Performance Analysis for the UK’s first 5th Generation Heat Network – the BEN Case Study at LSBU

Aaron Gillich[1]*, Julie Godefroy[2], Andy Ford, Mark Hewitt[3], Jonathan L’Hostis[3]

* Corresponding Author: Aaron Gillich – gillicha@lsbu.ac.uk
1. BSRIA LSBU Net Zero Building Centre
2. Julie Godefroy Sustainability: (https://www.juliegodefroysustainability.co.uk/)
3. ICAX Ltd. (https://www.icax.co.uk/)

Abstract

The decarbonisation of heat requires a transition from gas boilers to low-carbon heating systems such as heat pumps. Efficiency gains can be achieved by linking heating systems through ambient loops called Fifth Generation District Heating and Cooling (5GDHC) networks. The UK needs working demonstrators to understand both the technical and practical challenges in the heat transition. The Balanced Energy Network (BEN) links two buildings on LSBU’s campus and is the UK’s first 5GDHC system at scale and among the first in the world to be retrofit in parallel to an incumbent gas system and include an active demand side response control system to toggle between energy vectors in way that minimises cost and carbon emissions. This paper presents performance data from its first year of operation in baseline mode, as it was commissioned and optimised. High temperature heat pumps were retrofit to an existing gas boiler circuit and match the 79°C output temperature of the gas boiler system. No fabric upgrades were required and no pipes, ducts or heat emitters were resized, however the system maintained performance to reduce overall building carbon emissions by 13% and gas use by 40% across both buildings compared to the pervious heating season while the system was in use.

Highlights

- The UK’s first known installation a commercial scale 5th Generation ambient heat network retrofit to existing buildings.
- Working demonstration of bespoke high temperature heat pumps that can maintain a high COP and match the distribution temperatures of gas boilers (up to 79°C)
- Building performance data from heat pumps retrofit into existing gas systems with no other changes to building fabric or heat distribution systems.
- Demonstration of the potential for a ‘one at a time’ transition from gas to heat pumps in complex buildings. Data shows a 40% reduction in carbon emissions from gas in the first heating season, and identifies opportunities to further optimise the system over time.

Introduction

The UK must be net zero carbon by 2050 to meet its climate change targets. The Committee on Climate Change has said that this is impossible without a near complete decarbonisation of the heating sector [1]. There is currently no single cost effective and scalable alternative to fossil fuel heating the UK. There is potential for carbon-free gas such as hydrogen to provide a partial solution in the future, but this is likely a decade away [2]. Heat networks linked to low-carbon sources, and typically using heat pumps, are expected to form part of the solution.

Every country faces unique challenges in decarbonising heat. The UK has a deep reliance on the natural gas grid, with gas boilers heating ~85% of UK buildings [3]. Because of decades of infrastructure investment, the gas grid faces fewer capacity constraints than the electricity grid. The electrification of heat is an essential part of any decarbonisation strategy, but cannot replace the gas grid without other measures in parallel to reduce energy consumption and, crucially, peak demand.

Furthermore, there is a perception that heat pumps will struggle to match the performance of gas boilers. Most of the UK stock is heated by a hot water circuit at >70°C from gas boilers. Heat pumps struggle to match this output temperature and maintain a high Coefficient of Performance (COP) i.e. the ratio of heat output over the power supplied to the unit. Because of the higher distribution temperatures of incumbent gas systems, there is the prevailing assumption that retrofitting heat pumps to existing buildings requires fabric upgrades to accommodate lower distribution temperatures and operate the heat pump more efficiently. There is strong evidence that this is not required in all cases (see e.g. [4]), but potential changes to accommodate lower distribution temperatures are a design consideration that must be considered, and potential cost and complexity that this introduces can discourage uptake of heat pumps.

The climate emergency demands a more urgent response from the UK built environment. UK buildings must seek rapid decarbonisation by increasing the uptake of low-carbon heat pumps, while maintaining technology-neutral options that do not preclude future policy pathways.

The Balanced Energy Network (BEN) at LSBU was created to address this transition. BEN is a multi-vector 5th Generation District Heating and Cooling Network (5GDHC), which uses heat pumps linked to an ambient temperature loop as the primary heating source, installed in parallel to the existing boiler circuit. The system was commissioned in 2018 and represents the first such system in the UK.

The next decade is a critical window for action on climate change. The aim of this paper is to use BEN performance data to analyse how the UK can address several key challenges in the low-carbon heat transition over the coming decade while we await decisions about the future of the gas grid.

This paper will address the following research questions using the BEN case study:

1. Can heat pumps be retrofitted to existing buildings without fabric upgrades? What is the penalty of high distribution temperatures to the heat pump Coefficient of Performance (COP)?
2. What challenges does the UK face in incrementally retrofitting buildings to low-carbon 5DDHC networks? What are the initial carbon savings and how can the savings be increased over time?
3. What are the impacts of electrifying heat to overall utility costs at the building level, and how can costs be reduced?

The paper is structured as follows. A literature review describes how BEN addresses gaps in heat decarbonisation strategy in terms of: 1) increasing uptake of 5GDHC networks, 2) increasing need for active demand side control, and 3) heat transitions through multi-vector systems. The paper then addresses Research Question 1 using metered data from the BEN control system for its various components, and triangulating this against building level data from the LSBU Estate. It addresses Research Question 2 by comparing the BEN performance before and after initial optimisation exercises. Finally, it addresses Research Question 3 using LSBU utility billing data to consider cost optimisation alternatives. The paper closes with a discussion of the broader implications of BEN style networks for the UK heat transition.

Literature Review

A broad review of the literature on the decarbonisation of heat reveals three trends relevant to this paper. Firstly, the evolution of district heat networks into ambient temperature loops, secondly the increasing need for demand-side control to balance grid peaks, and finally the use of integrated hybrid heating systems that can select between energy vectors.

District heating can improve system efficiencies and will play a critical role in meeting future heating demand through low carbon sources. The literature is increasingly adopting the nomenclature of Generations to describe the evolution of heat network design [5]. Broadly, the first generation of heat networks were steam driven in the late 19th century. Over time, distribution temperatures have decreased and efficiencies have increased. The 4th Generation of District Heating systems operate across a temperatures range of 30-70°C water, reducing heat losses and facilitating the use of renewable sources or lower grade waste heat.

The term 5th Generation District Heating and Cooling Network (5GDHC) is increasingly being adopted to describe ambient temperature loops and networks, which utilise the mix of heating and cooling needs in an area, by allowing exchanges between these uses and minimising net energy demand. The most common configuration is for them to be linked to a large-scale heat sink/source (e.g. aquifer, flooded mine), circulating water at relatively low temperature (either a single loop or two headers, one cooler and one warmer), and with each building equipped with its heat pump and thermal storage, rejecting or extracting heat from the loop as needed.

Buffa et. al. [8] noted the need for more clarification and harmonisation of terms, suggesting the following definition:

> “A 5GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium and hybrid substations with Water Source Heat Pumps (WSHP). It operates at

> temperatures so close to the ground that it is not suitable for direct heating purpose. The low temperature of the carrier medium gives the opportunity to exploit directly industrial and urban excess heat and the use of renewable heat sources at low thermal exergy content. The possibility to reverse the operation of the customer substations permits to cover simultaneously and with the same pipelines both the heating and cooling demands of different buildings. Through hybrid substations, 5GDHC technology enhances sector coupling of thermal, electrical and gas grids in a decentralised smart energy system." (Buffa, et al., 2019) pg 508

The Chartered Institution of Building Services Engineers (CIBSE) has adopted a similar definition (CIBSE Guide L, 2020) [6]. While the idea is increasingly being adopted in practice, there is still relatively little peer-reviewed study of 5GDHC performance data. Buffa et. al. [8] conducted a review of 40 such examples across the EU.

Among Buffa et. al.'s case studies, none were UK-based. The Balanced Energy Network (BEN) at LSBU was commissioned in 2018, making it the first known example of a 5GDHC network at scale in the UK. In summer 2019, Plymouth began the first phase of construction of a 5GDHC network, linked to an aquifer and serving a range of buildings in the city centre [7].

Past work on 5GDHC has found that pumping loads as a fraction of the heat delivered by the system are higher for 5GDHC than for past generations of heat networks. This is due to the lower distribution temperatures and higher flow rates required. Furthermore, very little has been done to optimise control of 5GDHC systems due to the complex bi-directionality of the energy flows [8].

The electrification of heat has created a growing interest in active demand side response (ADSR) to shift heating demand and balance grid peaks. Conventional Demand Side Response (DSR) uses the capacity of electrical assets or stand-by generation as a grid balancing service. ADSR expands this to include electrical demand side management that influences the customers' load shape. This uses the building heating profile, occupant behaviour, and the thermal mass of the building itself as demand response assets that can be flexed in response to grid signals. Studies have shown that linking multiple electrical heating systems (heat pumps and resistance heating) through ADSR increases system flexibility and reduces operational costs [43]. The electrical load pattern can be shifted without affecting the quality of heat provision to the end user if it is suitably matched to the thermal inertia of the system [43]. In most cases this includes the thermal mass of the building itself, and any additional thermal energy storage such as hot water tanks.

Such studies typically consider how to aggregate spatially distributed assets across a smart grid or the integration of distributed renewables [9]. Some modelling has been carried out to consider how ADSR could be integrated into heat networks, [10] [11], however, BEN is the first known example of a working 5GDHC demonstrator with an active demand response strategy integrated into the control systems.

A final trend that is highlighted in the low-carbon heat literature is the potential for technology agnostic transition pathways using hybrid-heating systems [12]. Products as hybrid heat pumps that can toggle between energy vectors and utilise gas to handle peak loads have been effective in home trials (see e.g. [13]. The term hybrid is also used to refer to integrated or multi-vector systems in which separate heating devices work in parallel. The benefit of multi-vector systems is not only the flexibility to limit peaks, but also the potential to transition away from gas boilers one installation at a time. The challenge is that the multi-vector system typically requires a common distribution system within the building.

Case Study: The Balanced Energy Network (BEN) at LSBU

BEN is a demonstration project part funded by Innovate UK's Integrated Supply Chains for Energy Efficiency grant. The goal of the call was to bring together SMEs and academic partners with standalone innovations for which potential synergies were hindered by market barriers. BEN is therefore a consortium of seven partners with the stated goal of creating an integrated approach to balancing the provision of heat and electricity in a campus while minimising cost and carbon emissions.

The project partners and their roles are:

1. ICAX Ltd: Project lead and designers of the ambient temperature network and heat pumps
2. LSBU: system modelling and host venue for the demonstration, delivery organisation for pipework and plant room modifications
3. TFGI: borehole design and drilling
4. Mixergy: design and build smart thermal storage
5. Upside: demand side response aggregators
6. Origen Power: fuel cell calciner design
7. Cranfield University: fuel cell calciner prototype and testing

The funded portion of the project was from May 2016 to August 2018. During this time the project was designed, installed, and commissioned on LSBU's campus. It was switched on and has been heating two LSBU campus buildings since fall 2018, with a number of intermittent periods where downtime was used for experimental or optimisation purposes. Data collection and performance optimisation are ongoing. Consortium members have published several pieces of research on the design [14], modelling [15], and installation [16] of the system and its components [17]. This paper is the first in a series analysing aspects of BEN's performance in use.

The literature review introduced three trends in low carbon heat innovation:

1) 5GDHC networks use ambient temperature loops to increase efficiency and maximise the potential to exploit low grade/waste heat and exchange heat between buildings.
2) Active Demand Response (ADR) uses the building's thermal mass and distributed thermal storage to influence the load shape for heat and decrease the operational costs for both the end user and system operator.
3) Integrated Energy Systems (IES) or Multi-vector systems make use of more than one energy vector and can for example decide between the provision of heat through either gas or electricity at a given moment based on a defined set of performance criteria.

Each of these innovations have potential to increase the efficiency and decrease the costs of providing low carbon heat. Many demonstrations have used two out of the three in combination to great effect [8]. The potential for all three to work together has been modelled, but the Balanced Energy Network (BEN) demonstrator at LSBU represents the first known example of a multi-vector 5GDHC with ADSR in practice. A diagram representation of the BEN components is given in Figure 1. Note that as described below, only some of BEN design features were active in the baseline year that is the subject of this paper.

This section will describe the design capabilities of BEN, and then close with a description of which of these systems were active during the first year optimisation period that is covered in the empirical performance sections of this paper.

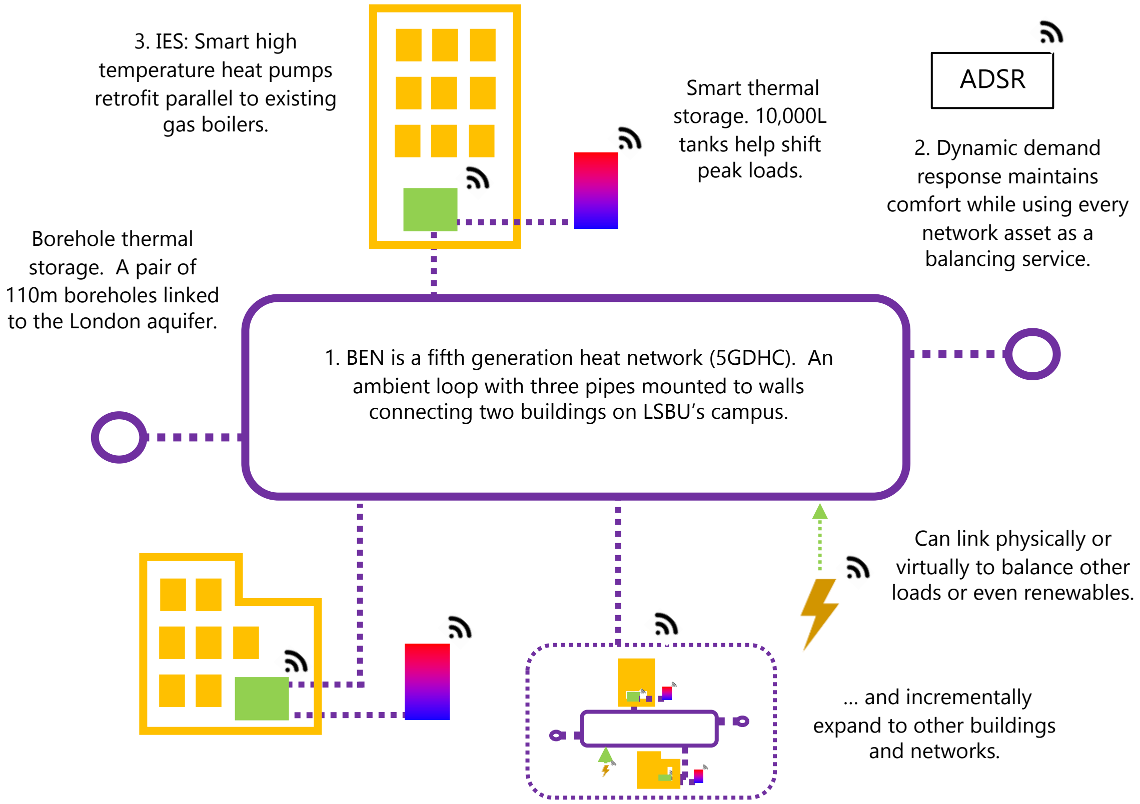

Figure 1: Diagram representation of the BEN network

1) 5GDHC: The BEN 5GDHC infrastructure consists of two buildings, labelled Tower Block and J-Block, linked via an ambient loop. The temperature of the loop is regulated by two 110 meter deep boreholes delivering and returning groundwater at up to 20 L/s from the London aquifer. In theory, the loop could be reversed allowing the

abstraction and rejection wells to be interchanged. In practice, site constraints required a single pump to abstract from the Tower Block well and reject to the J-Block well.

Both the Tower and J-Block buildings are heating dominated, and so there is a net removal of heat from the aquifer over the course of the year. A Phase 1 feasibility study identified these two buildings as the most suitable on campus [14].

Both buildings are mixed-use teaching and office spaces (Tower 9,077 m^2 and J-Block 10,610 m^2, each with an approximate annual heat demand of ~110 kWh/m^2). There is only a limited amount of diversity between the loads. Greater diversity in the loads and profiles, including a cooling load as well as a heating one, would increase the performance of the system.

The ambient loop brings water at a stable ~14°C to each of the two buildings. The boreholes are approximately 100m apart, and linked by a set of three lightweight plastic pipes, all above ground, and mounted to the walls of the buildings. The pipes have a small amount of insulation to prevent freezing. The setup includes two pipes for the ambient loop between buildings, and a third pipe to allow different modes of operation to be explored in future research.

In each plant room, a 300kWth high temperature heat pump has been retrofit into the existing heating circuit. It boosts the ~14°C water in order to match the existing distribution temperature on a common header with the incumbent gas fired boiler, to set points of 74°C for the Tower Block and 79°C for J-Block. The default control sequence is for the heat pumps to precede the gas boilers in a cascade. Because the systems have been installed in parallel, it is a completely multi-vector system, and the heating demand can be met by either or both of the heat pumps and gas boilers or, in the future, thermal stores. BEN can optimise this control sequence for different performance criteria e.g. costs, carbon.

The core function of transitioning from gas boilers to electric heat pumps served by an ambient loop will naturally decrease gas consumption and increase electricity consumption overall. The control system was designed to utilise ADSR and IES to do this cost effectively and reduce carbon emissions.

2) ADSR: Every major electrical load in BEN (the heat pumps, circulation pumps, water storage, etc.) is directly addressable as a demand response asset and integrated through BEN's control system. BEN will be able to use ADSR to increase the efficiency with which electricity is used to meet heat demand without impacting the quality of heat delivered. This will be achieved by linking the heat pump in each building to separate 10,000 L smart thermal storage tanks that can be charged or discharged at optimal times in response to signals such as price, carbon, or peak demand signals. In addition, Tower Block is a Brutalist 1970's concrete design and J Block is a mixture of early/mid twentieth century brick buildings, and 1970's Brutalist concrete: they are all high thermal mass buildings. This thermal inertia can be used as a tool to influence the heating load shape. Design stage modelling predicted that demand response revenue streams could offset ~10% of utility costs for each building [44].

3) IES: The decision to integrate the heat pumps in parallel to the existing gas boiler distribution system had several advantages. Firstly, it created a design redundancy that allows the system to be used experimentally without impacting the provision of heat to the buildings. This allows the system to serve as a living lab demonstration of how building systems can evolve in the low carbon heat transition without adversely affecting student experience in a densely packed London campus. For example, the system was switched off to upgrade the heat pumps with a lower global warming potential refrigerant, tested, then reintegrated with no interruption to heating services.

This integration was functionally very important as it served as proof that high temperature heat pumps can match the heat produced by gas boilers. The type of high temperature heat pumps used in BEN are capable of replacing virtually any existing gas boiler like for like, without costly resizing of heating system distribution equipment such as ducts, pipework and radiators or other emitters. While operating at lower efficiency than they would at lower heating temperatures, they still allow the start of a transition away from fossil fuels. This paper reports on heat pump performance and associated effects on energy consumption and carbon emissions.

The flexibility of an integrated gas/electric heating system is also useful operationally, as it allows the control system to select thermal storage, electricity, or natural gas, as the optimal vector (optimal on the basis of either cost or carbon) to meet heating demand in any given time interval.

The operational performance of BEN's innovations in 1) 5GDHC networks 2) ADR, and 3) IES will be explored over a series of papers. The first year of its operation, only the design options from item 1) 5GDHC were utilised. None of the 2) ADSR and 3) IES features were active. This paper will therefore consider the first year of BEN's performance as a 1) 5GDHC network to establish a baseline for the direct switch from heating via gas boilers to heating via an ambient loop with heat pumps. It points to possible performance optimisation steps, which have already been taken or can be implemented in the future. Subsequent papers will explore further performance optimisation from this baseline by utilising, 2) ADSR revenue streams and 3) variable tariff structures.

Methodology

Previous work has modelled the likely performance of the BEN system based on models and engineering calculations. This paper presents actual performance data from the system in use, from two sources: 1) BEN meters, and 2) Building utility bills.

1) Electricity and heat metering by the BEN system itself includes hourly data covering heat output from each boiler and heat pump, electricity input to each heat pump, electricity input to the well pump and to the circulation pump. All other building electrical loads are not included.

2) Gas and electricity metering by LSBU estates for the buildings overall includes monthly energy dashboards with gas and electricity readings. For several months pre and post installation of BEN, the long form billing was obtained from the energy supplier giving a detailed breakdown of LSBU's pricing structure.

The data below considers the periods:
Oct 2017- Sept 2018 as Academic Year 17/18 – BEN not yet active, J and Tower blocks heated by gas only
Oct 2018- Sept 2019 as Academic Year 18/19 – BEN active, J and Tower blocks heated by mix of gas and BEN heat pumps.

The total energy use of each component is summed through these months, and a degree day analysis will be used to control across heating seasons.

Results

Overview of BEN contribution to total heating load

The contribution of BEN to the heating load in each building is presented in Tables 1 and 2, in monthly data for the Academic year 18/19 i.e. the first year of operation of BEN.

Table 1: J Block Monthly Breakdown

	Electricity Consumed by Heat Pump (kWh)	Heat Output by Heat Pump (kWh)	Heat Output by Boilers (kWh)	Monthly Avg COP
Oct-18	25357	31525	32975	1.24
Nov-18	30912	73300	41458	2.37
Dec-18	25391	59085	30991	2.33
Jan-19	30878	74983	42799	2.43
Feb-19	24516	61481	73950	2.51
Mar-19	12252	30289	11331	2.47
Apr-19	330	77	71101	-
May-19	3172	10863	39709	3.42
Jun-19	907	3540	15724	3.90
Jul-19	352	-	-	-
Aug-19	339	-	14833	-
Sep-19	695	2007	52686	2.89
Sum	155099	347150	427557	
% of total heat output		45%	55%	

Table 2: Tower Block Monthly Breakdown

	Electricity Consumed by HP (kWh)	Heat Output by Heat Pump (kWh)	Heat Output by Boilers (kWh)	Monthly Avg COP
Oct-18	3474	11927	34941	3.43
Nov-18	1886	6811	60642	3.61
Dec-18	14459	40543	26061	2.80
Jan-19	12032	36842	49150	3.06
Feb-19	17178	50590	28200	2.95
Mar-19	10888	30593	37742	2.81
Apr-19	327	-	36752	-
May-19	345	3894	75	11.29
Jun-19	265	2195	-	8.29
Jul-19	350	-	-	-
Aug-19	337	-	-	-
Sep-19	337	-	-	-
Sum	61877	183395	273563	
% of total heat output		40%	60%	

In J-Block BEN delivered almost twice as much heat over the year as in Tower Block. In each building the heat pump contributed to a similar proportion of the overall heat output (45% in J Block, 40% in the Tower block). Their contributions however varied widely across different months, with potential for much higher contributions during some months (February and April in J Block, October, November, January and April in the Tower). The Tower Block heat pump had additional down time due to non-BEN related maintenance cycles.

Heat pumps and system performance

Table 3 gives the combined total electricity consumption and heat output for the overall BEN system for Academic Year 18/19 including the auxiliary load of the pumps.

Table 3: Academic Year 18/19 totals for overall BEN system serving J-Block and Tower Block.

	Electricity Consumed by Heat Pump (MWh)	Electricity Consumed by BEN Circulation Pump (MWh)	Electricity Consumed by BEN Well Pump (MWh)	Total Electricity Consumption (MWh)	Total Heat Output by Heat Pumps (MWh)	SEER
J Block	155.1			**155.1**	**347.1**	**2.24**
Tower Block	61.9			**61.9**	**183.4**	**2.96**
Auxiliary pumps		11.7	40.4	**52.1**		
						SSEER
Overall BEN System				**269.1**	**528.5**	**1.96**

The Seasonal Energy Efficiency Ratio - SEER is the ratio of heat output to electricity input for the heat pump over the heating season.

$$SEER = \frac{Total\ heat\ output\ by\ heat\ pumps}{Total\ electricity\ consumed\ by\ heat\ pumps}$$

The SEER was 2.24 in J Block, and 2.96 in Tower Block. This can be largely explained by differences in the required water temperatures: J Block has been around 79°C and Tower Block around 74°C. These high temperatures were required to meet the common header served by the other boilers in the cascade. This are clearly not favourable operating temperatures for a heat pumps, but it offered the opportunity to prove that a heat pump could meet these temperatures and maintain a high COP. Further improvement in the performance of the heat pumps would clearly be achieved by reducing these operating temperature set points.

This study carried out an indicative comparison of the observed SEERs with the manufacturers expected COPs using the evaporator and condenser temperatures, and outlet temperatures of each heat pump. It indicates that the Tower Block heat pump is performing in line with the manufacturer expected COP for an output temperature of 74°C. The J-Block heat pump however, is performing approximately 20% below the expected COP for an output temperature of 79°C. Investigations into this issue identified control elements in the J-Block plant room that could be adjusted to allow a decrease in header temperature without affecting occupant comfort. This highlights the series of performance optimisation exercises that must take place in order to ensure that heat pumps are operating as efficiently as possible.

The system SEER (i.e. SSEER), is the heat output from both heat pumps, divided by electricity consumption of both heat pumps and of the well pump and loop circulation pump.

$$SSEER = \frac{Total\ heat\ output\ by\ both\ heat\ pumps}{Total\ electricity\ consumed\ by\ overall\ BEN\ system}$$

The SSEER for BEN was 1.96. The large majority of pumping energy (80%) was for well pumping, rather than loop circulation. The overall consumption of the BEN pumps (well + circulation) is equivalent to 10% of the heat output by the system, or 20% of the heat pump system's electrical input. This is higher than the ~5% of heat output found in the Buffa et al. [8] review.

BEN therefore explored how to reduce pumping electrical consumption. In November 2019, the design team made changes to the well pump control strategy to reduce its consumption at times of partial load. The well pump was broadly all on / all off, regardless of the heating load within each building. For example, when the heating load decreased over the weekends, the well pump load remained unchanged. Following the controls change, the well pump load more closely follows the heating load shape.

The part load controls led to a 25-30% reduction in well pump energy consumption compared to pre-change levels. This savings is unlikely to be consistent across seasons, and will still leave overall circulation above the ~5% benchmark, but could still result in a significant improvement in SSEER.

BEN impacts on energy consumption, peak demand, carbon and cost - overall

This analysis next triangulates these results against utility billing data from LSBU Estates to assess the impact of BEN on the buildings' overall energy consumption and associated costs. This compares the data from 2017/18 pre-BEN to 2018/19 with BEN. The utility billing data covers all building loads, not just the BEN system, and thus includes several additional variables, the isolation of which is not possible without building sub-metering. The 2018/19 with BEN year included many months of downtime for improvements to both BEN systems and non-BEN related plant room issues as described above. Within 2018/19, BEN was principally active during the peak heating season from October 2018 to March 2019. For this reason, the results of Table 5 are presented in two parts, first showing the overall year, which includes significant downtime, and then separately showing the impacts of BEN during only the October 2018 to March 2019 heating season during which the system was most active.

Table 4: Comparison Estates Building Metering Data for Academic Year 17/18 (Pre-BEN) to 18/19 (With-BEN)

Combined J Block and Tower Block	**Academic Year 17/18**	**Academic Year 18/19**	**Change**	**Change %**
	(Pre-BEN)	(With-BEN)		
Heating degree days (17.5°C basis)[1]	2108	1990	-118	-5.60%
Comparisons for Full Year				
Electricity Consumption (MWh)	1,637	1,966	329	20%
Gas Consumption (MWh)	1,528	1,170	-358	-23%
Total Consumption (MWh)	3,165	3,137	-28	-1%
Electricity Cost @ 10 p/kWh (£)	£163,688	£196,626	32,938	20%
Gas Cost @ 3 p/kWh (£)	£45,838	£35,107	-10,730	-23%
Total Cost (£)	£209,526	£231,733	22,208	11%
Emissions from Electricity (TonneCO_2)	493	518	25	5%
Emissions from Gas (TonneCO_2)	281	216	-66	-23%
Total Emissions (TonneCO_2)	774	733	-41	-5%
Comparisons for heating season only: October to March (6 months)				
Electricity Consumption (MWh)	910	1,154	244	27%
Gas Consumption (MWh)	1,234	740	-494	-40%
Total Consumption (MWh)	2,143	1,893	-250	-12%
Emissions from Electricity (TonneCO_2)	287	310	23	8%
Emissions from Gas (TonneCO_2)	227	136	-91	-40%
Total Emissions (TonneCO_2)	514	446	-68	-13%

(-‘ve denotes savings.)

This shows, not surprisingly, an increase in electricity consumption and decrease in gas, over a period where heating degree-days were lower but not significantly so (5.6%). This results in an overall decrease of 6% in total consumption across both fuels.

The increase in electricity consumption of 329 MWh roughly corresponds to the 269 MWh total electricity consumption of the BEN system in Table 3. Bearing in mind that 329 MWh includes all other non-BEN building electrical loads such as lighting and process loads.

The cost difference between gas and electricity it equates to a £22k pa increase in utility costs due to *unit* consumption. Another contributor to energy cost relates to peak demand; peak demand and billing data was not available to carry out this analysis over the full academic years, but it is available for a period in January, as detailed further down in this section.

Note that these effects on energy consumption and associated costs do not yet include demand response measures. As it happens, the increase in unit costs – based on 10 p/kWh – could be mostly offset through the predicted demand response revenue streams [44]. There may also be potential to limit cost increases by utilising time-of-use tariffs.

<u>Impact of BEN on carbon emissions, and sensitivity to variations</u>

Even operating in its most ‘basic’ configuration (no demand response), the decreasing grid carbon emissions factor has allowed BEN to contribute to an overall reduction in CO_2 emissions by 5% in the overall academic year and 13% over the heating season during which BEN was most active compared to the previous year (at comparable, if slightly lower, heating degree-days). This will further improve in future years as the electricity grid continues to decarbonise.

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[1] This base temperature of 17.5C was found to be the one with the closest correlation to the total gas consumption of Blocks J and T, pre-BEN installation. Using instead the common UK default base temperature of 15.5C, the reduction in heating degree days from 17/18 to 18/19 is 8%, rather than 5.6%.

Table 5: UK Government Carbon emissions factors [18]:

Year	Gas (kg CO2e/kWh)	Electricity (kg CO_2e/kWh)
2017	0.184	0.352
2018	0.184	0.283
2019	0.184	0.256

This analysis of carbon savings uses the UK Government conversion factors for greenhouse gas reporting. This is useful as first step, but is based on annual average data and does not account for variations in grid carbon factors throughout the year. There is increasing interest in more detailed analysis that considers the carbon content of the grid at time of use, as this can now vary significantly with shifts in demand and renewable energy contributions.

BEN serves two multi-use campus buildings with heating load profiles are similar to most offices. This can require operating at peak times when electricity consumption is of higher-than-average carbon content.

On average, the boilers serving both buildings are assumed to generate heat at an efficiency of 85%[2], which equates to 0.216 kgCO2/kWh heat generated. BEN generates heat at an efficiency of 196% (COP 1.96). Therefore, when the grid intensity is greater than 0.429kgCO2/kWh, BEN would save carbon by providing heating using the gas boilers instead of the heat pumps.

Figure 2 shows the hourly grid carbon intensity in the UK from Oct 2018 to June 2019 [19]. During this time, the dynamic grid carbon intensity exceeded the threshold value of 0.429kgCO2/kWh for a total of 3.5 hours. This means that while BEN is capable of switching between energy vectors of gas and electricity, it will almost never be beneficial in carbon terms to select gas.

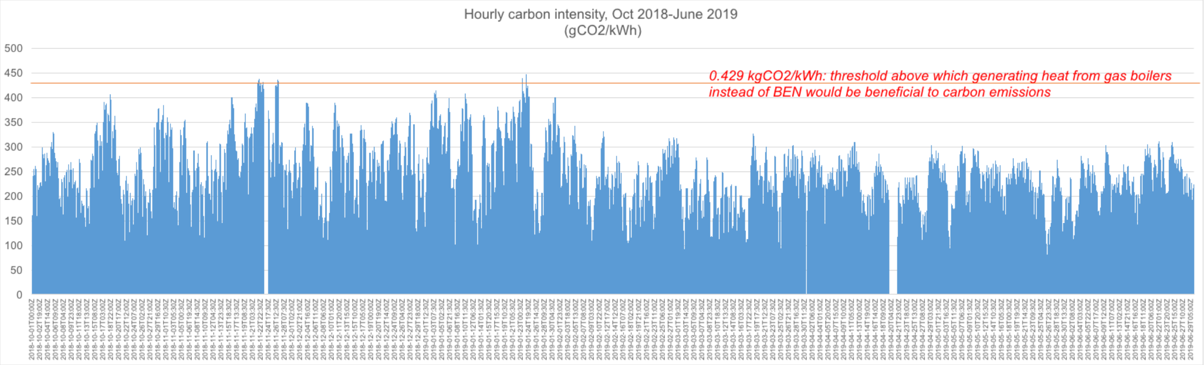

Figure 2: Hourly actual carbon content of grid electricity, October 2018 - June 2019 [19].

This could further improve as part of the BEN optimisation steps to make sure of thermal storage and generate heat at times of low grid carbon content - see analysis of a sample week in later section.

BEN impacts on energy consumption, peak demand, carbon and cost - focus on January

A more detailed analysis of a winter week in January 2019 was used to build a better understanding of the current operation of BEN, and to start to identify possible future optimisations. It operated regularly on weekdays, and contributed a large proportion of the thermal load. Indeed, from Tuesday to Friday, its heat output in the daytime was around 550kW i.e. nearly maximum heat pump capacity.

Consumption from the circulation pump broadly followed the heat pump operation; that of the well circulation followed a much coarser on/off pattern discussed in the previous section.

During that week, the electricity grid carbon factor was 0.285 kgCO2/kWh (i.e. broadly the same as the 2018 average). During the hours of that week when at least one of the two BEN heat pumps operated at medium to high load (i.e. at least 100kW output), it was 0.306kgCO2/kWh i.e. 8% higher than the annual average. This reflects patterns of higher grid carbon content in daytime rather than night-time.

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[2] Boiler efficiency inferred to be 85% but system losses may decrease this efficiency. This only makes the carbon case for BEN more convincing, but a value of 85% was used here in order to assess the potential of BEN against a system of reasonable performance.

It means that the actual carbon savings over a year may be lower than estimated with the average annual grid carbon content. However, the actual grid carbon content is still well below the threshold at which it would not be beneficial to use BEN instead of gas boilers.

One of the concerns about the electrification of heat is the pressure it could put on the electricity grid, particularly at times of peak demand. For some organisations, this also comes with concerns about energy costs, not only due to the unit price of electricity but because of the charges imposed related to peak demand.

At LSBU, energy costs related to peak demand are reflected in costs as follows:

- Variable charge: based on peak demand – in the BEN case study, this has no effect as the tariff for this at LSBU is nil.
- Variable charge: Transmission Network Use of System charges, based on peak demand – at LSBU this is charged monthly, on 85% of peak demand
- Fixed charge: available capacity in kVA – around the time of the installation of BEN, the Estates increased their “maximum available capacity” agreement with their electricity supplier from 700 to 1200 kVA, to account for possible increases.

In total, these costs are equivalent to 25-30% of those related to unit consumption i.e. smaller, but significant when carrying out an appraisal of financial viability.

Table 6 summarises these costs pre- and post-BEN for the Tower Block. A similar comparison cannot be made for the J Block due to metering issues in 2017-18.

Table 6: Comparison of peak demand and related energy costs pre- and post-BEN, for the Tower Block (note these figures are only estimates, due to partial data availability).

		Pre-BEN	With BEN
Period examined, linked to data availability		From energy bills: January 2017, April 2017, January 2018 and April 2018	From energy bills: January 2019, March 2019, January 2020
Peak demand, kW	Winter – January	201-204kW	258-351kW
	Spring – March or April	185-232kW	334kW
Peak demand charge, £	monthly	£0	£0
Transmission Network Use of System, £	monthly average	£788	£1,249
Maximum available capacity charge, £	monthly average	£857	£1,512
Total cost associated with peak demand: peak demand charge + TNUoS + availability	monthly average	£1,645	£2,761 i.e. +68%

Based on the data available, the effect of BEN on the Tower Block was an increase of, at most, 150kW on peak demand. This is a reasonable finding, as the heat pump itself is rated at 95 kWe. There are also a range of ancillary equipment and other non-BEN items included in the utility meter readings.

This was reflected in energy costs, equally through available capacity charges (= based on potential demand, which a non-domestic user would wish to account for) and through TNUoS charges (= based on actual peak demand). The effect was significant, of almost 2/3rd, although some of this was due to increased tariffs as well as increased demand itself.

The heat demand follows a regular profile with sharp increases in the morning and drops early evenings. Both heat demand and carbon content follow a roughly similar profile i.e. high heat demand in the Tower Block coincides with higher carbon electricity. This highlights opportunities for further carbon or cost savings through BEN optimisation, including pre-charging the thermal stores early morning, at times of low electricity cost and low grid carbon content, and possibly making use of the buildings’ thermal mass to reduce the heat output late afternoon, at times of higher electricity costs and grid carbon content. Each thermal store has a capacity of 10,000 L which, at storage temperatures of 74°C can deliver roughly a half-hour of heat at maximum demand. This could be incorporated into the control to pre-charge the stores early morning, and discharge them later on in the day, at times of high heat demand either to further reduce reliance on the boilers and cut carbon emissions, or to reduce the heat pump’s operation at times of higher electricity costs.

Results Summary

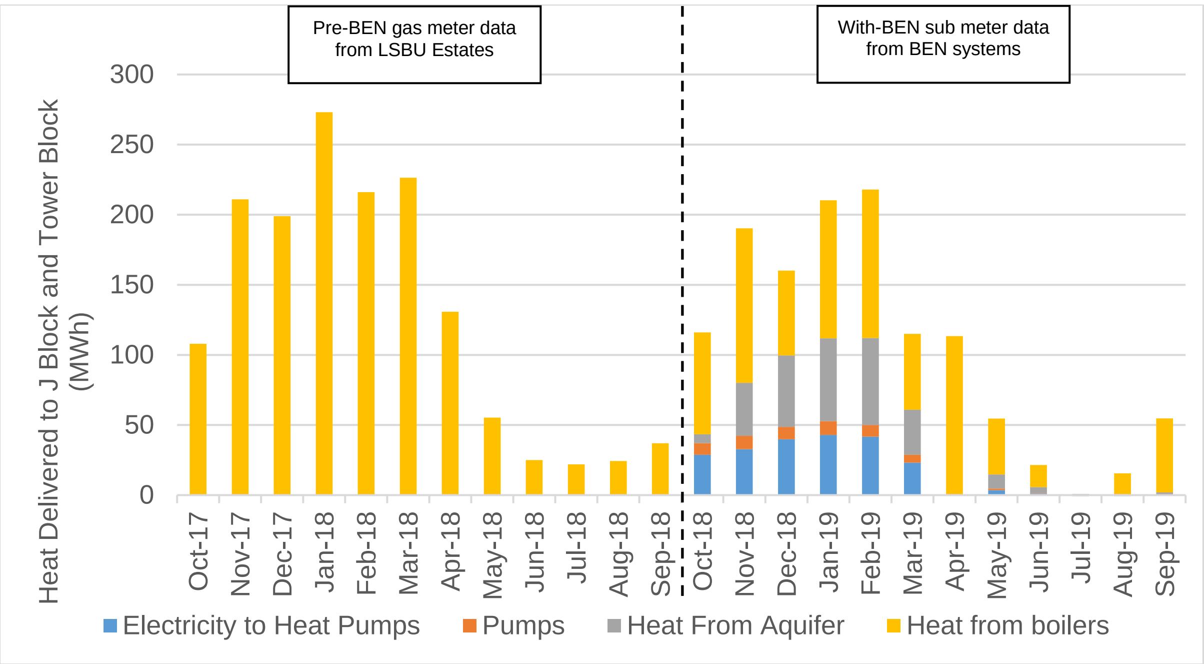

Figure 3: Data showing pre-BEN gas consumption from Estates building metering (Oct 2017 – Sept 2018) and with-BEN data from BEN system sub-metering. It shows the principle period of BEN activity for the heating season Oct 2018 to March 2019.

Figure 3 combines data from the two sources used in this paper; building level gas meter data provided by LSBU estates, and BEN sub-metering data collected from BEN systems themselves (from Table 1 and Table 2). Because these are two distinct data sources, the left and right halves of Figure 3 should not be compared quantitatively, but provide a useful visualisation of the contribution that BEN systems make to the overall heat delivered to the J Block and Tower Block buildings. On the right hand side of Figure 3, the total heat output from the heat pumps given in Tables 1 and 2 is broken down into three components: the direct electricity to the heat pumps, the electricity to the well and circulation pumps in the ambient loop (effectively counted as heat from friction), and the heat extracted from the aquifer.

It shows that when BEN was most active from October 2018 through March 2019, it contributed a significant proportion of heat to both buildings, and reduced gas use by 40% compared to the previous heating season. Note that the heat pumps were sized based on space and budget constraints for the innovation funding, they were not sized to meet the full heating load of the buildings. As the other boilers in each building reach end of life, it is feasible to replace them with heat pumps, and further the transition to low-carbon heating. BEN was largely shut down during the non-heating season (April 2019 to September 2019) to carry out maintenance and other experiments with BEN systems and non-BEN related plant room issues.

Discussion

Analysis of the BEN case study performance addresses each of the three Research Questions posed:

1. Can heat pumps be retrofit to existing buildings without fabric upgrades? and what is the penalty of high distribution temperatures to the heat pump Coefficient of Performance (COP)?

The BEN project team was under direct instruction from the University Executive that the project would not result in disruption to staff and student experience due to reduced comfort conditions. Thus, the distribution temperature of the main boiler header and all room temperature set points remained unchanged before and after the installation of BEN.

Upgrades to the thermal performance of the buildings would have allowed a reduction in distribution temperatures and an increase in heat pump performance; however, fabric upgrades were not included in the project budget. It was therefore a design challenge to create a system that could match the high temperature of the boiler distribution circuit, not affect occupant comfort, and maintain a high enough performance to reduce carbon emissions compared to the all gas counterfactual.

There is a clear trade-off between the output temperature of the heat pump and its performance. However, the data in Table 3 illustrates that it is possible to match the 74-79°C temperature of an existing gas circuit and still maintain an average COP of 2 or above.

Figure 6 also showed that at these temperatures and performance, the BEN heat pumps still offer considerable carbon savings relative to gas boilers for 99.9% of operating hours. In its first year of operation, even with service interruptions for experimental work and system refinements, BEN reduced overall CO_2 emissions by 5% for the year overall and by 13% over the heating season when BEN was most active. This was calculated using government emission factors (this is only approximate due to lack of sub-metering, but a reasonable estimate; using the latest carbon factors in SAP 10.1 would lead to even higher savings).

2. What challenges does the UK face in incrementally retrofitting buildings to low-carbon 5DDHC networks? What are the initial carbon savings and how can the savings be increased over time?

There are considerable challenges implementing low carbon heat that have been documented in previous papers on the BEN process [16]. This paper offered new insights by examining performance data. This shows that the incremental approach offered by BEN can improve with time through very simple interventions as date is gathered on the system, the buildings, and the interactions of various components. An important initial optimisation step already carried out, and described in this paper, was to reduce the consumption of the well pump.

The system needs a period of optimisation, before implementing further measures: this is always true but probably particularly in the case of integrating with existing systems, as the analysis and optimisation has to deal with “legacy” issues such as inefficient ancillary systems.

In its first year of operation, in the midst of numerous optimisation trials and maintenance cycles, the BEN system offers carbon savings and contributes around 40% of the heating load previously met by gas. This portion will increase considerably as the timing and controls are further optimised to the buildings’ heat loss characteristics, including the use of the storage assets and demand response to shift the load curves.

3. What are the impacts of electrifying heat to overall utility costs and how can costs be reduced?

Despite the UK’s ambitions to reduce the use of fossil fuels for heating, retail gas is significantly cheaper than electricity. Grid constraints force high costs for peaks in electricity use compared to relatively constant gas costs. Heat pumps will therefore struggle with high operational costs despite the clear carbon savings even at high temperatures as demonstrated by BEN.

BEN decreased gas use and increased electricity use. This resulted in an overall increase of 11% in the unit energy costs. It also led to a 68% increase in peak electricity use for the Tower Block for January 2018 (pre-BEN) versus January 2019 (with BEN).

LSBU can use a range of strategies to reduce both the unit costs and peak use. The analysis in Figure 4 and Figure 5 showed that most heating demand was occurring at peak times due to the building’s use profiles. BEN can use the storage and thermal mass of the buildings to shift these loads and reduce peaks. Unit cost savings could also be reduced through a variable tariff. These tariffs typically reduce costs at times of high renewables output. This means that optimising for cost on a variable tariff will likely increase carbon savings as well. Finally, there is also the possibility of directly monetising BEN electrical assets through demand response aggregators, which modelling valued at 10% of each buildings’ baseline utility costs (Gillich et al. 2017).

This paper has described BEN running in baseline mode during its first year of operation. It demonstrated that even with circumstances unfavourable to heat pumps it is possible to create a high performing system that reduces carbon emissions from heat. It also identified several opportunities for improving the performance, some of which have already been implemented such as the optimisation of circulation pump controls.
An obvious further improvement could be achieved by reducing the temperatures required by the heating distribution system. There are also potential carbon and cost savings by using the storage and flexibility in BEN systems to shift loads and avoid peaks. And finally, given that BEN reduced gas emissions by 40% compared to the previous year during its most active months, it is also important to have shorter and fewer downtime periods. LSBU will explore and quantify these options in the coming year as the management strategy for BEN is further refined.

Conclusions

BEN has reduced carbon emissions by retrofitting a 5GDHC network to ageing buildings in a densely occupied campus in central London. It has proven that high temperature heat pumps can match the performance of gas boilers and reduce carbon emissions. It has also proven that there is a considerable optimisation period for such systems. A direct switch from gas to electricity is likely to increase total utility costs due to relative retail costs of each fuel. Careful performance optimisation and tariff selection are needed in order to transition to low carbon heating at least cost.

BEN represents the first known example of a 5GDHC network retrofit to large commercial buildings in the UK. It is also unique in its potential to be fully integrated with an active demand side response (ADSR) control system and the ability to toggle between energy vectors (gas/electricity/storage). This paper explored the 5GDHC performance in baseline mode as the system was commissioned and optimised. Further work will explore the ADSR and multi-vector performance.

In its first year of operation, BEN offset approximately half of gas use for heat in each building. Compared to the previous year, BEN's buildings reduced gas use by 23% for the year overall, or by 40% for the Oct-March heating season during which the system was most active. It also increased carbon emissions from electricity use, resulting in a net decrease in overall building emissions compared to the previous year of 5% for the year overall, or 13% for the Oct-March heating season during which BEN was most active. Note that these calculations used government grid electricity carbon factors. However, LSBU is on a renewable electricity tariff that has near zero carbon emissions from electricity. Under such a tariff, the carbon benefits of shifting from gas boilers to heat pumps is even greater.

As each of the remaining gas boilers reaches end of life, the University will decide whether to replace them with another gas boiler or continue the transition to low-carbon heat. The optimisation period offered by this project helps de-risk this transition and serves as a useful example for the many similar buildings across London.

As we transition to low-carbon heating systems it is important to distinguish between the long-term abilities of a system and the short-term introduction difficulties. The initial conditions for the first year operation of BEN were not favourable to heat pumps, including requiring higher than optimal distribution temperatures, and not utilising the storage and flexibility features designed to shift peak loads. There were also a range of commissioning items such as optimising pumping controls and a range of other building factors outside of the BEN design team's control. The true performance for BEN will be reached when these unfavourable conditions have been addressed.

However, the most crucial takeaway is that even with these unfavourable conditions it is possible to install a system that maintains comfort and reduces carbon emissions by replacing gas with low carbon heat pumps. As grid carbon factors decrease, such systems will approach Net Zero emissions for heating. Phasing out gas boilers is not simple, but it is highly achievable, and we can do it one boiler at a time.

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