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Retrofitting a Fifth Generation District Heating and Cooling Network for Heating and Cooling in a UK Hospital Campus

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Abstract: There is an increasingly rich literature on the decarbonisation of heat and the evolution of heat networks. This paper investigates whether a novel fifth Generation District Heating and Cooling Network (5GDHC) could be retrofitted to an existing National Health Service (NHS) hospital campus for the purpose of heating and cooling. The building load was simulated and input into a custom-written script to carry out a series of parametric studies and optimise design options. The model was calibrated against site data available from hospital facilities management. The research found that it is feasible to use a 5GDHC consisting of a large single mass of water to utilise inter-seasonal thermal storage. A natural water resource such as an aquifer was not required. The model tested sizing options and found that larger thermal storage, heat pumps and chillers reduce operating costs and improve flexibility. The paper closes with a discussion of the practical factors in retrofitting 5GDHC networks to a densely occupied and highly constrained campus environment. The findings are novel in further describing the circumstances for which 5GDHC networks are suitable.

Keywords: heat network; 5GDHC; retrofit; decarbonisation of heat

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1. Introduction

All UK buildings must be effectively decarbonised to meet the government's target of creating a net zero-carbon economy by 2050 [1]. The UK is reducing its carbon dioxide emissions from power generation, but the decarbonisation of heat will also require ending the use of gas for heating in its current form [2,3]. District heating can offer efficiency gains over standalone building solutions; however, most district systems are also currently served by fossil fuels. The retrofitting of existing district networks into low-carbon heating systems is a critical component of any heat decarbonisation strategy. Fifth Generation District Heating and Cooling Networks (5GDHCs) circulate ambient temperature water and allow heat to be added or removed from the network by individual building systems. This is fundamentally different from conventional heat network design, in which heated water is distributed to buildings from a central plant. 5GDHC systems are emerging as a key tool for the planning of district heating, with numerous advantages over higher temperature systems being both modelled [4,5] and demonstrated [6]. The UK, which historically lags behind the EU in district heating innovation, has seen increasing interest in novel 5GDHC design, including the implementation of the UK's first scheme at scale in Central London [6].

In retrofitting older, fossil-fuel-based heat networks into net-zero-ready low-carbon systems, one option is to convert the existing high-temperature system into a 5GDHC. This paper contributes to the emerging field of studies exploring the use cases and design issues upon which this type of decision can be made. It focuses on a case study of a hospital campus currently heated using gas boilers feeding a steam-based heat network.

High-use areas such as hospital campuses offer useful case studies to consider this transition, as they illustrate the challenges of creating new building service solutions in areas with both space and use constraints. Low-carbon upgrades must be carried out in a way that minimises space requirements and avoids disruption to end users. As such, the hospital campus at Addenbrookes in Cambridge offers a test case with replicable findings at both hospitals and other densely occupied campuses across the UK.

This paper will describe the investigation of the building properties and energy consumption, comparing the energy balance in the winter of a specific year and energy consumption to allow a comparison of the published estimate with the calculated estimate from energy records. The heating and cooling demands from known information will be used to validate a thermal model created in the IES Virtual Environment 2019 (IESVE). The results will consider the environment needed to meet the current thermal environmental guidance set out in the Department of Health's Health Technical Memorandum 03-01: Specialised Ventilation for Healthcare premises. The paper considers the optimum combination of components and their viability and efficacy for complementing the operation of the proposed system and end with recommendations of what other NHS Estates may need to do to seriously consider similar retrofits.

Many 5GDHCs rely on natural features such as aquifers or other bodies of water to balance the heating and cooling demands across seasons. The paper will examine the viability of creating a dedicated mass of water to act as a balancing mechanism in the absence of a natural aquifer or water source. It will model the role of both energy efficiency retrofit measures and demand-side response in satisfying service needs. The paper closes with a discussion of the benefits and challenges for retrofitting such 5GDHC schemes to densely occupied UK buildings as part of a wider decarbonisation strategy.

Literature

There has been a gradual evolution in district heating systems, with the definitions shown in Figure 1 of Generations 1–5 becoming increasingly accepted parlance (see e.g., [7]). Buffa's review provides a useful clarification of the nomenclature as well as headline benefits and challenges of 5GHDC systems based on a review of 40 examples across the EU [8].

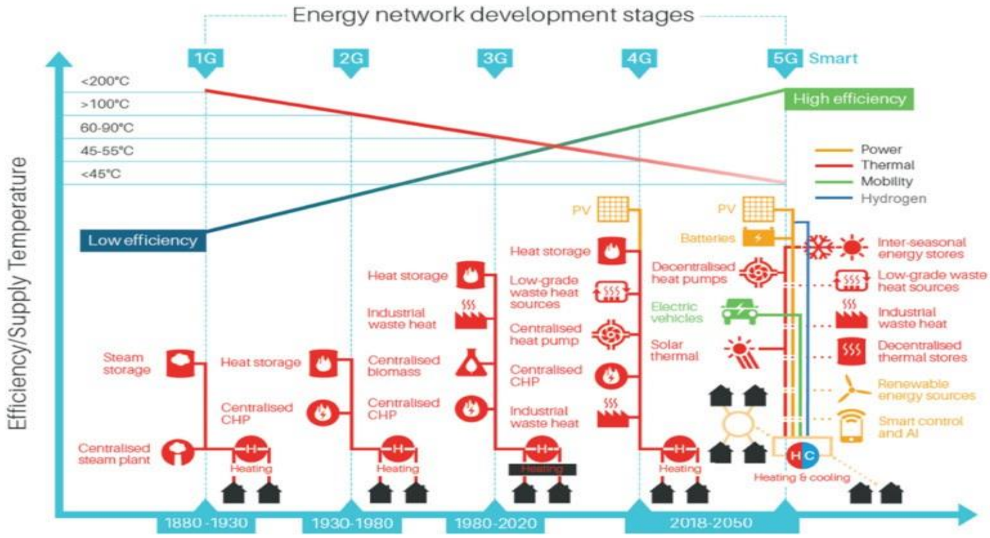

Figure 1. Fifth Generation Heat Network illustration (Figure taken from [9]).

There has been a steady increase in both the academic interest and practical applications of 5GDHC in recent years. However, most applications remain pilots and demonstrators with limited data and so much of the literature has focused on the development of numerical models for preliminary design, equipment sizing, and performance analysis of 5GDHC, as summarised by [10].

Most of these studies explore the parameter space of 5GDHCs for different use cases by calibrating the models to case studies. Gjoka et al. [11], for example, find applications for 5GDHCs in milder climates using an Australian university campus as a case study, noting in particular the potential savings and challenges for integrating the design across energy vectors and across seasons. The current paper is novel in exploring the applicability of 5GDHCs as a retrofit solution in a dense hospital environment without disruption of service.

The availability of a heat source to balance any asymmetric loads is often viewed as a critical constraint for 5GDHC feasibility and design. There is a growing literature in this space exploring borehole or aquifer thermal storage systems as a solution (see e.g., [12,13]). Exploring heat-balancing solutions in the absence of boreholes and aquifers is a useful contribution to understanding the feasibility of 5GDHCs under different scenarios.

This paper offers a novel contribution to the literature by considering the applicability of 5GDHCs in the challenging case of being a retrofit solution for a constrained hospital campus with limited plant space, no disruption of service, and no availability of borehole or aquifer thermal storage as a balancing heat source. The paper presents a multi-stage modelling methodology and results for a thermal storage solution using existing pipework and waste heat.

The performance of a heat pump system is characterized by the useful heat output divided by the energy input (denoted as the Coefficient of Performance—COP). The higher the COP, the more efficient the system. One of the most effective ways to boost the system COP is to draw heat from a source that is stable and predictable, particularly during colder weather across seasons. A heat pump typically uses air, ground, or water. Air source heat pumps (ASHPs) are simpler, but the air temperature varies considerably compared to water or ground source heat pumps (GSHPs). GSHPs are therefore more costly, but better performing than ASHPs [14,15].

As weather conditions are predicted to become warmer, the heat island effect of more densely populated areas [16] suggests that ASHPs may increase external temperatures locally. A 5GDHC, if correctly sized, would offer the advantage of storing the energy to increase the COP of a heating or cooling system as opposed to an ASHP, which would be victim to the temperatures and variability that would reduce the system COP.

Interseasonal storage captures rejected heat (e.g., from chillers) during warmer seasons, stores it for up to several months, and then uses it to boost the COP or a ground- or water-based system during periods of colder weather. This approach is predicted to become a growing presence in heat network design [17] and offers an effective example of the performance benefits of GSHPs across seasons [18].

This method of interseasonal storage has been carried out in various formats and is typically achieved by using ground storage using boreholes [19] or even abandoned spaces such as mines [20].

The use of thermal energy from groundwater for building heating and cooling using HPs is not a recent interest [21,22] and looks likely to increase with the decarbonisation of heating [20]. Particular interest has been found in using aquifer water for consistent temperature exchange for high-temperature heat pumps as a replacement for existing boiler installations [4], and others have aimed to use abandoned mine workings as thermal storage for low- and higher-temperature water [20] or to directly use mine water as a potential source of energy for district heating [23].

The efficiency of a 5GDHC using a chiller and large heat pumps is more profitable than a smaller heat pump when used with renewable electricity sources [24] for a district heating system. Projects that have been trialled have been promising and found a consistent COP of ~3 for the systems installed when used with aquifers [4]. In the UK, grid electricity to supply such systems is lower in carbon than fossil gas. The use of heat from mine water has also proven to return a COP of between 5 and 7, showing a reduction in carbon dioxide equivalent emissions of 65% on heating and cooling [20]. Other existing district heating systems using various water sources have achieved chiller system COPs of between 4 and 6 [8].

5GDHCs are therefore a promising option where there is a suitably sized water resource such as an aquifer or mine water to balance the main network's temperature across seasons. The size of the water resource needed depends on how much heat is being added or removed from the work based on the building loads and weather. The case study hospital for this paper does not have any known aquifer or water resource to provide this balancing service. One useful contribution of this paper is therefore to model the concept of using storage or the volume of the steam trunks themselves to hold the mass of water needed to balance the network across seasons. This would, in principle, increase the flexibility with which 5GDHCs could be retrofitted in the absence of a major nearby water resource.

The size of any system is driven by both the total demand across seasons, as well as the peak demand for a given day. The co-benefits of demand reduction through energy efficiency measures are widely documented and non-controversial. These include increased comfort and health outcomes, as well as reduced operating costs. The fabric-first principle is logical and should be followed wherever technically and economically practical. These technical and economical practicalities are case-specific, and so this study will use the case study hospital to explore the effectiveness and viability of energy efficiency measures in this case.

The peak demand can be reduced through the effective use of storage and load shifting. District heating systems can also be used as a form of demand-side response [25] where energy can be stored for use when energy is in high demand or intermittently available. Renewable power generation, by its nature, is an intermittent source and also the direction of future power generation [8]. Intermittency problems will need to be overcome by an active demand side and storage to reduce the problem [26–28]. TRIAD load shifting [29] generally favours using distributed generation at sites that are capable rather than a Demand-Side Response (DSR), resulting in local energy storage being used or equipment turndown of load [30], which overall results in less carbon dioxide efficient electricity generation, which potentially adds more carbon dioxide than any DSR measure could currently reduce.

2. Methods

2.1. Addenbrooke's Hospital Case Study

This paper analyses a case study for an active NHS hospital and considers a range of options for retrofitting the existing heat network into a 5GDHC. The Hospital currently uses fossil fuel systems to produce steam. Feasibility studies have suggested that the steam distribution infrastructure could be reused in a more modern system [31–34]. The site is currently formulating a decarbonisation plan [35] that includes feasibility studies for options to reuse the steam infrastructure. At the time of writing, no decisions have yet been made.

There is currently very little provision for cooling in the Hospital Campus buildings. This is identified as a critical priority for the site's future systems in a warming climate [36]. Any solution faces the practical challenge of ageing existing assets being removed, replaced, or rebuilt, without disruption to vulnerable occupants.

This study has chosen to centre on Building BU07 as it represents the paragon case for these challenges. BU07 is a 1960s concrete building constructed using lightweight flooring, pot and beam, with pre-cast concrete panels suspended from the building's ring beam and brick infill where retrofitted. There is single glazing with original hardwood framing. The patient bays in the wards are south orientated giving good daylight into the building but also leading to overheating complaints in summer [36]. Although heating was the designed consideration of the building only, limited space cooling has been added to the building over the years mainly by the addition of small Direct Expansion (DX) units local to each room where the air conditioning is required.

Firstly, the study makes a broad investigation of the building properties and energy consumption, comparing the energy balance in the winter of a specific year and energy consumption to allow a comparison of the published estimate with the calculated estimate from energy records. Next, the study considers the environmental parameters needed to meet the current thermal environmental guidance set out by the Department of Health Technical Memorandum 03-01 Part A: Specialised Ventilation for Healthcare premises. This will be informed by the heating and cooling demands for the building based on site surveys and the simulation software package from Integrated Environmental Solutions Limited, IES Virtual Environment 2019 Feature Pack 1 (IESVE).

This research will then focus on the optimum combination of components and their viability and efficacy for the purpose of complementing the operation of the proposed system and end with recommendations of what other NHS Estates may need to do to seriously consider such a retrofit.

Note that in practice, there are challenges in costing the options for the Addenbrookes Hospital decarbonisation plan. Following early meetings with the estate's teams, the aim of the current work was to help characterise the technical and practical feasibility of the 5GDHC option. As such, this study does not include costing and carbon calculations but will inform those studies in the future.

2.2. Methodology

This work was carried out over three stages.

2.2.1. Stage 1—IESVE and MATLAB Model

Use IESVE to model hourly building heating and cooling loads. Test impacts of energy efficiency measures. Use MATLAB and IESVE data to assess the most effective Cold-Water Heat Network (CWHN) mass. Lindhe et al. [37] argue that the wider temperature range of the heat source for a 5GDHC system can pose a challenge to the heat pump performance. Practical demonstrations have shown that this can be navigated with effective heat pump design [6]. The current paper takes the approach of considering thermal storage requirements to maintain consistent heat source temperature ranges. This echoes the approach of similar methodologies such as [13], who explored a techno-economic analysis of 5GDHCs linked to borehole thermal energy storage. Their analysis included a range of performance and cost factors but kept some parameters constant such as heat pump efficiency and temperature requirements.

Building inputs were obtained through private correspondence with the campus estate staff and relevant variables detailed throughout the calculations below.

Stage 1 considers good passive systems as a first measure to reduce the capital cost for equipment installation and the revenue cost of the installation, so uses IESVE to assess the most practical passive measures before, or alongside, any heating system conversion. From there, the mass of the ambient water loop within the 5GDHC system (here, termed a cold-water heat network—CWHN) is set to allow sufficient heat exchange and stability year-round, leaving capacity for the addition of future buildings.

2.2.2. Stage 2—Plant Equipment and Storage Sizing

Assess the most effective combination of heat pump and chiller sizing compared to storage and most economical generation times. The capacities of the heat pump and chiller at steps of 1000 kW from the minimum value defined and then varying the cooling and heating system thermal storage from the initial value in steps of 2500 kWh each. At the end of this investigation, a justified proposal for the passive measures is recommended which complies with the expected requirements of the local Building Regulation Office and further work required to take the proposal into a formal design stage. Use these results to explore the impacts of these sizes on operating costs and flexibility with demand response control.

2.2.3. Stage 3—Waste Water Heat Recovery (WWHR) Viability

Assess the viability of using Waste Water Heat Recovery (WWHR) as a part of the 5GDHC system.

3. Results

3.1. Stage 1: IES and MATLAB Model

The IES thermal model was created using building and documentary data provided by the onsite facilities management team, and supplemented with original data obtained by the researchers through direct onsite surveys. The information included the building plans, U-values, HVAC systems details including setpoints and flowrates, installed lighting and equipment data, and occupancy details. From these data, the researchers created a carefully calibrated baseline model that reflects the loads and performance of the building in use.

1. Existing building plans, converted from the original paper drawings to the AutoCAD (.dwg) format that can be converted to .xref for use inside IESVE—provided by Estates Management.
2. Building U-values for external building fabric [38]. (area averaged U-value = 1.2 W/m^{2}K)
3. Building ventilation rates [38].
4. Building heating system [38].
5. General lighting, 9 Wm^2, CIBSE Guide A.
6. People, occupancy 57 W/m^2 (sensible), 4.3 W/m^2 (latent), CIBSE Guide A.
7. Equipment, 3 W/m^2, CIBSE Guide A.
8. Gross internal floor area 236,329 m^2, heat recover throughout).

From this baseline, packages of measures were applied to determine the load reductions achievable through passive retrofit measures:

1. Baseline—no change to building fabric.
2. External insulation.
3. External solar shading.
4. External insulation and solar shading.

The heat pump and chiller loads for the four building scenarios can be seen in Table 1, which shows that installing both solar shading and insulation to the outside of the hospital building would potentially result in a system with the least power consumed.

Table 1. Total boiler and chiller demand simulated in IESVE with proposed building fabric improvements.

	"As Installed" (MWh)	External Insulation (MWh)	Solar Shading (MWh)	Solar Shading and Insulation (MWh)
Boilers	1994.7	1744.8	2035.2	1792.8
Chillers	2224.1	2348.4	2000.1	2117.4
Total	4218.8	4093.2	4035.3	3910.1

Table 1 summarises the results of the passive measures. External insulation gives approximately 3% improvement on the base case, solar shading gives ~4%, and both together give 7%.

External insulation would be a high practical cost and practically challenging to install. The type of insulation that would be installed would be a solid and heavyweight construction with a minimum density of 1400 kg/m^3, which for a 100 mm thickness covering the building's external walls only with an area of 10,470 m^2 would require an additional minimum 1,465,800 kg be added to the building. The constraint in how much insulation can be applied gives a low overall savings, and actually increases cooling demand by trapping gains in the warmer periods.

An external horizontal louvre over each window was used to model solar shading. Based on the modelled results, the solar shading-only option is used from here onwards in this study.

Having chosen the most appropriate IESVE building loads to model, the MATLAB script was then used to determine the required volume of water for the CWHN. The calculated options are summarised in Table 2 below.

Table 2. Cold-Water Heat Network (CWHN) mass calculation results for ΔT and water storage tank dimensions.

CWHN water volume (L)	50,000	100,000	150,000	200,000	250,000	300,000
ΔT (K)	11.76	5.88	3.92	2.94	2.35	1.96
Tank height (m)	0.64	1.27	1.91	2.55	3.18	3.82
Tank diameter (m)	10	10	10	10	10	10

Adding DHW to the IESVE thermal model increased the necessary capacity of the heat pump to 2500 kW, leaving 4% between peak demand and capacity. The calculation method used the binned frequency of the load requirement produced from IESVE, which is also the method used for selecting a chiller capacity of 2000 kW.

The DHW was added to each of the four building external fabric simulations and MATLAB simulations. Including DHW in the IESVE model added a constant heating requirement and resulted in a greater ΔT for the CWHN, although no difference in running cost for the system, as summarised in Figure 2 and Table 3.

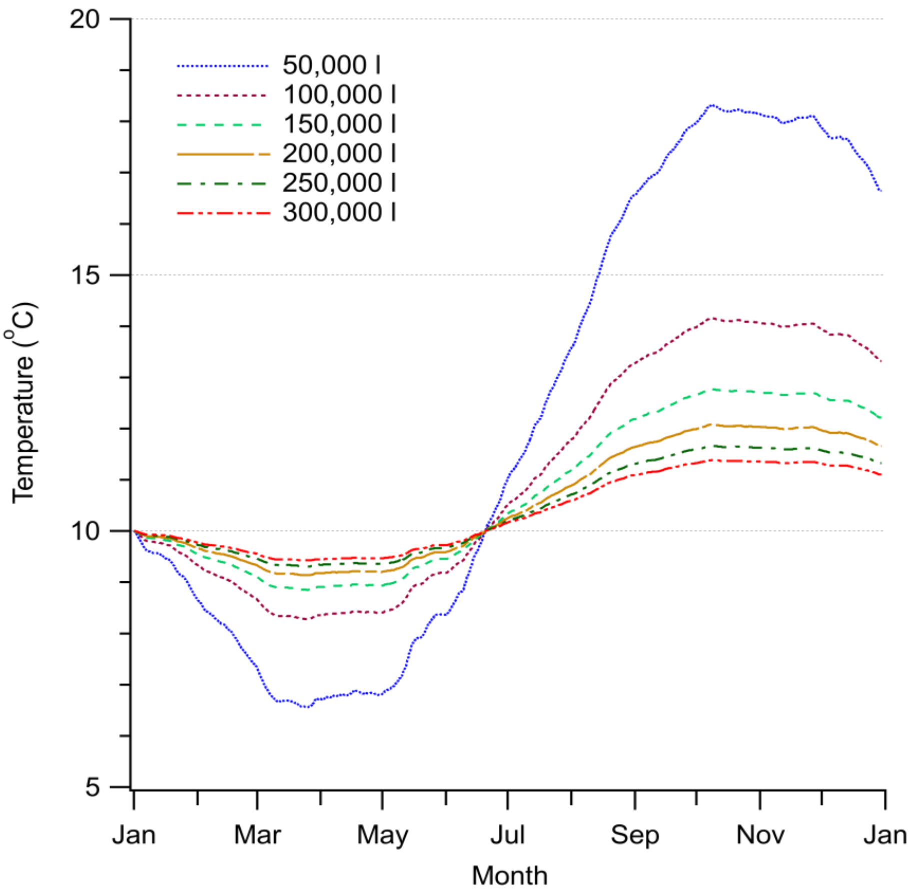

Figure 2. Different temperatures of the CWHN with varying volumes.

Table 3. Stage 2 annual running cost and CWHN ΔT for systems.

	Annual Running Cost (£)	Δ*T* (K)
"As Installed"	237,996	3.33
Insulated	233,661	2.22
Solar Shading	231,605	1.80
Solar Shading and Insulation	227,263	1.93

This resulted in the output in Table 3 demonstrating that the lowest Δ*T* for the CWHN comes from applying solar shading only to the external building fabric. Annual running cost is seen to be the same for the simulation output as the COP of the system has been modelled for both heating and cooling to be three, rather than changing with the CWHN temperature as expected in reality.

Figure 3 shows how the CWHN responds to building fabric modification through the year compared to the "As-Installed" model. The CWHN is modelled as starting the year with a temperature of 10 °C and the "As-Installed" model year ended with a CWHN temperature of 9.60 °C. The Insulated, Solar Shading and Insulated with Solar Shading models had a CWHN temperature of 9.98 °C, 9.22 °C and 9.58 °C, respectively.

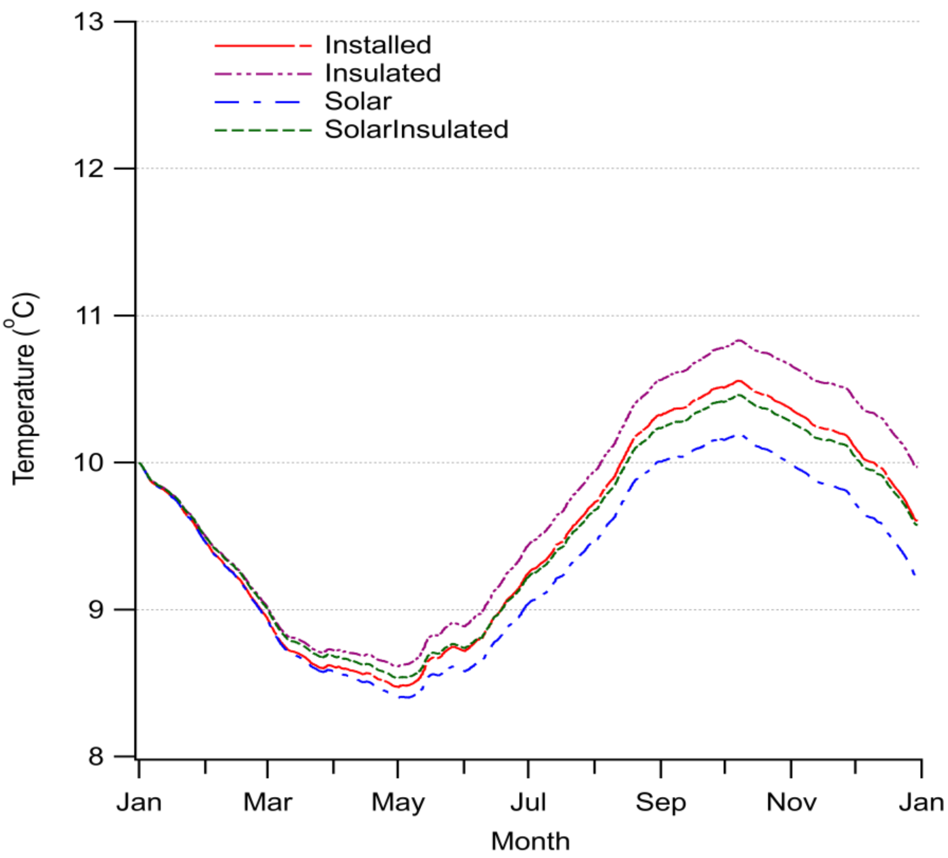

Figure 3. CWHN temperature data for four building fabric scenarios over one simulated year for Stage 2.

3.2. *Analysis Stage 2: Plant Equipment and Storage Sizing*

Having simulated the building fabric scenario and CWHN sizing in Stage 1, Stage 2 now determines an optimal building component combination (see Table 4).

Table 4. Stage 3 design simulation results summary for all nine system scenarios simulated. The base value of Heat Pump and Chiller capacity is 2500 kW and 2000 kW, respectively, with +1000 kW and +2000 kW adding to those base values. System scenario 3aiii showing the lowest running cost over one year and 3aix showing the least power consumed over one year.

System Scenario	Heat Pump and Chiller Capacity (kW)	Thermal Store Capacity (kWh)	Total Electrical Cost (£)	Total Power (kWh)	CWHN ΔT (°C)
3ai	Base	5000	231,605	2,253,266	1.80
3aii	Base	7500	225,832	2,254,933	1.81
3aiii	Base	10,000	223,647	2,274,757	1.82
3aiv	+1000	5000	232,591	2,252,704	1.78
3av	+1000	7500	226,859	2,252,064	1.79
3avi	+1000	10,000	222,123	2,251,213	1.80
3avii	+2000	5000	235,228	2,251,624	1.78
3aviii	+2000	7500	227,271	2,251,562	1.78
3aix	+2000	10,000	222,852	2,250,207	1.79

From the capacity base values set in Stage 1 for the heat pump and chiller of 2500 kW and 2000 kW, respectively, these values were then tested by an increase of 1000 kW and 2000 kW for these systems.

The thermal storage was also tested at values increased from the base energy capacity of 5000 kWh to 7500 kWh and 10,000 kWh. The result of this testing found that the simulation to revenue cost for running the system throughout a simulated year was simulation 3aiii, which combined the base heat pump and chiller values with the increased thermal store energy capacity of 10,000 kWh for both the heating and cooling systems (see Figure 4).

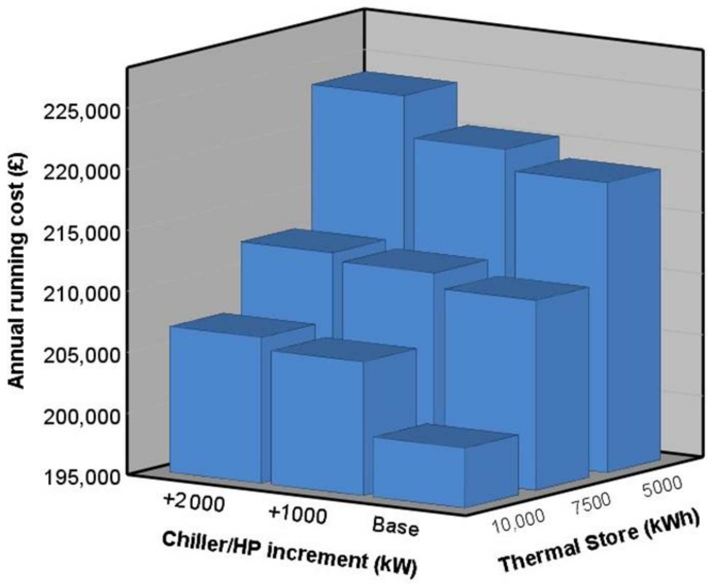

Figure 4. Stage 3 annual running costs of the nine scenarios simulated, showing that the base value for the heat pump and chiller systems combined with the greatest Thermal Store value produce the most cost-effective solution of GBP 199,889. The base value of heat pump and chiller capacity is 2500 kW and 2000 kW, respectively, with +1000 kW and +2000 kW adding to those base values.

This contrasted with the result comparing annual power consumed, where the least revenue cost for a simulated year consumed the greatest energy. The scenario that consumed the least energy was scenario 3aix, which had the combination of the greatest heat pump and chiller capacity of 4500 kW and 4000 kW, respectively, and a thermal store energy capacity of 10,000 kW for the heating and cooling systems (see Figure 5).

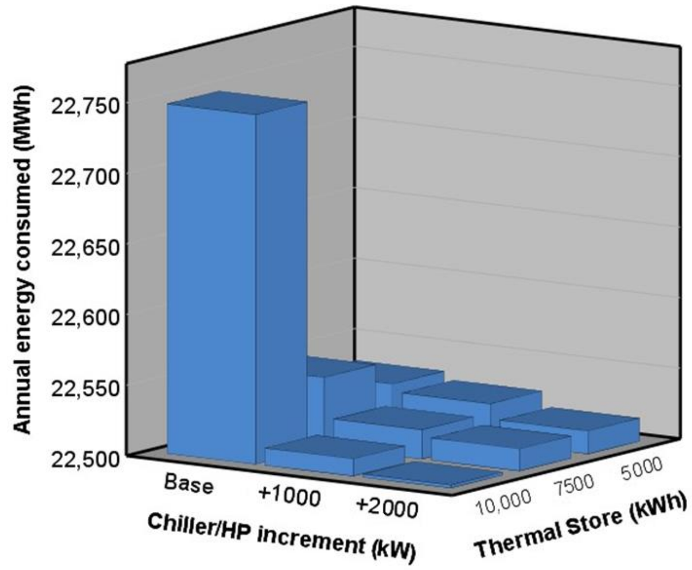

Figure 5. Stage 3 annual energy consumption of the nine scenarios simulated, showing that the 2000 kW increase to the base value for the heat pump and chiller systems combined with the greatest Thermal Store value produces the value of least power consumption of 2,250,207 MWh. The base value of heat pump and chiller capacity is 2500 kW and 2000 kW, respectively, with +1000 kW and +2000 kW adding to those base values.

From an examination of the extremes of temperature (see Figures 6 and 7), we can see that the thermal storage when they had been used from 07:00 had depleted later in the same day before the red Distribution Use of System (DUoS) charge period, which the HP and chiller were then forced to run through. The heat pump (see Figure 6) faces the challenge of sufficiently charging its thermal store, unlike the chiller, as the peak heating demand is seen at night when the store is charging. Scenario 3aiii failed to charge the thermal store owing to insufficient HP capacity, forcing an earlier depletion time in the day compared to the other two scenarios using a 10,000 kWh thermal store. Other simulated days where there was not such an extreme heating or cooling demand had a later depletion time in the day and days in spring and autumn did not require the demand to be met by running the HP or chiller in the red DUoS charge period.

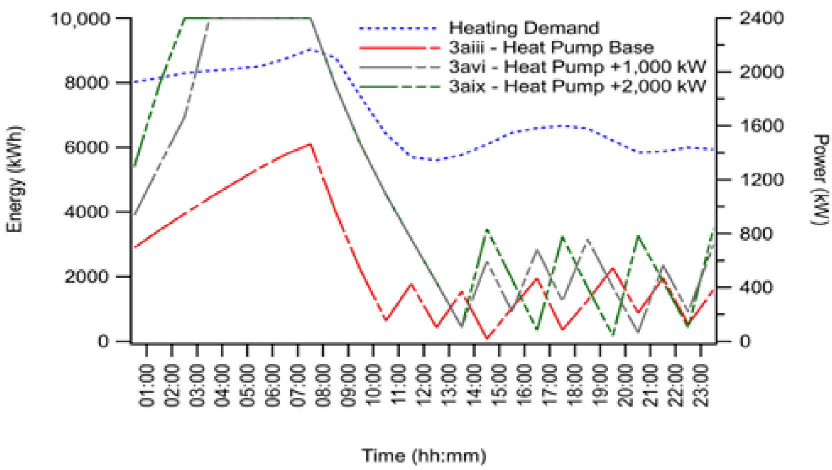

Figure 6. Heat pump system response on the greatest heating demand day, 25 December, is simulated. This shows that the Thermal Store was not fully charged in the low tariff period overnight for the lowest capacity heat pump when the building heating demand was greatest.

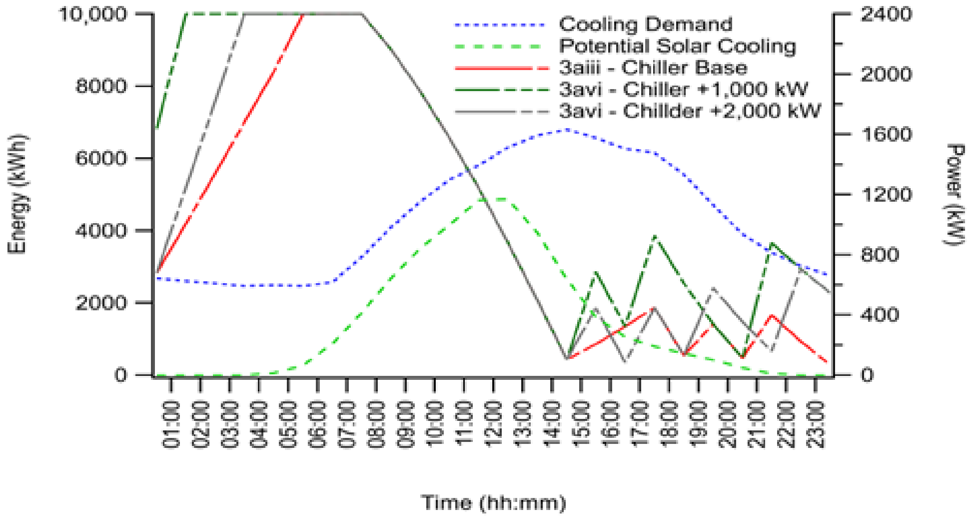

Figure 7. Chiller system response on the greatest cooling demand day, 11 August, is simulated. This shows that the Cooling Store had been insufficiently charged to cool the building through the most costly electricity charge period of the day.

Different to the peak scenarios, if the thermal storage is sufficient size compared to the heating or cooling demand, the demand can be served by the thermal store in the high tariff period during the day entirely (see Figures 8 and 9). Rather than the need to run the heat pump or chiller during the high tariff and, particularly, amber or red DUoS charge periods, all of the load can be served by the heat pump and chiller at a low tariff charge in the night between 00:00 and 07:00.

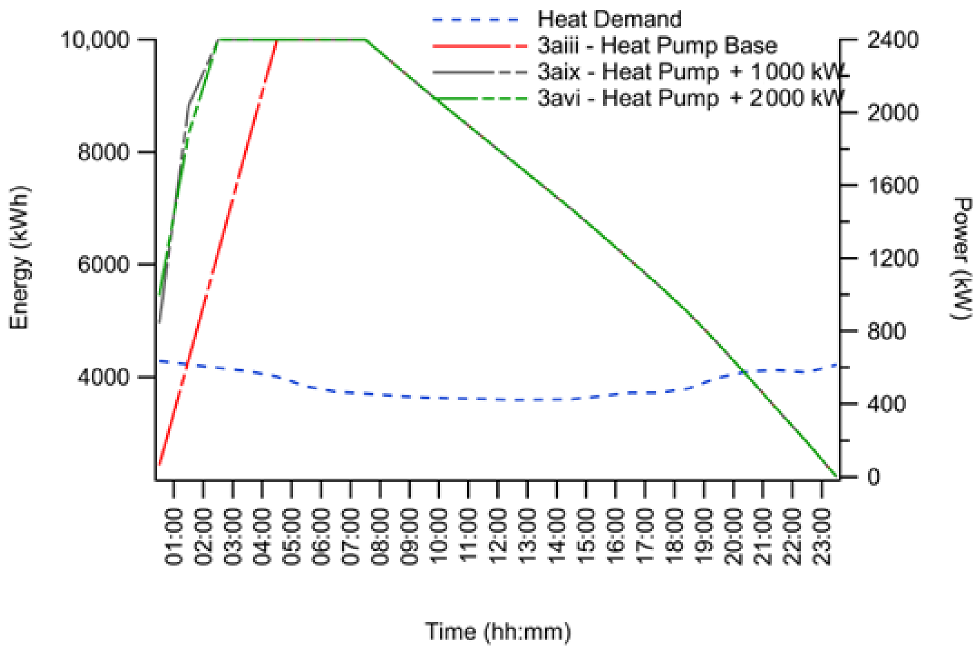

Figure 8. Heating demand met throughout the day entirely by the thermal store without requiring the heat pump to run at all during the high electrical tariff period.

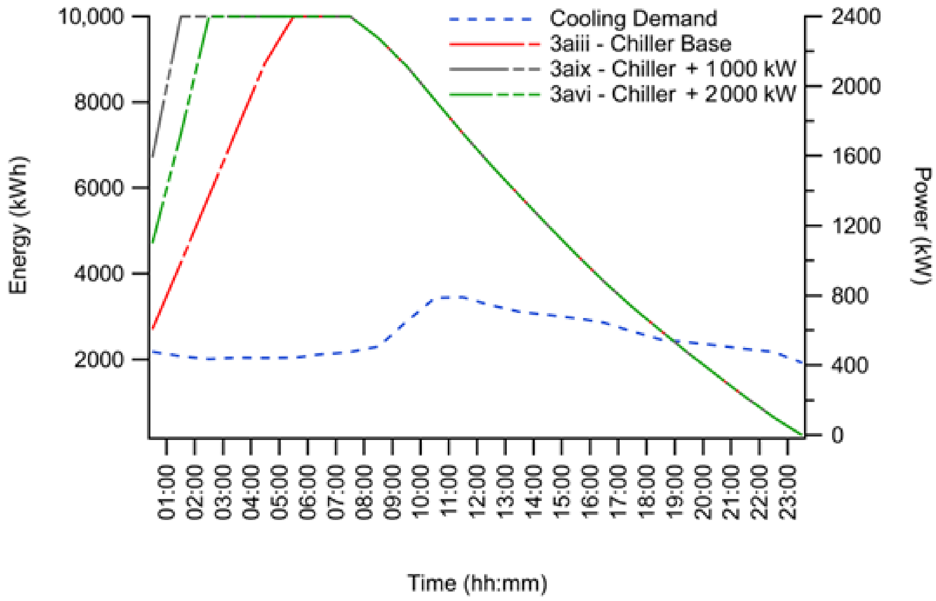

Figure 9. Cooling demand met throughout the day entirely by the thermal store without requiring the chiller to run at all during the high electrical tariff period.

3.3. *Stage 3: Waste Water Heat Recovery (WWHR) Viability*

One of the benefits of a 5GDHC network is allowing a platform to exchange and exploit low-grade heat from sources that would otherwise go to waste. One example is waste water heat recovery.

The MATLAB code was then used to calculate the waste water heat recovery (WWHR) options based on the sizing from the IESVE thermal model. The purpose of using MATLAB rather than an Excel spreadsheet for these simulations was to enable more detailed DSR calculations. That is, power will be consumed as much as possible during low-demand periods throughout the day. These periods are reflected in the tariff price used to make the system running decisions for heating and cooling systems.

During the high tariff, the thermal storage is depleted throughout the day until the heat pump or chiller must run. The heat pump or chiller will run for one hour at full load as it is desirable not to run at part-load conditions [39], which will then partly charge the thermal store in the process.

When the tariff is low, the heat pump will run to maintain the maximum value of the heat store. It runs at full load in each hour of low tariff until the heat store maximum value is reached and then only serves the Domestic Hot Water (DHW), Constant Temperature (CT) and Variable Temperature (VT) circuits at part load.

WWHR options have been calculated using the below assumptions:

1. Blended water (half raw and half softened water) is only used for Domestic Hot Water (DHW).
2. Cold-Water Down Service (CWDS) is 10 °C at the point of use.
3. DHW used is 80 °C at the point of use (note, this is to match existing infrastructure and future operations should seek to reduce this set point.)
4. All water used is reduced to 41 °C at the outlet.
5. Meter readings supplied from the hospital are all accurate where available.
6. It is reasonable to estimate the water volume used, where the meter has failed, with an average value taken from available data.
7. All site blended water is used for the WWHR calculation.

There is more than one drain removing the waste water from the hospital and also a fixed temperature that patient, staff and visitor washing facilities must meet. Given this information and meter data, it is possible to make a reasonable estimate of the combined cold-water flow and the washing outlet water flow to the drain at the potential location of a WWHR unit. The waste water temperature that can be returned to the main sewer is assumed to be the same as the CWHN circuit, giving a monthly estimate of the WWHR that could be recovered into the CWHN.

The results in Table 5 suggest that this would be a good measure for a primarily heating-dominated system. Furthermore, given that the Domestic Hot Water (DHW) value has been modelled at a constant heat load [8] for design within IESVE, it would be unlikely that this load would be this high or constant, so the difference between HP and chiller loads might in reality reduce further, making it possible that the CWHN would not have required additional energy, and that the WWHR could have provided from 30 October to preserve a temperature of 10 °C. In brief, while the sums in Table 5 represent a significant and useful fraction of heating demand at face value, only a fraction of this value could be practically exploited.

Table 5. Potential monthly WWHR by calculation, which could be added to the CWHN.

	Total Site Water (m^3)	WWHR (kWh)
June 2019	26,105	157,975
July 2019	33,655	158,871
August 2019	30,193	182,288
September 2019	37,295	182,288
October 2019	16,094	182,288
November 2019	28,795	182,288
December 2019	26,987	182,288
January 2020	29,064	182,288
February 2020	25,319	165,470
March 2020	28,872	182,288
April 2020	22,019	229,589
May 2020	23,816	219,160

4. Discussion

Evaluation of the CWHN requires two criteria at the hospital to be satisfied: 1. the most stable system volume, and 2. physically siting the system on the hospital site. Information was gathered from MATLAB so as to ascertain the appropriate volume of water for the CWHN. To arrive at a CWHN volume that offers system stability over one year of supply, a low-temperature heat source in the form of aquifer water with a variation of approximately 2 K is used to provide a stable COP for a similar system [4]. With regard to the physical location of the tank, two areas of approximately 10 m in diameter are identified for placement in Figure 10. The result of this stage is that the CWHN volume should be set to 200,000 L. This volume is derived from a direct calculation using the initial data produced by MATLAB (version 9.10). The choice of 200,000 L for the CWHN shows that a 2.94 K differential temperature can be achieved, assuming a perfectly insulated system.

Location A shows a CWHN tank location that could be situated underneath a car park to the side of an existing building. Location B shows the possible location of the CWHN tank alongside the WWHR unit that could be sited at the larger foul drain location as it exits the hospital site. The plant room location does not change and is alongside the existing heating plant for the building. The building modelled for this case study is shaded blue. The blue boundary line is the hospital land boundary.

Having selected the CWHN mass in Stage 1, and then confirmed the most sensible fabric consequential improvement for the building and investigation of WWHR usefulness in Stage 2, in Stage 3 we investigate the consequences of changing the system capacities of the heat pump and chiller system and the thermal storage and examine their efficacy. A discrepancy between running cost and energy used has been found through an examination of the data returned from the simulations. It seems offsetting the running of the heating and cooling systems with the thermal store is effective in reducing the running cost over a year, although the design decision would need to be made about whether the thermal store should be sufficient for the thermal demand of all of the high tariff parts of a day (17 h) on the highest forecast thermal demand days or if the thermal storage should cover a set majority of the daily demand to allow for system running in the amber Distribution Use of System (DUoS) charge times to avoid the red DUoS charges.

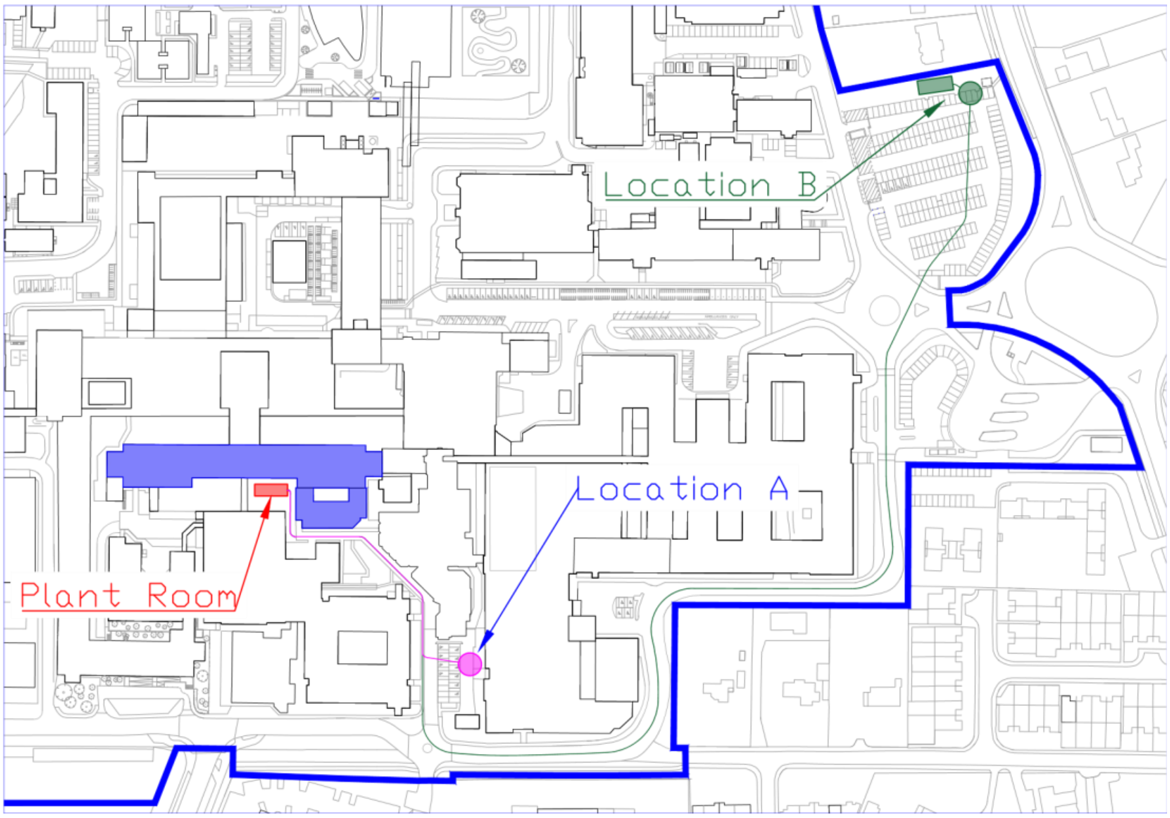

Figure 10. CWHN location on site and Waste Water Heat Recovery (WWHR) option.

On the coldest simulated day (see Figure 11), the heat pump system needed to charge the thermal storage while experiencing the peak heating demand for the building, which only allowed scenario 3aiii with a base capacity to charge to 3481 kWh during the low tariff period and so needed to run through the day, unlike scenarios 3avi and 3aix where the thermal store had completely charged and depleted by 15:30 in the same day, requiring the heat pump to run during the red DUoS charge period. For 25 December, the system costs for the day were GBP 1126.99, GBP 1059.09 and GBP 1003.64, and for 29 December GBP 366.52, GBP 305.72 and GBP 348.90, each with respect to scenarios 3aiii, 3avi and 3aix. This suggests that for the heat pump, a larger system at more extreme temperatures is more beneficial, whereas when the heating demand is lower, a lower capacity system is more financially beneficial.

With regard to cooling, a similar result is seen in the system response to heating, except the peak demand is now when the thermal store is depleted during the day (see Figure 12). On the peak cooling day, the system costs for the day were GBP 1128.45, GBP 1131.04 and GBP 1166.75, and for a similar day, see Figure 12, they were GBP 554.45, GBP 516.24 and GBP 545.02, all with respect to scenarios 3aiii, 3avi and 3aix. This shows that for more extreme temperatures, the larger chiller shows a greater running cost, whereas, for a day of reduced cooling, the load had the same relation as is seen with the HP, in that the lowest running cost is found with a reduced capacity for the chiller. It is seen that examining the individual HP and chiller systems shows that there is a reduced cost for using a system of increased capacity as simulated in scenario 3aix as the thermal storage can be recharged more quickly after depletion, although for the other six scenarios, we have seen that a smaller store will mean that the thermal storage is depleted earlier and the result is that if the HP and chiller run, it is nearly exclusively at the red DUoS time charge and peak tariff charge between 16:00 and 19:00.

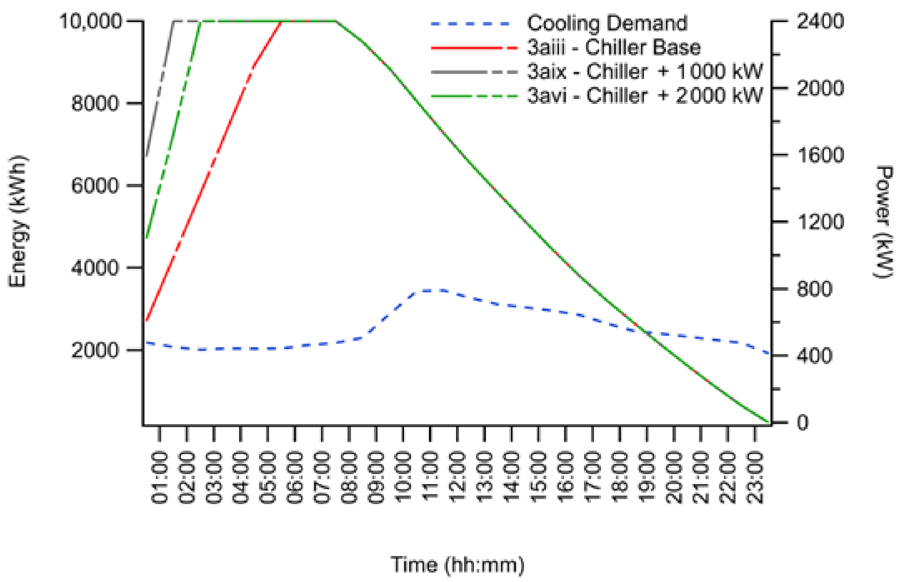

Figure 11. Stage 3 thermal store value comparison for the coldest simulated day. The thermal store value of 10,000 kWh is used for Heat Pump (HP) system capacity of the base, +1000 kW and +2000 kW (3aiii, 3avi and 3aix, respectively). This shows the thermal energy depletion throughout the day from the thermal store requiring the HP to start running at the least cost-effective, red Distribution Use of System (DUoS) charge time of day.

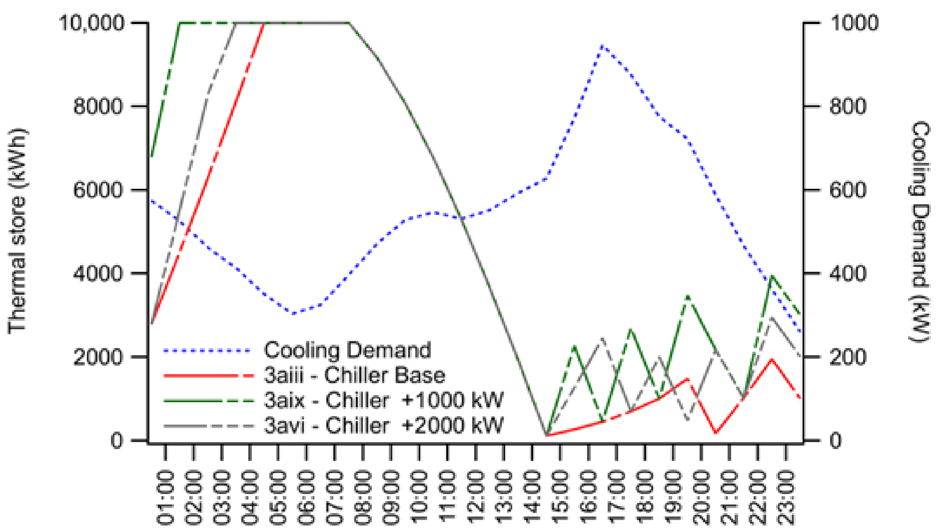

Figure 12. Stage 3 thermal store value comparison for the hottest simulated day. The thermal store value of 10,000 kWh is used for the chiller system capacity of the base, +1000 kW and +2000 kW (3aiii, 3avi and 3aix, respectively). This shows the thermal energy depletion throughout the day from the thermal store requiring the chiller to start running before and through the least cost-effective, red Distribution Use of System (DUoS) charge time of day.

With regard to energy consumption, larger systems typically consume less. System scenario 3aiii required the greatest power consumption of all nine scenarios and scenario 3aix the least of the nine scenarios.

Comparing individual days' power consumption similar to the cost as before demonstrates that on the peak cooling day, the power consumed was 10,980.28 kWh, 11,605.06 kWh and 10,877.00 kWh (relative to scenarios 3aiii, 3avi and 3aix), demonstrating a peak power requirement in the middle chiller capacity of 3000 kW, unlike the HP system, which showed a correlation between the increase in HP capacity and reduction in peak day running cost.

For the base capacity of the chiller, it seems that when the thermal store is depleted, the thermal store is not at any point charged enough to be used independently again until the low tariff period, whereas the chiller of 4000 kW could use the thermal store intermittently as it had sufficient capacity to charge the store in one hour and serve the load to do so. The scenario in between at 3000 kW did neither successfully with the parameters provided within the script, which implies that with further work, there is a breakpoint where charging a thermal store is less efficient than not attempting to do so. For a similar day, which was approximately half of the cooling load, see Figure 12, this showed the same dip in consumed power as it did for the heating system for a similar load.

The increased cost of running would appear to be attributed to the amount of energy that an hour of runtime for the HP or chiller can produce at higher capacities after the thermal store is depleted during the day.

Demand on the HP and chiller system, if varied with a modular configuration of multiple units feeding into a common header with inverter drives, could reduce the running cost, but larger thermal storage in the order of 36,082 kWh and 25,052 kWh for heating and cooling for the 17 h period would have been most beneficial as this will remove the need to use HP and chiller system during the combined peak DUoS and tariff period but also require a substantially larger capacity HP and chiller.

Oversizing thus leads to reduced operating costs due to not only shorter operating times (as is typically the case) but also due to the increased ability to more fully exploit variability in price signals and demand response opportunities. Oversizing has well-known disadvantages including increased capital cost, control challenges and space constraints. This study shows the impact of the operational factors as relevant to a 5GDHC system. The strengths and weaknesses of these oversizing options should be considered at the design stage for a given project.

5. Conclusions

The proposed 5GDHC is a novel heat network capable of utilising poly-generation for the addition of energy which can be stored for interseasonal use. Although the network model used set the COP to three, a supply that has been tested in some systems has been shown to achieve a COP of up to seven [20] for a heat pump, and this may be similarly achievable for chillers using the principle of interseasonal thermal exchange.

This paper contributes to the growing body of case study evidence exploring the parameter space for which 5GDHC systems offer a viable decarbonisation option as we phase out fossil fuels for heating. Specifically, it explored the application of a retrofit in a densely occupied hospital campus scenario, for which there is no aquifer option as a balancing mechanism and limited scope for fabric improvements.

The first point of the modelling created a Cold-Water Heat Network (CWHN) system to act as the balancing mechanism for the 5GDHC in lieu of an aquifer or other naturally occurring water source. The analysis found that a single insulated mass of water can be used to support NHS inpatient ward buildings in the existing building stock where ground-source heat pumps cannot be utilised. Different from groundmass thermal storage, the modelled 5GDHC has the advantage of being deployed in a relatively small area on an existing site which would not require reliance on an available aquifer or where there is no other organisation that is currently using the space for the same purpose to cause a conflict.

The CWHN is modelled with a starting temperature of 10 °C, which is the average temperature of the ground that the majority of the CWHN would be sited in. The energy used would be reduced compared to the delivery of energy in third- and fourth-generation heat networks [40] and could be thought of as a neutral thermal loss [8] as this system has been modelled. This novel fifth-generation heat network produces the lowest thermal loss for the transport of heat around a district.

The 5GDHC is by definition the first to require substations [8,40] as opposed to a central energy centre which produces energy to be used at the point of use at other parts of the district. The CWHN will provide the ability for heating and cooling to each substation on a retrofit basis to existing building stock and supply high-temperature hot water in the range of 70–80 °C to existing heating and DHW systems at the same time as serving new buildings with far lower heating requirements with the decentralised DHW and chiller systems as modelled here.

Unlike the typical centralised plant room or energy centre model, the novel CWHN as part of a 5GDHC could be deployed incrementally to each building on an existing hospital site and could be retrofitted to existing building stock.

The model also showed that over a 12-month period, the existing building stock did not significantly benefit from thermal insulation as a cost-effective energy-saving measure. This was also less practical from an implementation perspective given site constraints. The fabric-first approach is logical for a host of reasons and should be pursued wherever feasible; however, this study supports a growing literature that while beneficial, fabric measures are not always a prerequisite to the decarbonisation of heat.

This study also explored the use of demand-side response as a balancing option to utilise the CWHN and other thermal storage and found this could be practically applied to the NHS building stock to satisfy service needs. Oversizing both the plant and storage options led to reduced costs due to reduced operating times and a better ability to charge storage assets during favourable pricing windows. These benefits would have to be weighed against negatives such as increased capital costs during project design. Mass energy storage has proven to be a fruitful concept that has gone from pilot to full-scale production in other systems, where energy clusters have been used when the rejected energy has been planned for use in the first stage in a different building before calling on a larger thermal store [20], which proves that controls, as much as energy storage, make recovered heat a feasible concept for a 5GDHC.

Finally, it is useful to close with a brief summary of the practical implementation factors that give context to this particular case study and its generalizability.

This system has been designed in mind of being retrofitted to an existing hospital estate's building stock. It would be possible to retrofit this system whether a network shutdown was possible or not. A packaged plant room and thermal storage—ideally installed in the ground in a bunded chamber possibly directly beneath the packaged plant room—could be installed alongside the existing plant room and valves installed live into the existing pipework to be connected to this new system. This would inspire confidence in Estates Management that a contingency plan of putting the existing system into operation could be achieved if required. The CWHN itself requires space to run the pipework, which would be sized for the building demand for each site. The tanks required to store the large mass of water could be purchased and sunk into the ground to reduce the risk of flooding if the integrity of the tank failed and also to reduce the need for insulation dependence. There could be numerous tank installations should space be limited or the network itself be expanded. This mass of water could also be installed in the footings of any new building.

An air source solution was not modelled for the reasons described above, namely, space constraints and variability of the performance due to site density and seasonal issues. Air source heat pump performance is rapidly evolving and would offer capital cost savings over the ground-source options explored in this paper. There are many sites in the UK for which spatial constraints and in-use factors will severely limit the range of options for decarbonising heat at scale. This paper explored some of these factors but further studies should seek to expand on this work considering a wider range of heat pump types and lifecycle costings and whole-life carbon considerations for 5GDHC networks.

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