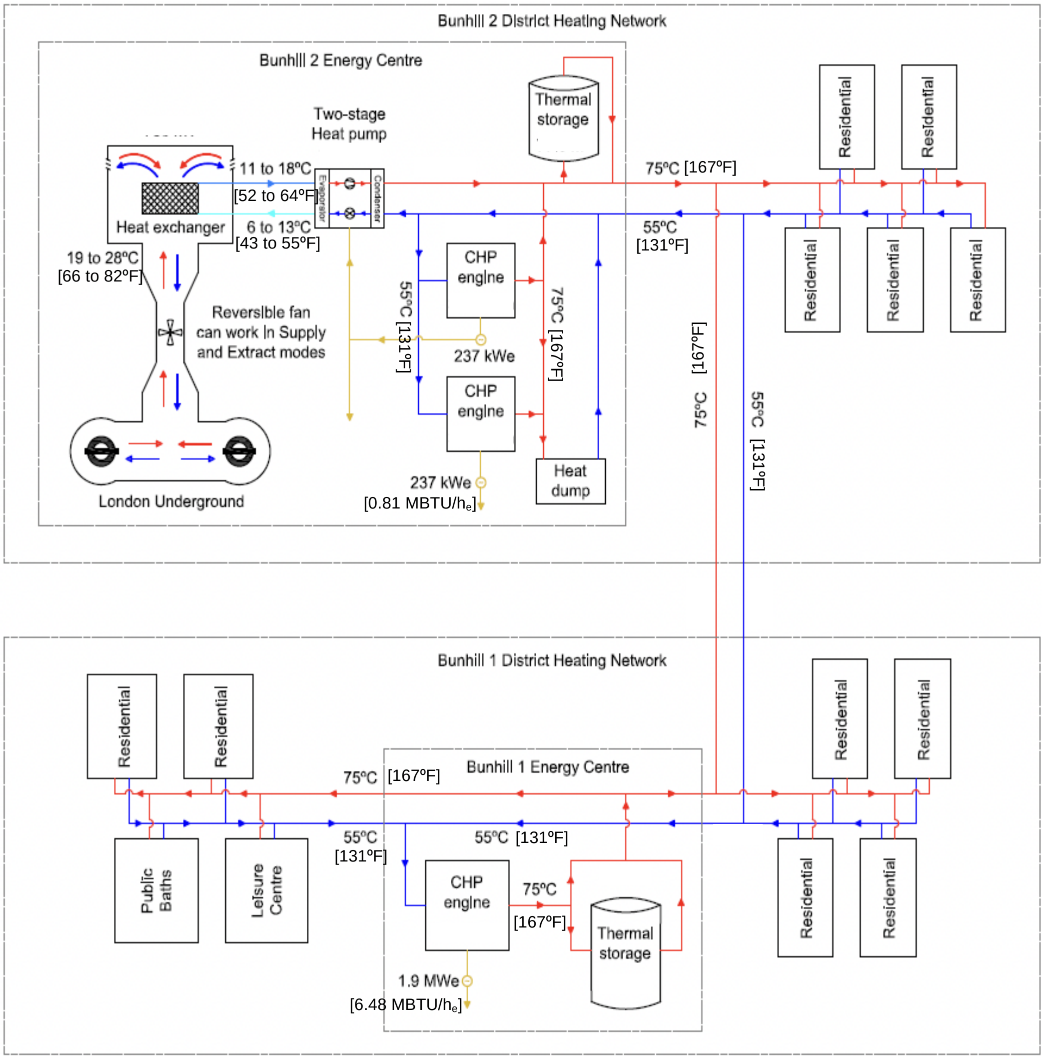

Figure 2: Schematic of Bunhill Heat and Power Network (Lagoeiro et al., 2019)

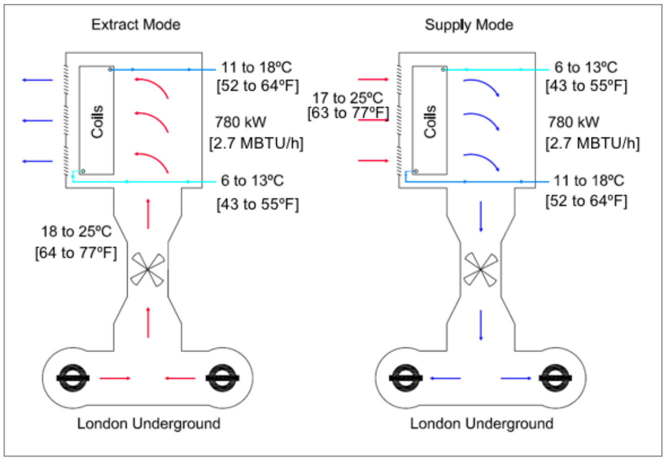

Figure 3: Schematic of heat exchanger and ventilation shaft at the Bunhill 2 energy centre (Lagoeiro et al., 2019)

5TH GENERATION GREENSCIES ENERGY NETWORK CONCEPT

In June 2019 the London borough of Islington (LBI) declared a Climate Emergency and pledged to work towards making Islington net zero carbon by 2030 (LBI, 2019). In order to achieve this ambitious target, LBI will have to deploy a wide range of low carbon energy systems across the borough. GreenSCIES is a 5th generation (5G) Smart Local Energy System (SLES) that is currently being designed to serve more than 33,000 residents, 11,000 homes and 70 very large non-domestic buildings in Islington. The GreenSCIES smart energy network integrates heat, power and transport and aims to connect to three neighbouring district heating networks. The 5G ambient loop network recovers waste heat from the London underground and local data centres. These 5th generation schemes require a balancing mechanism e.g. to counteract high winter heat demands and in GreenSCIES this will be provided by boreholes using aquifer water to provide inter-seasonal warm and cold thermal storage, often referred to as Aquifer Thermal Energy Storage (ATES). The ambient loop will also allow interchange of heating and cooling between buildings, usually referred to as prosuming. The greater sharing (prosuming) between heating and cooling demands in buildings, the greater the economic and carbonic savings. Local power will be generated with solar photovoltaics (PV) and low carbon mobility is provided by electric vehicles. The system has several decentralised energy centres across the network that function as a 'micro-grid' flexing the heat pumps, PV and electric vehicle batteries in relation to the electricity grid demand and tariffs. The GreenSCIES concept is illustrated in Figure 4.

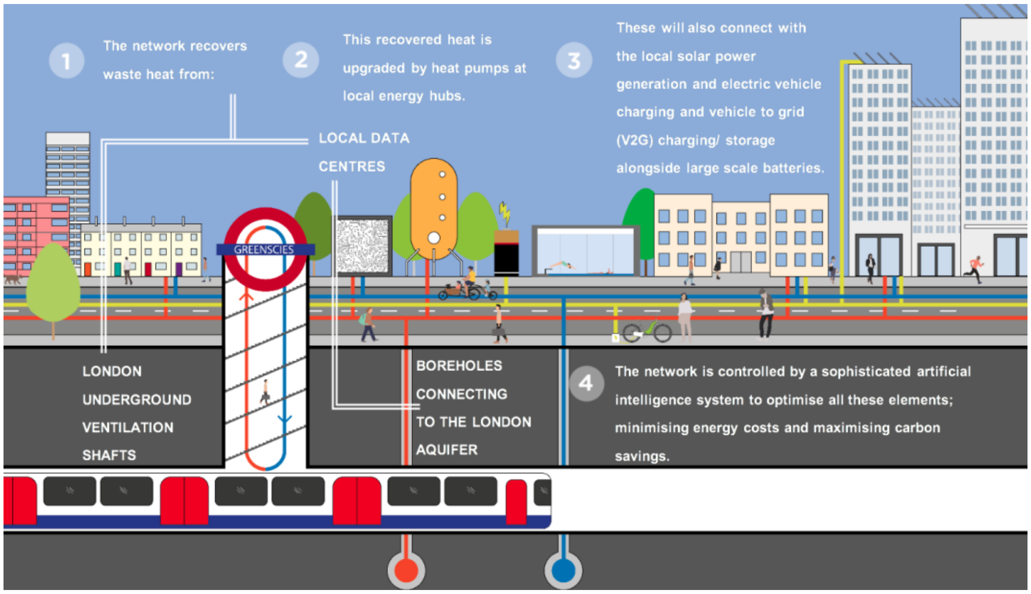

Figure 4: GreenSCIES concept design

CONVERTING 3RD AND 4TH GENERATION NETWORKS INTO 5TH GENERATION SYSTEMS

The GreenSCIES concept design has been divided into four individual smaller build-out schemes, each with its own local energy source. This paper focuses on the GreenSCIES scheme connecting to the Bunhill heat and power network, with secondary heat recovered from a local data centre and connecting to three additional buildings.

In order to model connecting the Bunhill 3rd generation network into a 5th generation ambient loop energy system, the existing CHP in Bunhill 1 was replaced in the model by a 1MW [3.4 MBTU/h] heat pump. Figure 5 shows the proposed GreenSCIES-Bunhill scheme with the ambient loop connecting the energy centres in the network.

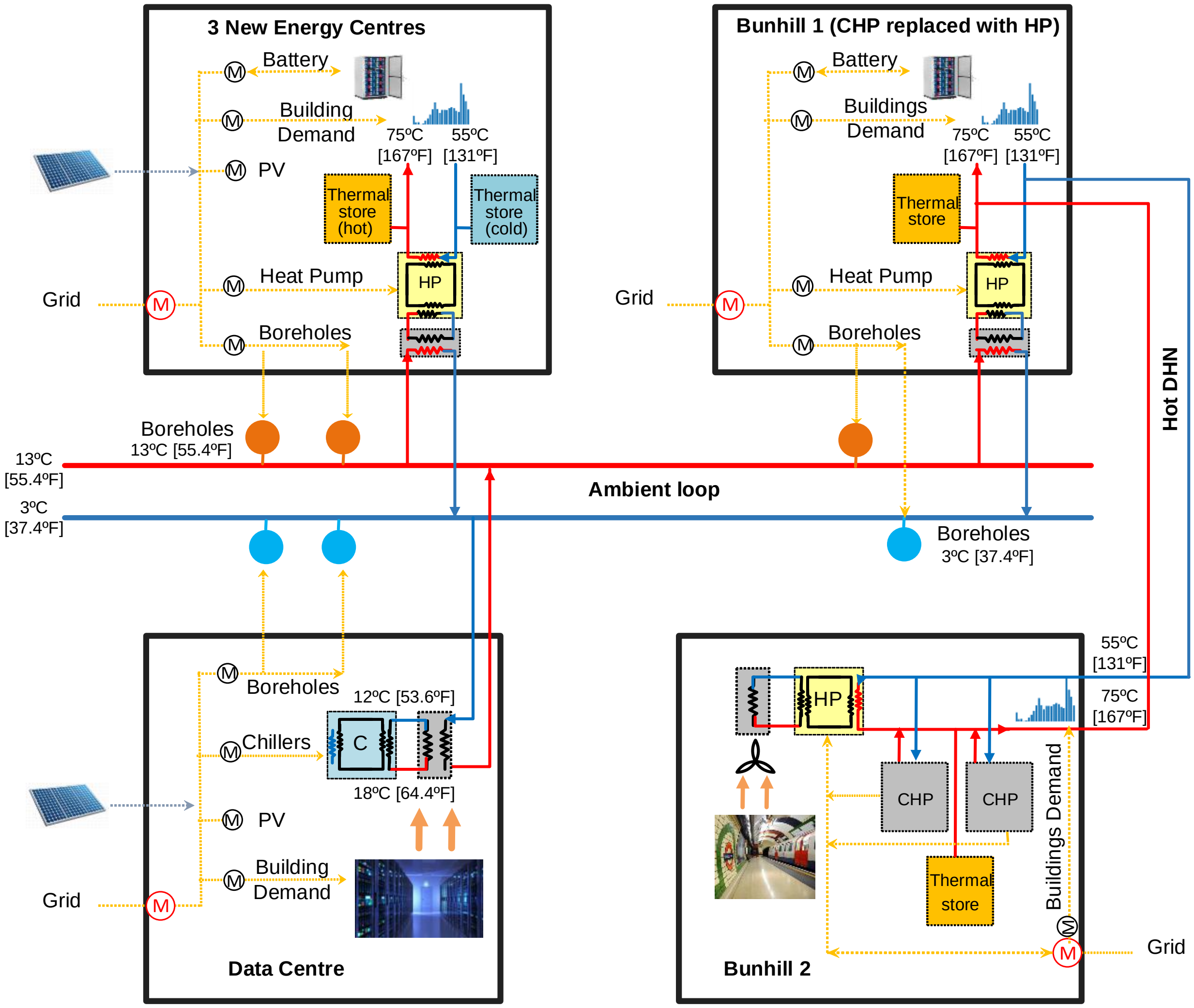

Figure 5: Proposed 5th generation GreenSCIES-Bunhill network concept

The top left energy centre diagram in Figure 5 shows the technologies, e.g. stationary batteries, PV, borehole connections, heat pump and thermal stores, this is the proposed configuration for the plant rooms in the new buildings connected to the network. The dashed yellow line shows the 'behind the meter' electrical connections and although not shown in the diagram EV charging points can also be connected to the network. The boreholes supplement and balance the network and are connected directly to the ambient loop, with the warm and cold wells at approximately 13°C [55°F] abstraction and 3°C [37°F] reinjection respectively. The total heat demand of the network is 10,509 MWh [358,580 thm] and the cooling demand is 9,254 MWh [315,758 thm], with the data centre accounting for 95% of the total cooling demand. The fact that the GreenSCIES-Bunhill network is well balanced in terms of heating and cooling demand makes this scheme technically and economically viable as it allows for interchange of heating and cooling between buildings and additional revenue from cooling sales. Table 1 compares the key differences between 4G and 5G DHNs. The cost of trenching is considerable in London at approx. £2,500/m [$3,598/yd] and one option in 5G systems is to share the trenching for the pipework and electrical cables. A major advantage of 5G over 4G DHNs is that the ambient loop pipework does not need to be insulated.

Table 1. Differences between 4th and 5th generation district heating networks

4th Generation DHNs	5th Generation DHNs
Centralised energy centre supplying heat to buildings	Decentralised energy centres in each building
Supply temperature: 60 - 45ºC [140 – 113ºF]	Supply temperature <45ºC [<113ºF]
Separate heating and cooling systems	Seasonal thermal storage to balance the network
Insulated pipework	Un-insulated pipework
No interchange between buildings	Interchange of heating/cooling between buildings

Capital expenditure for the proposed 5G GreenSCIES-Bunhill network

The capital expenditure (CAPEX) of the proposed GreenSCIES-Bunhill build-out network was estimated taking into account the cost of the ambient loop, connection to Bunhill 1, the data centre and three other energy centres/buildings. The following is included in the CAPEX model: water source heat pumps, thermal storage, boreholes, plant room building works, heating and cooling building services, metering, source connections, solar PV, anticipated road crossings and a fund for the design, commission and contingency for building the network. In this scheme the CAPEX does not take into account the electric vehicle charging points but does include PV. Figure 6 shows the CAPEX breakdown for the whole system.

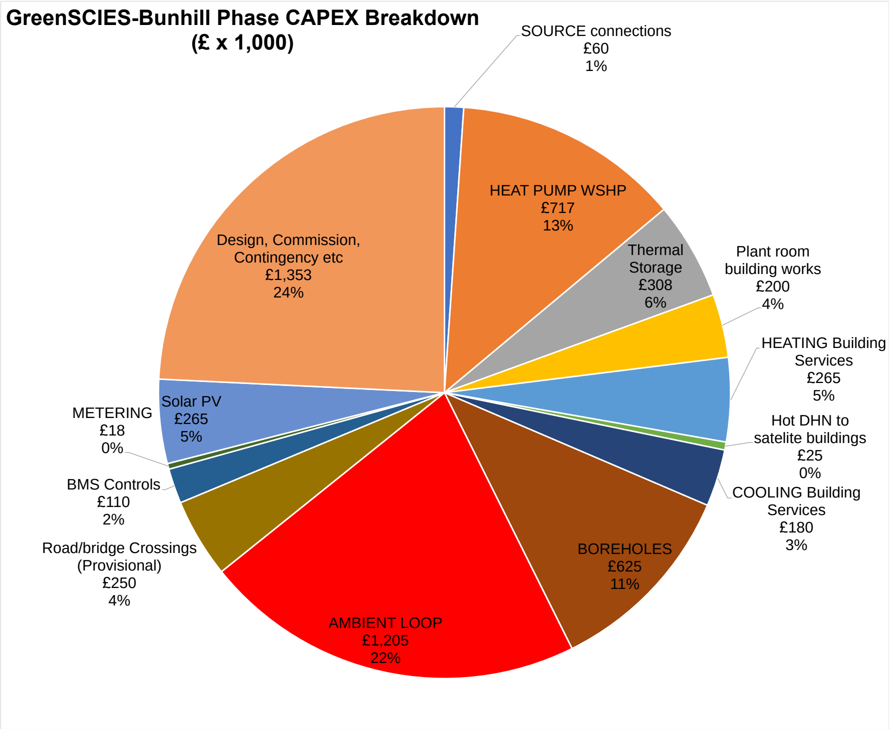

Figure 6: CAPEX for the 5th generation GreenSCIES-Bunhill network

The total CAPEX for the GreenSCIES-Bunhill network is £5,580,000 [$7,343,810], with the ambient loop and the design, commission and contingency fund representing 22% and 24% of the total capital cost respectively.

Techno-economic model assumptions

Techno-economic modelling was undertaken to determine the operational expenditure, revenues, CO_2 and NOx emissions of the proposed 5G GreenSCIES-Bunhill network and the existing Bunhill (1 and 2) hot 3^{rd} generation network. EnergyPRO (EMD, 2014) was the commercial software modelling tool employed which uses half hourly supply/demand data alongside complex electricity tariffs, control strategies and demand side management (DSM). EnergyPro can optimize the operation of any combination of energy supply and demand in accordance to all preconditions such as weather conditions, technical properties of the different units, maintenance costs, fuel prices, taxes, subsidies, etc. The key model financial and technical assumptions are summarised in Table 2.

Table 2. Techno-economic model financial and technical assumptions

Financial assumptions	Technical assumptions
2019 UK spot market electricity import and export prices downloaded from Elexon	a) Bunhill 1 (CHP) and 2 (HP & 2 x CHP units)
Electricity Import Price Levies (RO, FITs, CfD etc.) for 2019	b) GreenSCIES-Bunhill [HP replaced CHP in Bunhill 1 with data centre providing a year-round constant heat source (cooling load)]
Climate Change Levy rates for 2019	Carbon factors based on diminishing figures using predicted figures published by GOV.UK (2019b)
UK Power Networks DUoS Red Amber and Green tariff structure and prices for London for 2019	Heat pumps supply 75/55°C [167/131°F] to the connected buildings
Triads modelled as 20x 2hr Triad warning periods	Electricity connections 'behind the building meter'

Techno-economic model results

Table 3 compares the annual operation surplus, CO_2 and NOx emissions for both schemes estimated by the tecno-economic modelling.

Table 3. Techno-economic model results for a 3^{rd} and 5^{th} generation network

	Existing 3G Bunhill 1 & 2	New 5G GreenSCIES-Bunhill scheme connection
Operating Surplus 2021 (£/$ x 1000)	250/327	638/833
CO_2 (Tonnes/yr) Annual Average over 25 yrs	6,887	2,886
NOx (kg/yr) [lb/yr] Annual Average over 25 yrs	8,068/17,787	749/1,651

The annual operational surplus of the 5^{th} generation GreenSCIES-Bunhill network connected to the existing 3G scheme is over 2.5 times higher than the existing 3^{rd} generation Bunhill scheme due to additional cooling sales to the data centre. The NOx and CO_2 emissions were also reduced by 90% and 42% respectively by replacing the 2.3 MW_{th} [7.85 $MBTU/h_{th}$] gas fired CHP with a 1MW [3.4 MBTU/h] heat pump.

CONCLUSION

This paper investigated how existing 3rd and 4th generation networks can be connected into 5th generation smart energy systems that integrate heat, power and transport. The 3^{rd} generation Bunhill CHP installation in the London borough of Islington was used as a case study to investigate the relative performance when connecting a system. The CHP unit in Bunhill was replaced by a heat pump and connected to the ambient loop GreenSCIES-Bunhill network (with additional buildings and heat recovered from a data centre). The techno-economic model compared the 5G GreenSCIES-Bunhill network and the existing 3G Bunhill (1 and 2) network performance. The results show a 90% and 42% reduction on NOx and CO_2 emissions respectively, in the integrated GreenSCIES-Bunhill network. This study clearly shows the benefits of 5G energy networks in improving air quality and reducing carbon emissions, providing a pathway towards net zero carbon cities. Increased revenues from 5G networks also allow network owners, such as local councils to offer reduced energy bills to consumers, effectively tackling fuel poverty.

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