

Millar, M.-A., Yu, Z., Burnside, N., Jones, G. and Elrick, B. (2021) Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks. *Applied Energy*, 291, 116672.

(doi: [10.1016/j.apenergy.2021.116672](https://doi.org/10.1016/j.apenergy.2021.116672))

This is the Author Accepted Manuscript.

There may be differences between this version and the published version. You are advised to consult the publisher's version if you wish to cite from it.

<https://eprints.gla.ac.uk/234558/>

Deposited on: 13 April 2021

Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks

Michael-Allan Millar^{a,*}, Zhibin Yu^a, Neil Burnside^b, Greg Jones^c, Bruce Elrick^c.

^a James Watt School of Engineering, University of Glasgow, Glasgow, G12 8QQ

^b Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, G1 1XJ.

^c Hoare Lea, Highlander House, Glasgow, G2 7DA.

Abstract

Mass adoption of renewable heating is essential for achieving Net Zero 2050 emission targets. Rapid decarbonisation of heating could be delivered by 5th generation district heating networks, which share heating and cooling and offer energy, cost and carbon savings. We present an assessment framework for determining the economic, operational, and carbon benefits of heat pump driven energy sharing networks for an urban centre. Our analysis of complementary heating and cooling loads enabled novel identification of the building types which are best suited to thermal energy sharing. An urban street was modelled using Integrated Energy System Virtual Environment software, which produced heating, cooling, and hot water loads. These were implemented into a linear programming cost and carbon optimisation problem, producing operating curves for a pool of de-localised heat pumps under either cost or emission minimalization scenarios. Results show that energy sharing networks may reduce the Levelised Cost of Energy by 69% and carbon emissions by 13% when compared to an electrified non-shared energy system. Based on these findings, a load matrix was constructed to identify which energy loads from different building types can be suitably used for energy sharing. Despite promising cost-savings results, we conclude that low temperature district heating networks have much greater financial benefit when utilising appropriately sized thermal storage and time of use tariffs, rather than energy sharing. However, carbon savings can be made over alternatives, such as natural gas boilers. For developers undertaking a heat network project, the primary goal should be clearly defined as either carbon saving or money-making objective, as these are difficult to achieve synergistically.

KeyWords: district heating; 5th generation; energy sharing; linear optimisation

Symbol	Description	Units
C	Cost	GBP
HP	Heat pump	-
LCOE	Levelised Cost of Energy	p/kWh
Q	Thermal Energy	kW
TESC	Cold side thermal store	-
TESH	Hot side thermal store	-
TOUT	Time of use tariff	-
<i>Subscripts</i>		
C	Cold side	
Dem	Demand (heating/cooling)	
H	Hot side	
I	Energy to storage	kWh
J	Energy directly to demand	kWh
K	Wasted energy	kWh

Offset	Shared energy	kWh
TESC	Thermal Energy Storage -- Cold	
TESH	Thermal Energy Storage -- Hot	
<i>Superscripts</i>		
inv	investment	
rev	revenue	

1.1 Introduction

Climate change has far reaching consequences and can only be mitigated by concerted global efforts. The current lack of international consensus is problematic for taking effective action. The UK emitted the equivalent of 460 million tonnes of carbon dioxide as greenhouse gases (GHGs) in 2017, with almost 40% from natural gas used for heating [1]. It has legally binding commitments to reduce GHGs to Net Zero by 2050, making decarbonisation of the heating sector a key priority [2, 3]. UK 1st and 2nd carbon reduction targets (budgets) have been met, the 3rd is on track, but efforts to meet the 4th by 2027 are lagging [4]. As part of a government carbon plan, the UK has committed to development of district heating networks (DHNs) and determining the likelihood of mass electrification of heat [5]. This poses an interesting opportunity for 5th generation heat networks, which combine mass electrification, heat networks and energy sharing between buildings.

DHNs in the UK are fairly uncommon, providing only 2% of overall UK heat demand [6]. Almost 90% are supplied by natural gas boilers and Combined Heat and Power (CHP). This may have been a good alternative to coal in the past but as more coal fired power plants are decommissioned and renewables enjoy increasingly wide scale penetration, the carbon intensity of electricity is projected to fall below that of natural gas by 2035. Some estimates suggest electricity will be as much as 140gCO₂/kWh lower than natural gas by 2050 [7]. This will encourage the electrification of heat, moving away from natural gas boilers towards direct electric heating and electrical heat pumps. The majority of operational DHNs in the UK are largely 3rd generation (3G) networks [8, 9], with high supply temperatures (circa 90°C) [10], high thermal losses [11], and are difficult to manage [12, 13]. It has been shown on many occasions that reducing the supply temperature and incorporating a larger share of low-grade heat into DHNs can offer improved efficiency but will still face many of the same challenges as 3G DHNs [14-19]. These problems include high thermal losses (particularly in low population density areas), few connections to the network (connection uncertainty), and difficulty in procuring usable low-temperature sources. These challenges could be addressed by 5th Generation (5G) DHNs which allow heat and coolth to be exchanged across a network via an ambient loop, allowing lower distribution temperatures (and therefore lower thermal losses) and reducing connection risk through a “plug and play” approach.

DHN research in the past has largely focused on methods to reduce the supply temperature for 4th generation (4G) applications. Østergaard and Lund [20] present a proposal and technical method for Frederikshavn (Denmark) to become a 100% renewable city, utilising low temperature geothermal energy in a DHN. Gadd and Werner [21] analyse low temperature substations for fault detection. Østergaard and Svendsen [22] define the need to replace critical heat emitters in secondary distribution, Best and Orozaliev [23] suggest an economic benefit to “ultra low temperature” networks over low temperature networks.

In more recent years, the research focus has moved away from reducing the supply temperature and towards smart energy networks. A key part of smart energy networks is demand side management (DSM). Cai, Ziras [24] provide mathematical modelling to optimise heating demand response on a CHP heat network. Wang, Hu [25] create a CHP dispatch optimisation based on retail energy markets, and Saletti, Zimmerman [26] propose to optimally manage the state of charge in heat networks for peak reduction in a CHP network. Many of these studies have focused exclusively

on using CHP. It is expected that the uptake of CHP will be greatly reduced in future due to the challenge in decarbonizing these systems.

The reduction in supply temperature and inclusion of smart demand side management has allowed waste heat recovery to be considered in more detail. Bühler, Petrović [27] evaluates through spatial analysis the potential for waste heat to be used in DHNs. Broberg, Backlund [28] studies the untapped potential for industrial excess heat in Sweden. Weinberger, Amiri [29] show the economic and environmental benefits of heat recovery for a case study in Sweden. Much of the current literature on waste heat recovery focuses on one waste heat source (e.g. data centre, CHP exhaust) being delivered through the main heat network to the end users. However, there is also scope for decentralised prosumer thermal energy sharing as well.

There have been several terms coined for thermal energy sharing networks; examples include “Cold District Heating Networks” [30], “Bidirectional low temperature networks” [31], and “Peer to Peer Network” [32]. Each definition has subtle differences, which has caused some disparity within literature. For the purpose of this study, we describe a thermal energy sharing network as a “5th generation district heating and cooling network”. We give details of what we have included in our definition, below.

1.2 5th Generation District Heating and Cooling

For the purpose of this study, we define a 5th Generation District Heating and Cooling Network (5GDHCN) as having the following key points:

- A significant number of end users capable of prosuming heat and coolth
- Energy is distributed via a low (ambient) temperature distribution loop
- Low grade thermal sources used to buffer the ambient loop.

Additionally, many proposed 5GDHCNs will utilise a decentralised pool of two-directional heat pumps which can provide both heating and cooling to the end user. This is largely in accordance with the definition provided by Boesten, Ivens [33]. It is acknowledged that this definition is flexible and evolving, but for the purpose of this study we use this definition.

Bünning, Wetter [31] discuss the concept of operational control in 5GDHCNs, using dynamic modelling based on a set temperature in the distribution loop. The case study is used to test performance of the novel control algorithm, but limited discussion is given around the importance of the energy sharing demand profiles. Revesz, Jones [34] give a detailed techno-economic and feasibility study for a case study in London, UK. The study focuses primarily on the case study, and offers useful insights, but uses a limited and less common combination of demand profiles. Similarly, Murphy and Fung [35] present a techno-economic case for energy sharing between a data centre and a single apartment block. In principle, this case is a 5GDHCN but as the scheme is fairly small, is excluded from our definition. In the future, this may be classes as a “5th generation communal district heating and cooling network” as the modern equivalent of 3rd generation communal networks. Boesten, Ivens [33] describe an energy sharing network for the case study of the Mijwater system in Heerlen. The contribution discusses the definition of 5GDHCNs but does not give any technical insight to the performance drivers of these networks.

To our knowledge, there are currently no wide-scale applications of these systems. However small systems are both in operation and under construction. One of the first in the UK is present at the London South Bank university, which uses a cold water network to exchange heat between two tower blocks and is supported by aquifer thermal abstraction [36]. This is an example of an integrated system which uses thermal storage, smart demand side response and time of use tariffs to minimise the effect electrification of heat can have on the national electrical grid. This example showcases the key requirements of a 5G heat network but is unclear how this model could be replicated in more diverse end user groups or with a different asset owner. Until now, DHNs have been a purely consumer driven market, with heat flows in one direction from the energy centre to the consumer. This is the sensible solution when the heat source is from chemical conversion (e.g. natural gas or biomass), but if an electrified heating market is established, heat pumps become the sensible option. When using heat pumps in heating mode, heat is abstracted from a lower

temperature source (e.g. air, ground, rivers), making the source colder. This produces offset coolth which could be used to meet the cooling load of another building. This would require the energy sharing buildings to be hydraulically connected through a heat network. If the temperature of this network is kept low (circa 20-40°C) then a 2-pipe system could be used with a heat pump to provide either heating or cooling, removing the need for a 4-pipe system, while reducing thermal losses dramatically when compared to 3G networks. However, as the temperature is so low, each building or subnetwork will require its own heat pump to boost the network energy carrier to the required temperature.

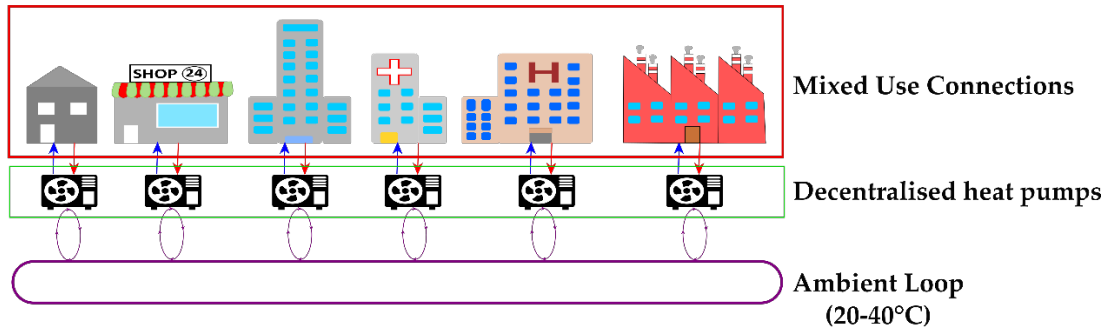


Figure 1. Schematic of potential 5th Generation Heat Network with mixed end users with different load profiles, a group of decentralised heat pumps all connected hydraulically via low temperature, “ambient”, network.

Although 5G DHNs are being encouraged via government supported trials, it is unclear of the technical or economic feasibility of these systems for larger applications. This will have significant implications for investors and will make uptake unlikely due to the uncertainty.

1.3 Novel Contributions

Previous studies have evaluated very small scale thermal energy sharing (i.e. no more than two energy sharers) [35, 36] with a very limited number of thermal demand profiles; typically residential buildings, and others have considered commercial sub-let space as a microgrid [37].

The current literature has considered the implications the of electrification of heat may have; some studies have focused on managing the end user electricity demand [38], other studies have presented a top-down model of electricity network interactions [39], and further works have propose power to heat scenarios during curtailment periods [40]. While these studies have importance in energy sharing, they do not discuss in detail true thermal energy sharing via hydraulic connection. There are currently no studies which evaluate the benefit of 5GDHCNs over traditional networks, and there are no studies which evaluate the key drivers to a successful energy sharing network.

It is proposed that this paper will address the knowledge gaps discussed above. The paper presents a detailed analysis of complementary heating and cooling loads that implies which building types may be well suited to thermal energy sharing; this has not been addressed in literature prior to now.

The findings are presented with comparison to traditional heat networks and assess the economic and carbon benefits of each case. This is achieved through a multi-objective Mixed Integer Linear Programming (MILP) optimisation dispatch problem, where the objective is to minimise both capital investment and operating cost, which is similar to the methodology proposed by Akter, Mahmud [41]. We produce heating and cooling load profiles from Integrated Environmental Solutions Virtual Environment (IES VE) for a busy, mixed use street in the UK. This is used as a basis for equipment selection, including heat pump capacity and Thermal Energy Storage (TES) capacity.

The contributions of this paper are therefore to:

- Propose a framework for assessing the economic feasibility of 5th generation energy sharing networks

- Provide a comparative analysis of technical metrics between traditional networks and energy sharing networks.
- Identify the significance of tariff structure on an energy sharing network design and demand response strategy.
- Identify the importance of key design metrics on the ability to share thermal energy between buildings
- Identify the economic and technical benefit energy sharing networks may have
- Assess the compatibility of different building usages to offer complimentary heating and cooling loads

1.4 Paper structure

The remainder of the paper is organised as follows. Section 2 describes the mathematical modelling and optimisation framework. Section 3 gives the metrics used for comparison between scenarios. Section 4 gives details on the case study used. Section 5 is the results and discussion. Section 6 gives the limitations of the study. Section 7 is the conclusions, and Section 8 gives the proposed future work.

2 System Description

In a perfect 5G heat network, all of the shared heating and cooling would be utilised. This is not possible due to system losses, response time and load matching challenges. The system is designed that each user has a heat pump which can operate either in heating mode or in cooling mode, supported (when necessary) by large scale energy source (e.g. ground source, mine water). For this study, heating is inclusive of domestic hot water (DHW) (e.g. Total heat demand is space heating plus DHW). The system is modelled from a network operator perspective, with one aggregate hot-side demand and one cold-side demand for the network to respond to. In practice, this could be multiple end user heat pumps or heat pumps in distributed substations; for our study we assume the aggregate demand is equivalent regardless of the heat network distribution choice.

The hot-side heat pump abstracts energy from the ambient loop and will upgrade this to a higher-grade heat using electricity. This heat can either be utilised immediately by the demand, or it can be stored for later use. As the heat pump produces heat, it will also produce coolth from the evaporator which can be shared via the ambient loop. This coolth can either be used immediately to meet the cold-side demand, can be stored for future use or can be wasted.

The cold side heat pump rejects heat to the ambient loop, absorbing coolth, to provide a cooling effect using electricity. In a similar manner to how the heat is used in the hot-side, coolth can either be sent direct to demand or stored for later use. As the cold-side heat pump produces coolth, it will also produce heat from the condenser which can be shared via the ambient loop. The heat can either be used immediately to meet the hot-side demand, can be stored for later use or can be wasted.

It is anticipated that the smart management of loads and energy sharing will keep the ambient loop temperature approximately constant, allowing the utilisation of low grade energy sharing. This is summarised diagrammatically by Figure 2.

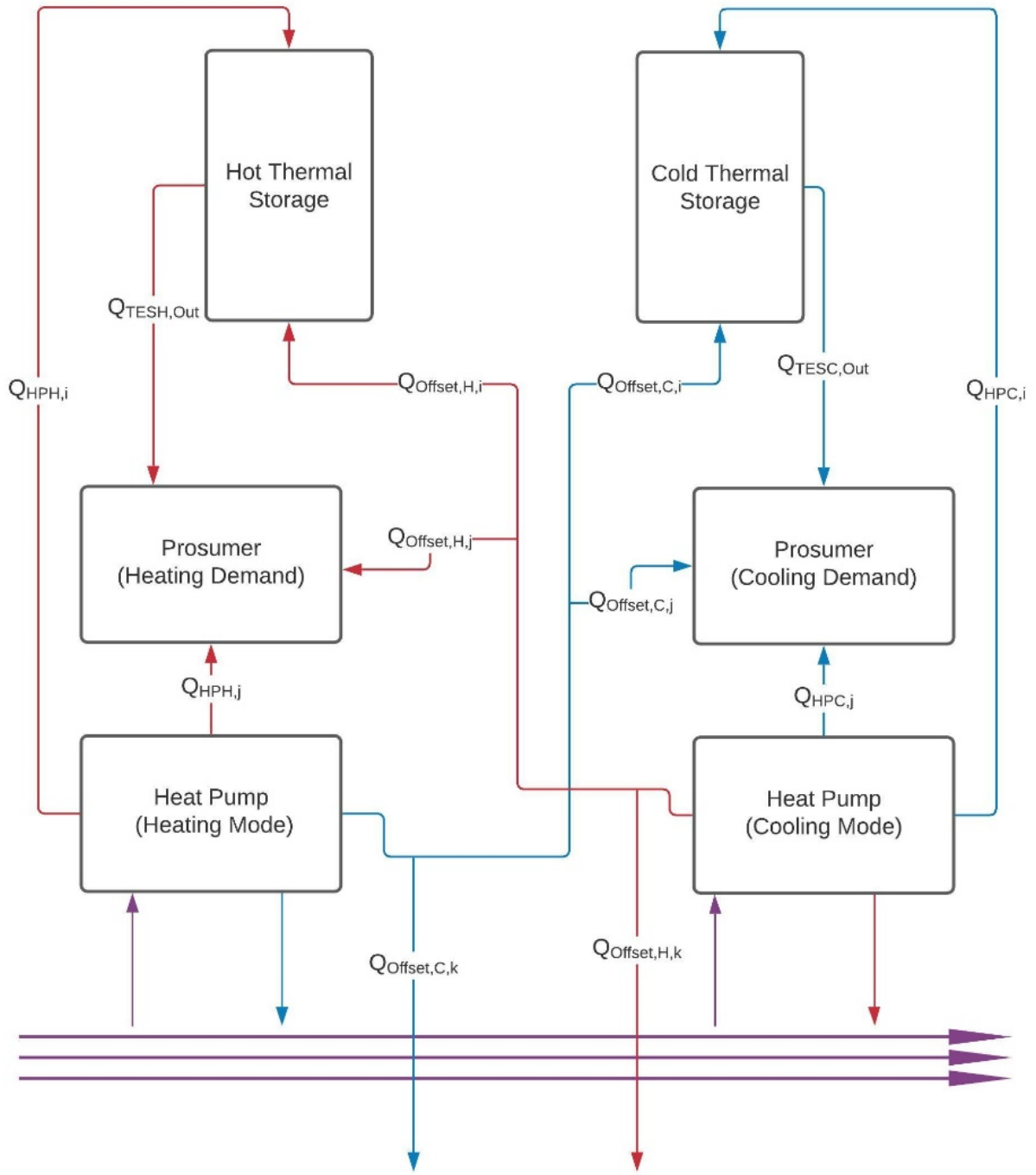


Figure 2. Block diagram of modelled 5G DHN. Each prosumer can abstract or reject energy to the network, and is able to share with other prosumers connected to the network

2.1 Optimisation Framework

The objective of the optimisation is to maximise the Net Present Value (NPV). This is achieved using a mixed-integer linear programming (MILP) problem which, designed to select the most cost effective combination of heat pump capacity, TES and heat pump operating profile that can be used to meet the demand. The objective function becomes Equation 1, where C^{inv} is the investment cost, C^{opr} is the operating cost, r is the discount rate (8%) and n is the life of the project, 25 years. C^{rev} is the revenue from heat and coolth sales at £0.04/kWh to be comparable with

alternative systems in the UK (i.e. natural gas). It is assumed that the revenue will rise at the same rate of escalation as the operating cost, set at 0.2% per year.

$$\max \text{NPV} = \max \left\{ \sum_{n=0}^{25} \frac{C^{\text{rev}} - C^{\text{opr}}}{(1+r)^n} - C^{\text{inv}} \right\} \quad 1$$

The investment cost is the sum of all initial capital expenditure (n=0), shown in Equation 2.

$$\begin{aligned} C^{\text{inv}} &= C_{\text{HPH}}^{\text{inv}} + C_{\text{TESH}}^{\text{inv}} + C_{\text{HPC}}^{\text{inv}} + C_{\text{TESC}}^{\text{inv}} \\ &= C_{\text{HP,kw}}^{\text{inv}}(Q_{\text{HPH,max}} + Q_{\text{HPC,max}}) + C_{\text{TES,kw}}^{\text{inv}}(Q_{\text{TESH,max}} + Q_{\text{TESC,max}}) \end{aligned} \quad 2$$

where $C_{\text{HPH}}^{\text{inv}}$ and $C_{\text{TESH}}^{\text{inv}}$ is the investment cost of the heat-led heat pump and hot side TES respectively. $C_{\text{HPC}}^{\text{inv}}$ and $C_{\text{TESC}}^{\text{inv}}$ are the investment cost of the coolth-led heat pump and cold side TES. The investment costs are based on maximum capacities, $Q_{\text{HPH,max}}$, $Q_{\text{TESH,max}}$, $Q_{\text{HPC,max}}$, and $Q_{\text{TESC,max}}$ are the installed capacity of the heat-led heat pump, hot side TES, coolth-led heat pump and cold side TES, respectively. The program is formulated as a discrete binary integer problem such that:

$$Q_{\text{HPH,max}} = \sum Q_{\text{HPH,n}} \cdot Q_{\text{HPH,max,cap}} \quad 3$$

$$Q_{\text{TESH,max}} = \sum Q_{\text{TESH,n}} \cdot Q_{\text{TESH,max,cap}} \quad 4$$

$$Q_{\text{HPC,max}} = \sum Q_{\text{HPC,n}} \cdot Q_{\text{HPC,max,cap}} \quad 5$$

$$Q_{\text{TESC,max}} = \sum Q_{\text{TESC,n}} \cdot Q_{\text{TESC,max,cap}} \quad 6$$

$Q_{\text{HPH,n}}$ is a binary decision vector of equal magnitude to $Q_{\text{HPH,max,cap}}$. The decision vector can take an integer value of either 0 or 1 in each place holder but must sum to 1, so that only one capacity per piece of equipment is selected. The optimisation algorithm will place a 1 in the position which correlates to the chosen equipment size. $Q_{\text{TESH,n}}$, $Q_{\text{HPC,n}}$ and $Q_{\text{TESC,n}}$ are similar binary decision variables for the hot-side TES, the cold-side heat pump and the cold-side TES respectively.

The operating cost is the electricity used by the heat pumps multiplied by the unit cost per kWh of electricity, C_{el} , shown in Equation 7. This is taken from the Scottish Power charging statement for unrestricted domestic users, shown in Table 1. This is effectively a wholesale price and not the price the end user would pay. This is used to remove ambiguity around electrical tariffs which will vary from user to user. COP_H and COP_C are the Coefficient of Performance (COP) for the hot side and cold side heat pumps, chosen as 3 for both. The performance of hot and cold side heat pump is chosen to be the same to offer a cleaner comparison in the absence of detailed information on the modelled building internal distribution equipment.

$$C^{\text{opr}} = C_{\text{el}} \times \left(\frac{Q_{\text{HPH,out}}}{COP_H} + \frac{Q_{\text{HPC,out}}}{COP_C} \right) \quad 7$$

Table 1. Tarriff structure for electrical costs based on the Scottish Power Charging statement. Showing high cost (red), medium cost(orange) and low cost (green) periods. Domestic Unrestricted is shown as high cost as this tariff would typically lead to the largest cost per year. 1p is equal to £0.01GBP

	Domestic (p/kWh)	Non-Domestic (p/kWh)
--	---------------------	-------------------------

Time Period	Domestic Unrestricted (Mon-Sun)	Low Voltage Network Domestic (Mon-Fri)	Low Voltage Network Domestic (Sat-Sun)	SP Distribution Low Voltage Half-Hourly Metered 2019 (Mon-Fri)	SP Distribution Low Voltage Half-Hourly Metered 2019 (Sat-Sun)
00:00-08:00	2.618	1.227	1.227	1.211	1.211
08:00-16:30	2.618	2.005	1.227	1.761	1.211
16:30-19:30	2.618	9.419	2.005	7.271	1.211
19:30-22:30	2.618	2.005	2.005	1.761	1.211
22:30-00:00	2.618	1.227	1.227	1.211	1.211

The total operating costs are calculated as the cost of electricity at time period, $C_{el,t}$, multiplied by the units of power consumed at that time interval, $P_{HP,in,t}$, shown in Equation 8.

$$C^{opr} = \sum_{t=0}^{t=8759} P_{HP,in,t} \times \left(\frac{C_{el,t}}{COP_H} + \frac{C_{el,t}}{COP_C} \right) \quad 8$$

2.2 Energy Balance

On the hot side, the demand is made of heat provided directly from the heat pump in heating mode, $Q_{HPH,j}$, shared heat from the heat pump in cooling mode, $Q_{offset,H,j}$ and heat from the hot side TES, $Q_{TESH,out}$, summarised in Equation 9.

$$Q_{dem,h} = Q_{HPH,j} + Q_{TESH,out} + Q_{offset,H,j} \quad 9$$

The heat pump uses electricity in the form of work energy to upgrade a low-grade thermal resource to a higher-grade resource. This is the heat produced from the heat pump, $Q_{HPH,out}$, and can either be stored in the hot side TES, $Q_{HPH,i}$, or can be used directly to meet the demand, $Q_{HPH,j}$, shown in Equation 10.

$$Q_{HPH,out} = Q_{HPH,i} + Q_{HPH,j} \quad 10$$

Equivalent equations for the cold side are shown in Equation 11 and 12.

$$Q_{dem,c} = Q_{HPC,j} + Q_{TESC,out} + Q_{offset,C,j} \quad 11$$

$$Q_{HPC,out} = Q_{HPC,i} + Q_{HPC,j} \quad 12$$

For the hot side, the shared energy, $Q_{offset,H}$, can be stored, $Q_{offset,H,i}$, used directly to meet demand, $Q_{offset,H,j}$, or can be wasted to the environment, $Q_{offset,H,k}$, shown in Equation 13. The equivalent cold side is shown in Equation 14.

$$Q_{offset,H} = Q_{offset,H,i} + Q_{offset,H,j} + Q_{offset,H,k} \quad 13$$

$$Q_{offset,C} = Q_{offset,C,i} + Q_{offset,C,j} + Q_{offset,C,k} \quad 14$$

There is a hot and cold TES. The energy balance around the hot TES is shown in Equation 15.

$$Q_{TESH,t} = Q_{TESH,t-1} + Q_{HPH,i} + Q_{offset,H,i} - Q_{TESH,out} \quad 15$$

$Q_{TESH,t}$ is the hot-side energy stored in the hot side TES at time, t . $Q_{TESH,t-1}$ is the hot-side energy stored in the TES at the previous time step. The cold side is shown in Equation 16.

$$Q_{TESC,t} = Q_{TESC,t-1} + Q_{HPC,i} + Q_{offset,C,i} - Q_{TESC,out} \quad 16$$

The amount of energy that has the potential be shared is based on the energy balance of a heat pump, shown in Equation 17 and 18.

$$Q_{offset,H} = Q_{HPC,out} + \frac{Q_{HPC,out}}{COP_C} \quad 17$$

$$Q_{offset,C} = Q_{HPH,out} - \frac{Q_{HPH,out}}{COP_H} \quad 18$$

2.3 Carbon based optimisation framework

The overarching goal of implementing renewable and low carbon technology is to minimise carbon emissions; however, this can come at the expense of choosing the most cost-effective option. The aim of the carbon analysis presented is to assess the deviation in financial cost between the most cost effective and being the lowest carbon option. The variables and constraints on the optimisation are the same as the cost-based optimisation, however the optimisation function is updated to reflect the “carbon cost”, or carbon intensity, per hour of electricity from the UK national grid. The carbon intensity will vary due to the changing share of renewables in the mix. A sample day is given in Figure 3.

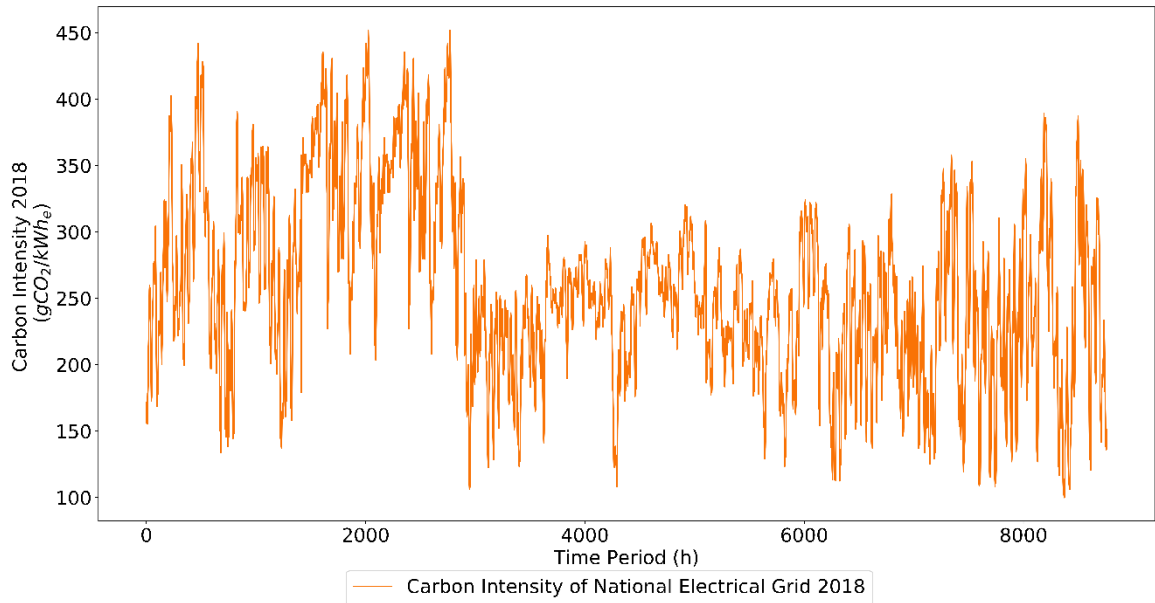


Figure 3. Typical carbon intensity across a sample day for the UK electrical grid, taking from the National Statistics Database.

The cost of carbon can be defined by the carbon EU Allowance (EUA). This is around £25/ tonne CO₂ emitted. The impact of a carbon-based tariff on energy sharing is assessed by introducing a carbon-cost to the objective function, shown in Equation 19.

The objective function for the carbon-based optimisation becomes Equation 19.

$$\max \text{ NPV} = \max \left\{ \sum_{n=0}^{25} \frac{C^{\text{rev}} - (C^{\text{opr}} + C_{\text{tot}}^{\text{CO}_2})}{(1+r)^n} - C^{\text{inv}} \right\} \quad 19$$

$C_{\text{tot}}^{\text{CO}_2}$ is the total carbon cost across the life of the project and EUA is the cost of carbon in £/tonne carbon. This is shown in Equation 20.

$$C_{\text{tot}}^{\text{CO}_2} = \sum_{n=0}^{n=25} \sum_{t=0}^{t=8759} P_{\text{HP,in},t} \times C^{\text{CO}_2} \times \text{EUA} \quad 20$$

C^{CO_2} is the carbon intensity of the electrical grid at time period, t . To our knowledge, an hourly carbon intensity forecast is not available for the next 25 years. Instead, a sample historical year data normalised against the average for that year is used. Hourly profiles are then produced from the forecast yearly average for the next 25 years.

3 Analysis metrics

There are a number of metrics which can be used to assess the benefit provided from energy sharing. In this study, these are divided into technical, economic or environmental.

3.1 Technical Metrics

The technical metrics are chosen as simple indicators of performance. These metrics show benefit for the distribution network, the electrical grid, or as an aid for decision making around network topology.

3.1.1 Diversity Factor

When distributed energy networks are not used (e.g. each user has a gas boiler/air conditioning), the peak load on the energy system is the peak of the individual user. In a distributed system, it can be incorrectly assumed that the peak load on the network is the sum of the peak demand of each individual user connected to the network. In practice, it is unlikely that all users connected to a network will have a peak demand simultaneously. The occupancy of a space can vary drastically and therefore the Domestic Hot Water (DHW) demand. The probability of coincident peak loads is known as “diversity”. Space conditioning is much more likely to be coincident and therefore diversity factor is not typically applied to this. The diversity factor is defined in Equation 21.

$$\text{Diversity Factor} = \frac{Q_{EC}}{\sum Q_{\text{peak}}} \quad 21$$

Q_{EC} is the peak energy provided from the energy centre or production plant and Q_{peak} is the peak energy demand of an end-user. The diversity factor of the hot and cold side heat pumps can be calculated from Equation 22 and 23.

$$Hot\ Side\ Diversity = \frac{Q_{HPH,max}}{Q_{peak,h}} \quad 22$$

$$Cold\ Side\ Diversity = \frac{Q_{HPC,max}}{Q_{peak,c}} \quad 23$$

A lower diversity factor implies a greater diversity. A greater diversity will place reduced strain on the national grid electrical network when coping with mass electrification of heat/cooling. The increased diversity will reduce the installed capacity of production equipment and distribution infrastructure, and therefore reduce costs. A greater diversity encourages production equipment to operate at peak installed capacity for greater duration; this operating style will increase the overall COP of the heat pump network.

3.1.2 Floor Normalised Loads

From the case study presented, it is possible to extract floor normalised load profiles from the IES VE calculated heating and cooling loads. This can be used to select a priority order of building classes for energy sharing. The floor normalised loads for a range of scenarios are fed to the optimisation algorithm which is arranged to produce the best cost-case utilisation of shared heat. This is presented for four key building types – office, retail, hotel and residential, as a guide to which building topologies are inherently better suited to energy sharing. This relies on energy loads in buildings being modular – the heating load can be separated from the cooling load. This offers a greater degree of freedom with a much larger range of heating and cooling load combinations. This is presented as the percentage of potential shared energy which is wasted.

3.2 Economic Metrics

The Levelised Cost of Energy (LCOE) can be used along with the NPV to assess the economic incentive of energy sharing. LCOE provides a measure of the average net present cost of generating heat or coolth across the lifecycle of the scheme, shown in Equation 24. It is the revenue per kWh of energy which must be recouped to cover the costs used in the assessment.

$$LCOE = C^{inv} + \sum_{n=0}^{25} \frac{\sum_{t=0}^{8759} \frac{C^{opr}}{(1+r)^n}}{\frac{Q_{dem,h} + Q_{dem,c}}{(1+r)^n}} \quad 24$$

For the scenarios with carbon tax (EUA), the LCOE becomes Equation 25.

$$LCOE = C^{inv} + \sum_{n=0}^{25} \frac{\sum_{t=0}^{8759} \frac{C^{opr} + C_{tot}^{CO_2}}{(1+r)^n}}{\frac{Q_{dem,h} + Q_{dem,c}}{(1+r)^n}} \quad 25$$

This LCOE calculation only accounts for the capital investment and operating profile chosen by the optimisation algorithm. It does not account for additional overheads, such as staff costs of operating the network, maintenance etc. The total energy consumed remains the same across all scenarios. The LCOE will provide a metric to compare the optimised operating profile for each scenario.

4 Heating and Cooling Profiles – A case study

Heat networks work best in high population density areas but an additional requirement for 5G DHNs is that there is a constant baseload of heating and cooling demand. The baseload heat could be from DHW and the constant cooling could be from supermarket refrigerators; however due to the challenges in providing de-centralised refrigerator cooling, this is excluded from this study. In order to demonstrate the proposed framework for system optimisation, a city-centre street in the UK is chosen for a case study, which is the Glasgow Queen Street (centred on 55.8625°N, 4.2512°W). In real terms, this could be an ideal location due to the high heating and cooling demand, with mixed use buildings. The network length is approximately 322m (0.2 miles).

The energy demands are produced from Integrated Environmental Solutions Virtual Environment (IES VE), a thermal simulation tool, using typical weather file for Glasgow. The IES VE modelling approach is documented in detail elsewhere, and therefore only provided in light detail below [13].

A 3D model of the street is first produced in IES VE. Assumptions around the building constructions are made based on visual inspection and the year of construction. Historic thermal properties are taken from Appendix S of RdSAP 2012, the standard assessment procedure for existing dwellings in the UK [42].

The key driving factors of building energy usage are the building fabric, internal gains, and the external air temperature. For the purpose of modelling, the street is grouped into building usage types shown in Table 2. From literature and experience, indicative values of occupancy, lighting, and small power gains are chosen. These are connected with sensible usage profiles, shown in.

4.1.1 Modelling Approach

The heating and cooling demand will vary depending on the external air temperature, building fabric (e.g. conductivity, air exchanges), and internal gains. These are summarised in Table 2 and Figure 4. Standard values are used for the equipment and lighting gains. The occupancy gains are dependant on the activity of the space and therefore has variation across building uses (e.g. a person doing heavy labour will sweat more and therefore contribute greater latent gain to the space).

Table 2. Summary of the internal gains per building class used in demand modelling. The profiles are created using best practice guides, experience, and common sense.

Internal Gain Type		Dining – Bar/Lounge	Dining – Cafeteria/Fast Food	Dining – Family	Hotel	Dwelling	Museum	Office	Retail	Warehouse
Equipment	Maximum Sensible Gain (W/m ²)	1.076	1.076	1.076	60	15	2.69	16	2.69	1.08
Lighting	Maximum Sensible Gain (W/m ²)	10.872	9.688	9.688	15	15	10.98	12	13.56	7.1
Occupancy	Maximum Sensible Gain (W/m ²)	80	80	80	73	73	73	73	73	186
	Maximum Latent Gain (W/m ²)	80	80	80	58	58	58	58	58	282
	Occupancy density (m ² /person)	9.29	9.2	9.2	23	23	27	25	27	30
DHW	l/hour.person	1	1	1	16	5	1	0.625	1	0.5

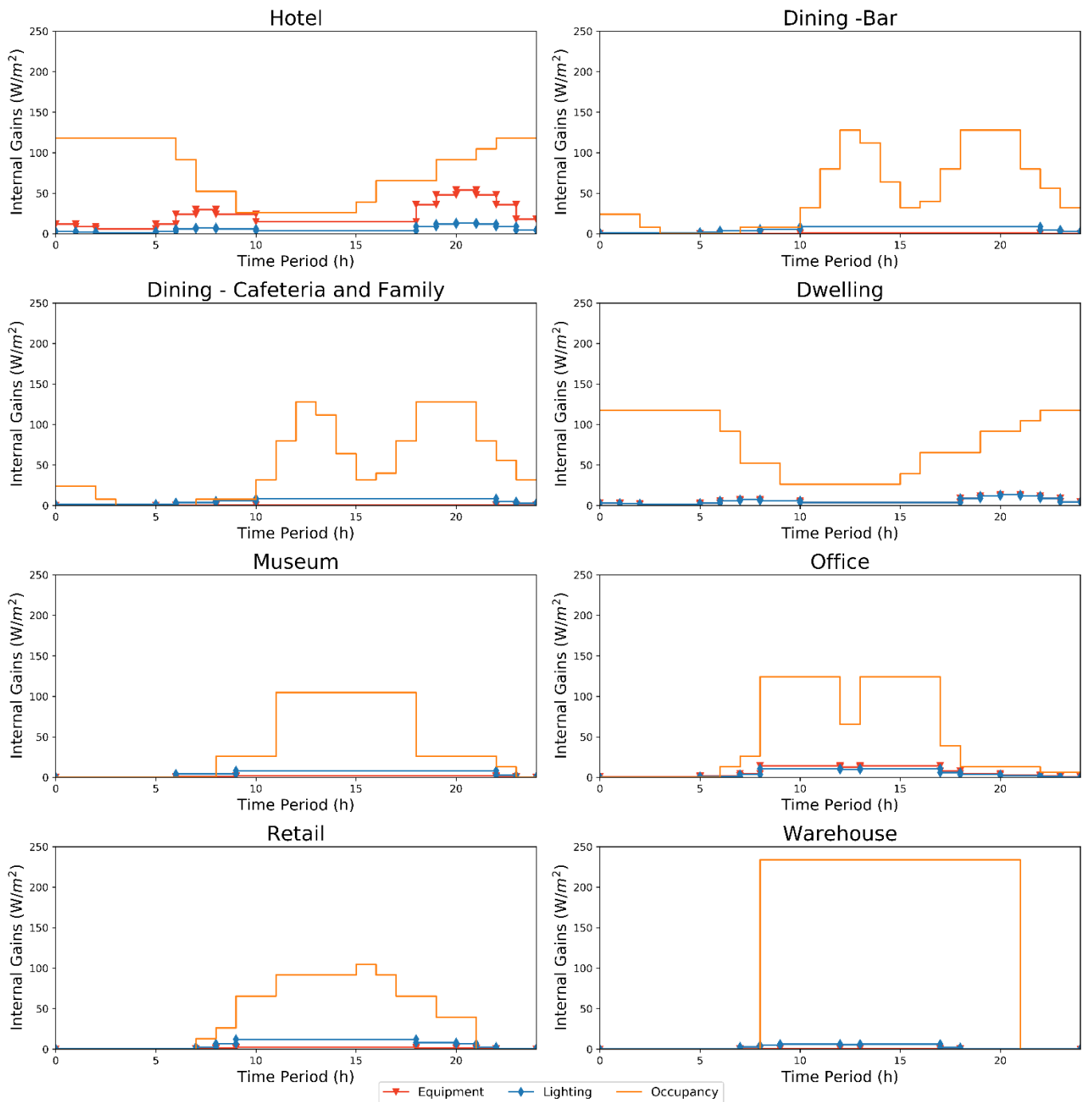


Figure 4. Daily variation in internal gains, shown in watts per square metre. The occupancy gain profiles are not divided by activity groups (e.g. bedroom, kitchen etc.).

A summary of the energy loads for each building type is provided in Table 3 and the 3D model is presented in Figure 5.

Table 3. Summary of Building Types and corresponding heating, cooling, and domestic hot water demand for the modelled building types

Building Type	Floor Area (m ²)	Heating Demand (MWh)	Domestic Hot Water (MWh)	Cooling Demand (MWh)
Dining – Bar/Lounge	249	22.9	4	0.47
Dining – Cafeteria/Fast Food	884	70.6	14.2	2.23
Dining – Family	911	67.1	14.6	2.7
Hotel	8'672	320.6	1171	19.7
Dwelling	6'557	245	276.8	0
Museum	6'927	476	37.6	1.8
Office	43'576	1'338	259	409.31
Retail	50'667	944.5	349.5	1'205
Warehouse	7'368	439.6	0	0
Total	<u>125'811</u>	<u>3'925.98</u>	<u>2'127.7</u>	<u>1541</u>

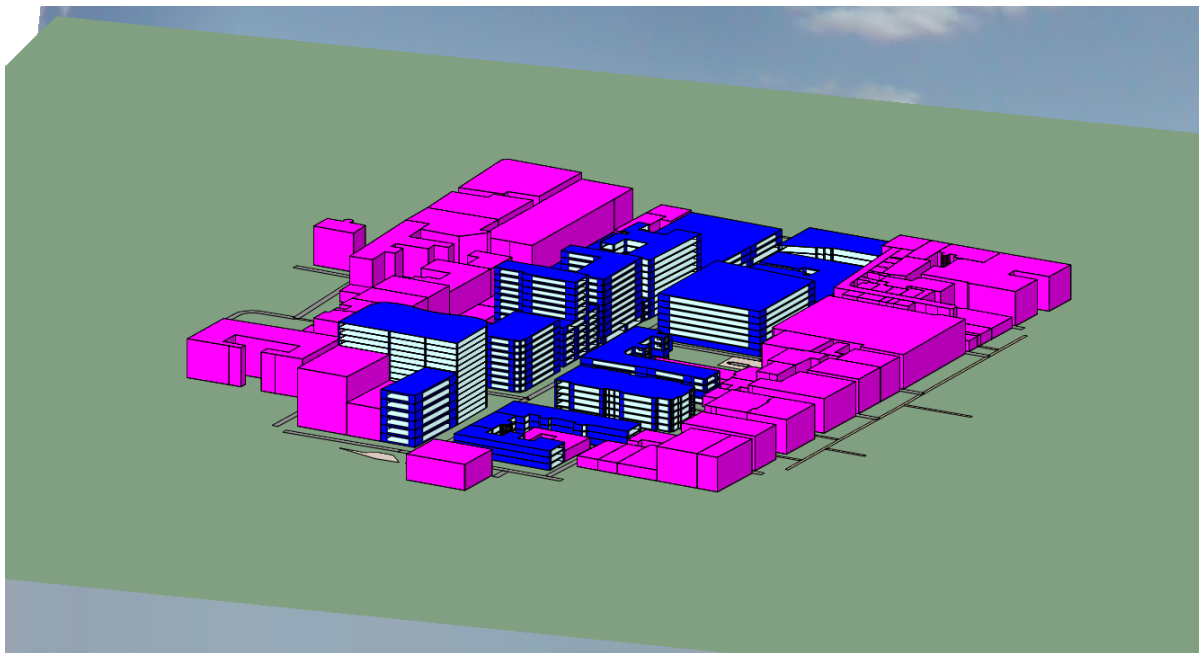


Figure 5. 3D model of the presented case study. Blue buildings show modelled zones and pink shows shading objects.

Figure 6 shows the simulated aggregate heating and hot water and cooling load for the sample study. The cooling load is much smaller than the heating load. The peak heating demand is 7.2MW and the peak cooling demand is 3.4MW.

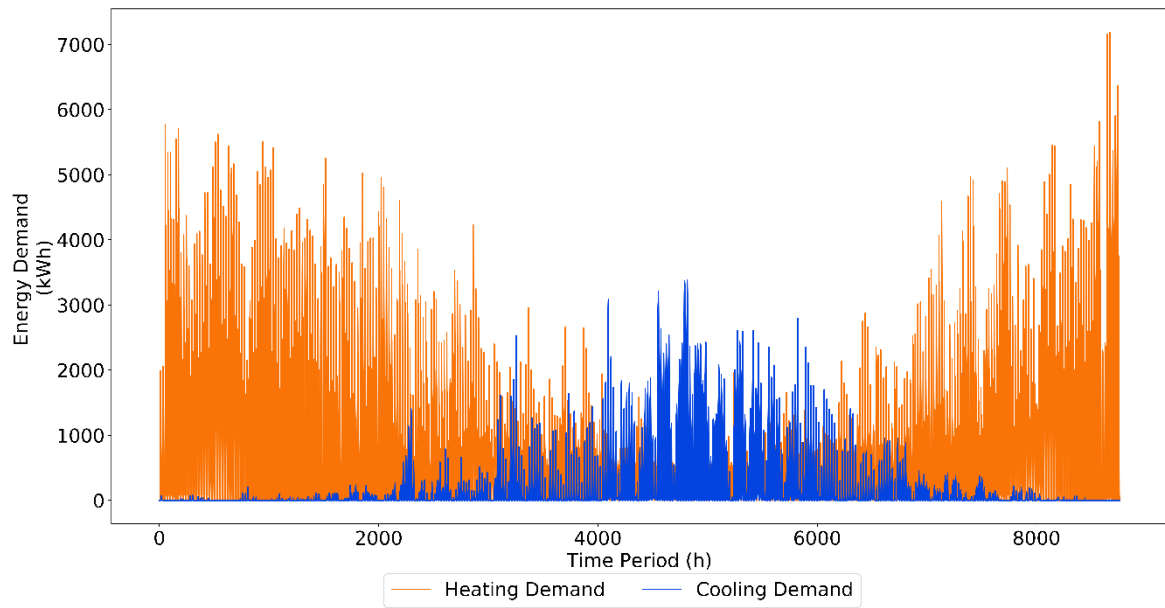


Figure 6. Simulated total Heating and Cooling loads for the sample stud showing significant seasonal variation in heating (orange) and cooling demand (blue)

4.1.2 Case Study Scenarios

Sixteen distinct scenarios were considered with the case study to assess the influence of demand side management (DSM) and energy sharing on the techno-economic feasibility of the system. These are summarised in Table 4 and Table 5.

Table 4. Description of scenario variable used; tariff, energy sharing, thermal storage, and carbon taxation.

	Scenario Variable	Description
Tariff	Fixed Rate	Electricity is charged at one rate
	Tout	Electricity cost varies across the day/week. Lower rates are given for off-peak periods
Energy Sharing	With Share	Offset energy can be shared through the network
	No Share	No energy can be shared (becomes 4th generation network)
Thermal Storage	With Store	Energy storage can be utilised (hot and cold)
	No Store	No energy can be stored
Carbon Tax	With Carbon	A carbon levy is added based on the national grid carbon factor
	No Carbon	No carbon levy is added

Table 5. Summary of tested scenarios showing the tariff, energy sharing, thermal storage, and carbon tax combinations assessed.

Scenario Number	Tariff	Energy Sharing	Thermal Storage	Carbon Tax
1	Fixed Rate	No Store	With Share	No carbon
2	Fixed Rate	No Store	With Share	With carbon
3	Fixed Rate	No Store	No Share	No carbon
4	Fixed Rate	No Store	No Share	With carbon
5	Fixed Rate	With Store	With Share	No carbon
6	Fixed Rate	With Store	With Share	With carbon

7	Fixed Rate	With Store	No Share	No carbon
8	Fixed Rate	With Store	No Share	With carbon
9	TOUT	No Store	With Share	No carbon
10	TOUT	No Store	With Share	With carbon
11	TOUT	No Store	No Share	No carbon
12	TOUT	No Store	No Share	With carbon
13	TOUT	With Store	With Share	No carbon
14	TOUT	With Store	With Share	With carbon
15	TOUT	With Store	No Share	No carbon
16	TOUT	With Store	No Share	With carbon

5 Results and Discussion

Energy sharing networks are novel technology and not found extensively anywhere. The discussion presented in this section makes some assumptions around the business model and structure which is necessary to understand and reason the results and conclusions.

The following statements are assumed for the discussion:

- The network customer is charged for the heat, cooling, and hot water from the network operator as one charge based on the energy absorbed from the network (ie no distinction is made with regards to the grade of heat absorbed)
- no compensation is provided for energy rejected to the ambient loop
- the network operator and/or owner are responsible for the capital investment cost. In this scenario, all financial metrics are from the network owner/operator, who in practice may be the same entity.

A summary is given in Figure 7.

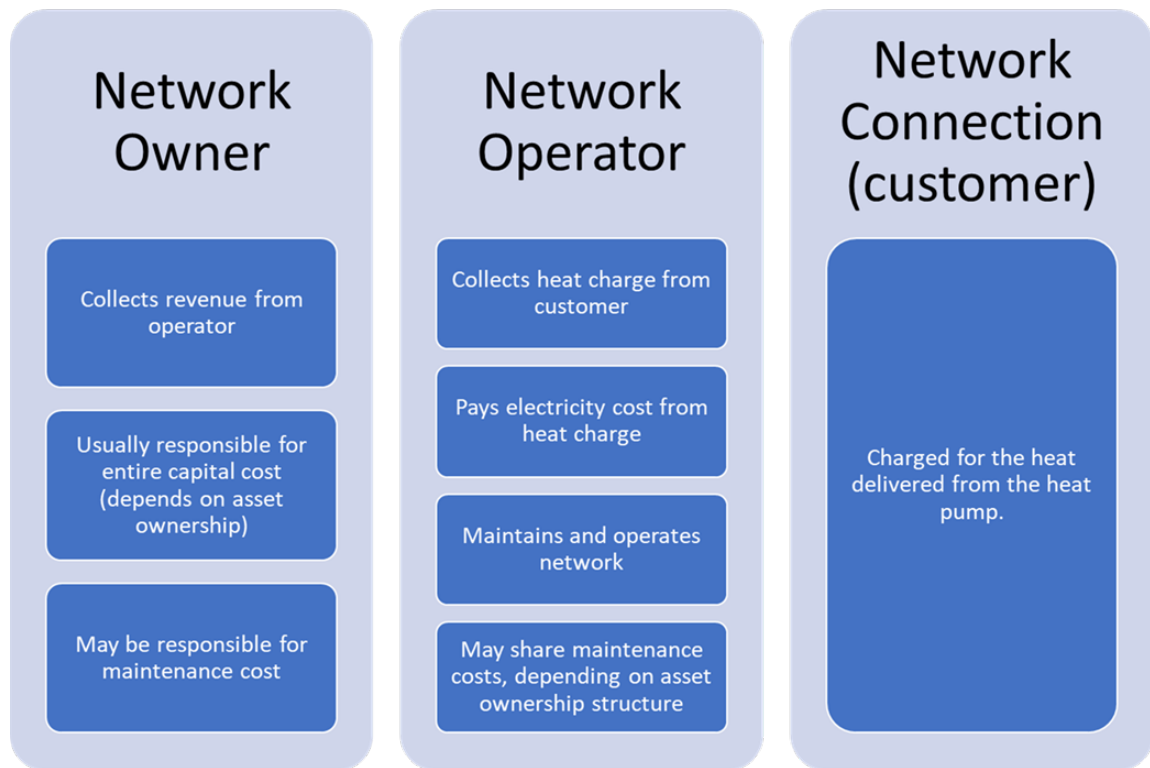


Figure 7 Bubble diagram of a potential 5G DHN asset ownership structure and responsibilities. This is only an example structure and should not be taken as a finite solution.

5.1 Technical Metrics: Installed Capacity

A summary of results is given in Table 6. This summarises key values for heat pump and TES sizing under energy sharing and non-energy sharing conditions. This is presented under fixed rate tariff, time of use tariff, fixed rate with carbon tax tariff, and time of use with carbon tax tariff.

For all tariff scenarios, the heat pump in heating mode had a lower installed capacity in the Fixed rate tariff than the equivalent time of use tariff (range=0.7MW, 10% diversity). For the heat pump in cooling mode, there is very little deviation in installed capacity for the energy sharing scenarios (range for energy sharing=0.2MW, 5% diversity) but the time of use tariff did have a slightly higher installed capacity. The installed cooling capacity is significantly higher in the absence of energy sharing (overall range=2.4MW, 70% diversity) and has a greater range within sub-scenarios (e.g. with/without energy sharing; range without energy sharing=1.7MW, 49% diversity). The time of use tariffs had

a lower installed capacity of heat pump but higher installed thermal store. This implies a greater dependence on tariff structure in the absence of energy sharing.

There is only a small deviation in thermal storage across all scenarios in installed hot TES (range=5.4MWh). The range is greater for the cold TES (range=11.1MWh). This suggests an optimum TES capacity, which is not influenced significantly by the tariff structure for the hot TES. Tariff structure has much more significance for the cold side TES.

The installed capacity of heat pumps and storage was greater in the scenarios without energy sharing.

Table 6. Summary of Heat Pump and Thermal Storage optimisation results for installed capacity of hot side heat pump and thermal store, and cold side heat pump and thermal store under energy sharing and non-energy sharing tariff combinations.

	Tariff Structure							
	With Energy Sharing				Without Energy Sharing			
	Fixed Rate	Time of Use	Fixed Rate & Carbon Tax	Time of Use & Carbon Tax	Fixed Rate	Time of Use	Fixed Rate & Carbon Tax	Time of Use & Carbon Tax
Heat Pump Heating Max (MW)	2.0	2.7	2.1	2.7	2.3	2.7	2.3	2.7
Heat Pump Heating Diversity Factor (%)	28.0	37.0	29.0	37.0	32.0	38.0	32.0	38.0
Heat Pump Cooling Max (MW)	1.0	1.1	1.1	1.2	3.4	1.7	2.6	1.7
Heat Pump Cooling Diversity Factor (%)	30.0	34.0	32.0	35.0	100.0	51.0	77.0	51.0
Hot Thermal Store Capacity (MWh)	22.2	20.8	22.2	20.8	26.2	21.5	26.2	21.5
Cold Thermal Store Capacity (MWh)	10.0	11.1	8.0	11.1	0	12.6	3.0	12.7

The benefit of using 5G DHNs is to share energy between users. This is done by harnessing the offset (or rejected) heating or cooling from heat pumps. The shared energy should be considered carefully. If shared heat (provided by the cold-side heat pump) is utilised, this will reduce the demand on the hot-side heat pump. If shared coolth (provided by heat pump in heating mode) is utilised, the demand on the cold-side heat pump will be reduced. Therefore, there is a trade-off between utilising shared heat or shared coolth. Coolth for space conditioning is commonly provided by an electric air handling unit and heat pump. As electricity is more expensive than natural gas (for heating) it may be cheaper to provide the cooling from offset heat. However, if carbon savings is the objective then minimising natural gas usage should be the decision; therefore, it may be more beneficial to allow the cooling-led heat pump to operate and capture the offset heat.

In the case presented, shared cooling is used to offset the peak heating demand, which is shown by the lower heat pump heating diversity factor than heat pump cooling diversity factor in Table 6. However, the benefit is only significant with the fixed rate tariff. This would imply that the shared energy has minimal impact on the installed capacity. The tariff had a much greater impact on the installed capacity. This is likely because of the significant cost benefit the time of use tariff offered. At a low cost period, the heat/cooling in the scenario presented may cost as low as £0.004/kWh_{th} (electricity cost £0.01227kWh_e with COP of 3). If heat/cooling is generated at high cost periods, this could be as much as £0.0314/kWh_{th}. The time of use tariff offers a greater penalty for generating heat/coolth at high cost times than the betterment provided by the utilisation of shared energy. Therefore, there is a greater cost incentive to charge the thermal stores at low cost and discharge at high cost, than there is incentive to only utilise the energy sharing at peak times.

This scenario could change, if the demands on the network are significantly. However, in practice this would mean equal and opposite heating and cooling loads, which is unlikely to happen.

The carbon tax is a form of time of use tariff which uses a cost based penalty to encourage utilisation of low carbon electricity. These carbon tax scenarios offered almost no deviation from the non-carbon tax equivalent scenario. This is because the carbon tax penalty is too low to encourage a shift in response behaviour.

5.2 Tariff Structure and demand response

Figure 8 and Figure 9 show the optimised dispatch response for a peak heating and cooling 48 hour period. The first column graphs show the dispatch response with energy sharing; the second column graphs show the dispatch response with no energy sharing. The red line shows the heat pump response.

In the fixed rate scenarios, the heat pump operates below the demand (green line) for the majority of the period. For the equivalent time of use tariff, the heat pump operates an almost inverse of the cost (black line, second axis). The instantaneous demand is met almost entirely from direct production and energy from the thermal store (ie there is little energy sharing utilised at peak periods).

The heat pump operates slightly higher in the scenarios with no energy sharing when compared to the scenarios with energy sharing. This deviation is very marginal.

The scenarios with a carbon tax were almost identical to the equivalent scenario without the carbon tax.

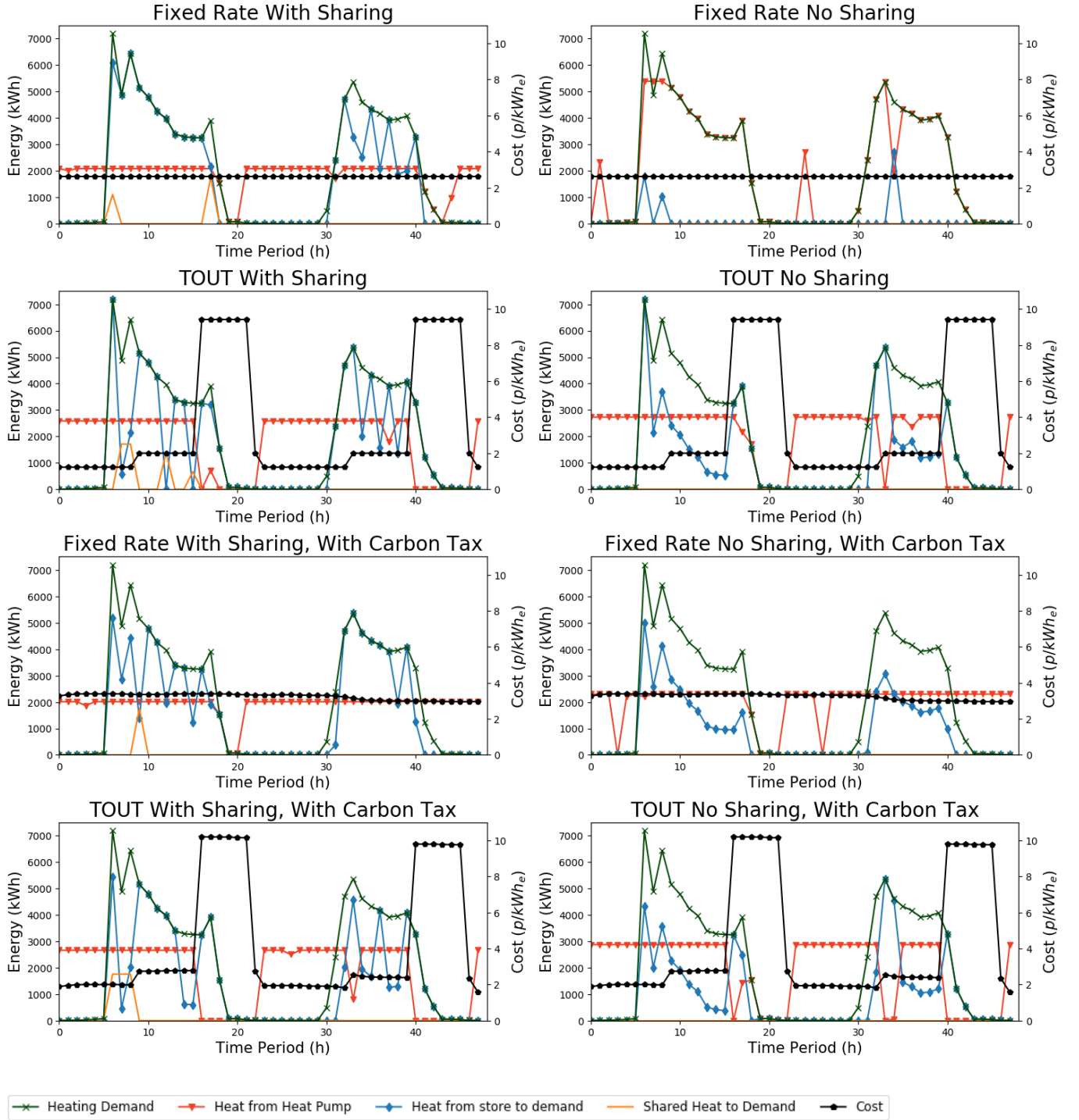


Figure 8. Hot-side dispatch profiles for tariff structures (TOUT, Fixed rate, and Carbon Tax). Scenarios with energy sharing are shown in the left hand column, while non-energy sharing is shown in the right hand column.

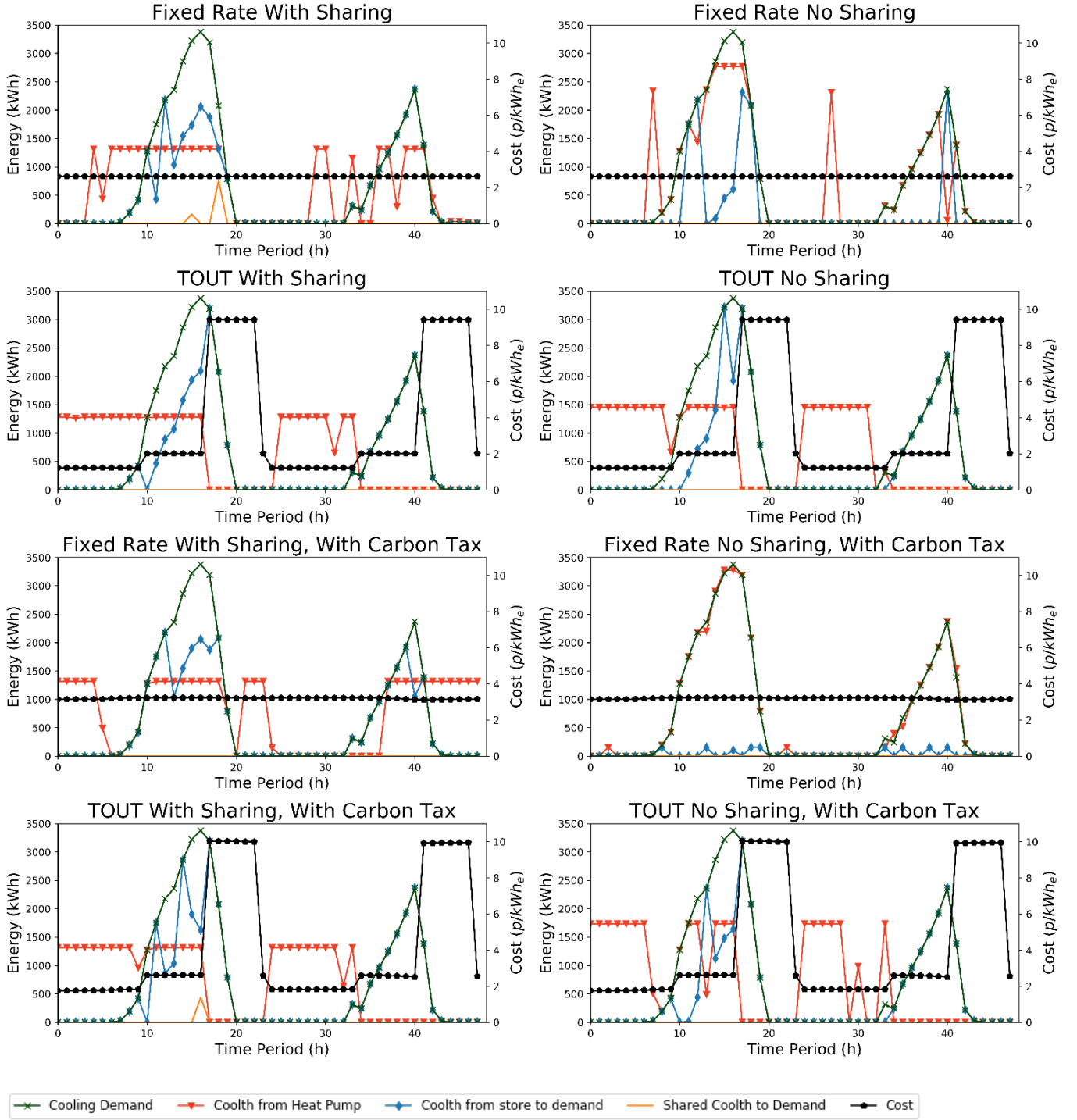


Figure 9. Cold-side dispatch profiles for each tariff structure (TOUT, Fixed rate, and Carbon Tax). Scenarios with energy sharing are shown in the left hand column, while non-energy sharing is shown in the right hand column

From Table 6, the fixed rate tariff had a lower diversity factor for installed hot side heat pump capacity compared with the time of use tariff for all scenarios. These differences can be further understood by considering Figure 8 and Figure 9. These figures show the heat pump operating profiles for peak heating and cooling days. For the time of use tariff, the heat produced by the heat pump (red line) follows a recurring pattern, where the heat pump operates above the demand (green line) to charge the thermal store at lower cost periods and switches off during high cost periods, in a peak shifting strategy [43]. When the higher cost period occurs, the heat pump switches off and the heat from the store (yellow line) follows the demand. However, at certain high cost periods the heat pump capacity is too small to

follow the demand. Instead, the heat pump operates at full capacity while supplementing from the thermal store, moving from peak shifting to peak shaving [43, 44]. This is the optimised trade-off between the heat pump capacity and the TES capacity, accounting for the tariff structure. Saffari, De Gracia [45] reports a linear increase in cost saving with increasing TES capacity when a TOUT is utilised; this is supported by our findings but is not the full picture. The overall financial benefit (i.e. NPV) is sensitive to the cost of storage and the range of high/low cost periods. The optimisation is performed over the range of values and is therefore aware of the predicted peak load and has not accounted for loss from the tank, which may diminish the benefit of this type of demand side management in practice. However clear benefit is shown in reducing the impact electrification of heat may have on the national electricity grid [46, 47].

In the fixed rate scenario and when there is no sharing, there is no financial benefit to charge the thermal store and so the heat pump follows the demand. However, when the demand peaks, it is better financially to minimise the peak load of the heat pump, and so prior to the demand increase the heat pump operates above the demand to charge the store. This discharges during peak period, reducing peak electrical demand in a peak-shaving operation. The financial benefit is found by minimising the necessary capital investment, rather than operational benefit.

The carbon-taxed tariff introduces an incentive to move away from energy production at high carbon intensity periods; these are essentially a variation of TOUTs. However, the carbon-taxed dispatch profiles in Figure 8 and Figure 9 do not show significant deviation from the non-carbon-taxed dispatch profiles. In this case, the carbon tax is too small to drive a change in operation. The greatest influence on reducing carbon emissions was found to come from utilising energy sharing, shown in Table 6, followed closely by the presence of TES and the carbon tax. The hourly grid carbon intensity is anticipated to decrease significantly across the 25 year modelled lifecycle. This means the impact of a carbon tariff is expected to diminish as the grid de-carbonises. However, this study does not present a full lifecycle carbon assessment to account for the embodied carbon of equipment. If the embodied carbon of the installed equipment is included, this may encourage greater diversity, but further investigation is needed to confirm.

Energy sharing may reduce the installed capacity, but only when there is financial benefit, or there is a significant coincident heating and cooling load at peak periods. The peak heating demand is in December and the peak cooling demand is in July. Figure 6 shows very little cooling demand in the winter and very little heating demand in the summer. This can explain why the diversity of installed heating plant equipment is not significantly affected by the ability to exchange heat or coolth, shown in Table 6. However, the diversity of the cold side equipment varies much more significantly. This is because there is much more shared cooling than there is shared heating, and the cooling demand is much smaller than the heating demand. This means the shared energy will have a greater impact on cooling diversity.

When energy sharing is allowed, across all three scenarios, the amount of energy being shared does not deviate significantly. The cooling demand is met by 5% shared cooling, while the heating demand is met by around 20% shared heating. The smaller share of shared cooling utilisation is to be expected due to the lack of simultaneity, discussed above. The useful shared heating utilisation (shared heat to demand and store) is almost identical in all cases. This suggests there is a point of maximum shared benefit which is independent of the tariff. This supports the idea that it may not be financially beneficial to utilise all shared energy potential. Further study is needed to explore this concept.

5.3 Design Metrics for Energy Sharing

Figure 10 shows how the demand was met for the different tariff structures. The cold side is almost exclusively met directly from the cold side heat pump, but the hot side utilises much more offset energy. The total utilised shared energy is almost the same for all tariff structures (approx. 80% of total energy supply) but the ratio of shared energy used directly to meet demand compared with the energy sent to store varies. The scenarios with carbon tax stored more energy than the scenarios without a carbon tax.

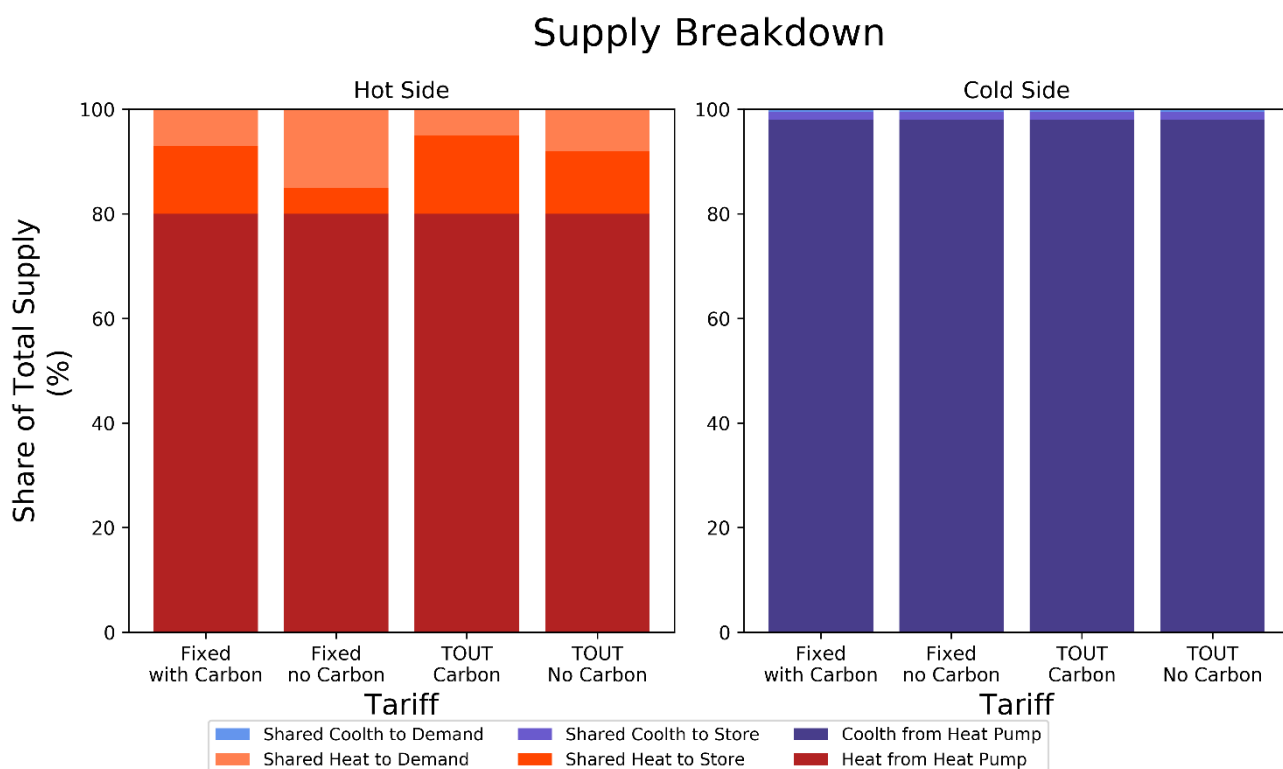


Figure 10. Bar graphs showing how the shared energy of each scenario is used as a percentage of total demand. The hot side break down is shown on the left, while the cold side break down is shown on the right.

Figure 11 shows how the shared energy is utilised with and without thermal storage. As Figure 10 showed, almost none of the offset cooling is utilised in any scenario.

When thermal storage is used with fixed rate tariff, there is the same overall offset energy usage as in the fixed rate tariff with no thermal storage. The time of use tariff benefits more from thermal storage and therefore utilises more shared energy when there is thermal storage. The carbon tax scenarios follow similar trends but the time of use tariff does not utilise as much offset energy as the time of use scenario without the carbon tax.

Shared Energy Usage

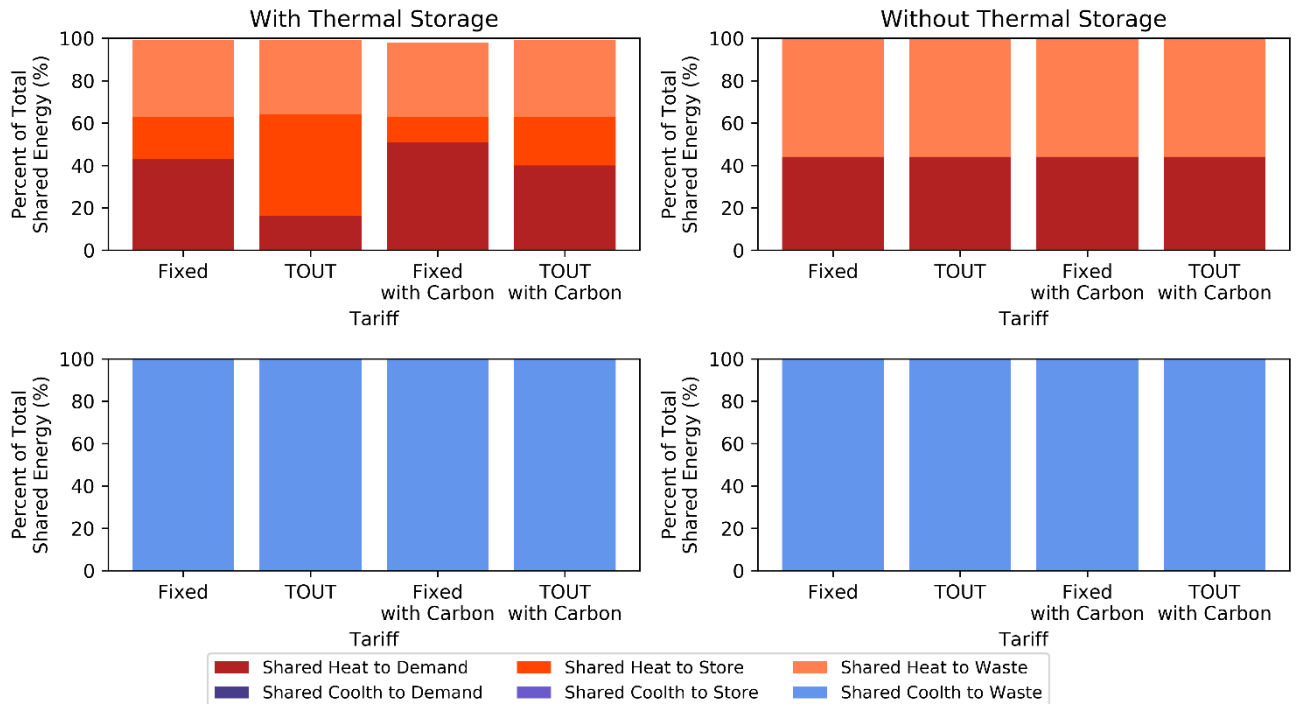


Figure 11. Bar graphs showing how the shared energy is used as a percentage of the total shared potential. Hot side data is presented in the upper two plots, while cold side data is presented in the lower two plots. The left two plots show scenarios utilising thermal storage, while the right two graphs show scenarios which are not utilising thermal storage.

Figure 12 shows the levelized cost impact of energy sharing and thermal storage on the cost per kWh of energy supplied (i.e. the levelized cost of energy). The time of use tariff had a lower LCOE than the fixed rate tariff when thermal storage was used, but higher when only energy sharing was used with no thermal storage. The thermal storage had the largest impact on the levelized cost. Adding storage without sharing reduced the time of use tariff LCOE by approximately 50% and the fixed rate by 14%. Adding sharing and no storage reduced the time of use tariff LCOE by 12.5% and the fixed rate by 7%. This implies that, even under a fixed rate tariff with no time based usage penalty, thermal storage made the biggest improvement on LCOE and energy sharing offered little financial benefit.

As expected, the LCOE is highest when there is no sharing/storage, and lowest when there is sharing and storage. This supports the previous conclusions; thermal storage is necessary to achieve the lowest costs, with energy sharing being of greatest benefit when used in conjunction with a time of use tariff and thermal storage. There is a 69% reduction in levelized cost between the highest cost scenario (time of use tariff, no sharing, no storage, with carbon tax) and the lowest cost scenario (time of use tariff, with sharing and storage), but only a 63% reduction between the highest cost and second lowest cost (time of use tariff, no sharing, with storage). This cost analysis was simplified and therefore omitted many additional costs; the financial benefit would be even lower if they had been included. Therefore, it is unlikely there would be a significant financial value in energy sharing under the conditions of this study. However, it is difficult to attribute the long term financial cost of global warming. Climate benefits must also be considered when assessing viability.

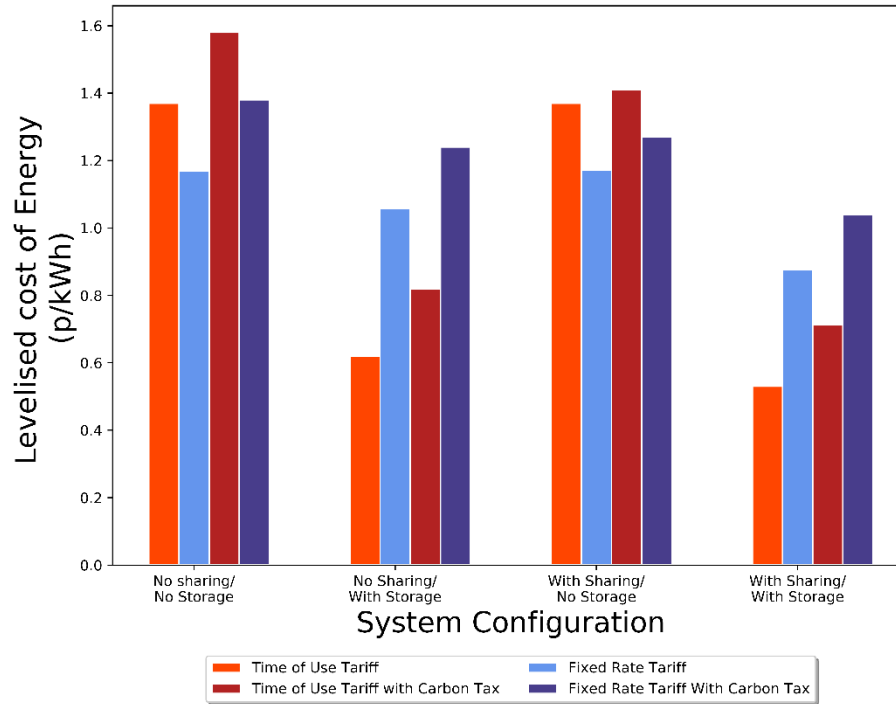


Figure 12. Levelised cost of energy comparison for Time of use Tariff and Fixed rate tariff, both with and without carbon taxation. Data presented is for four different system configurations. Time of use tariff data is shown in orange tones, while fixed rate tariff data is shown in blue tones.

5.4 Overall Design Metric Importance

Figure 13 provides a summary of metrics used for each variable. Each column is the average of all 16 scenarios.

The largest impact on performance was the availability of thermal storage. The NPV with thermal storage was 20% higher than without. Energy sharing had a much smaller impact on NPV (7.7% higher with sharing than without). The LCOE was 50% higher without thermal storage, but only 22% higher without energy sharing.

On average, the tariff had no impact on the shared energy usage but had an impact on NPV and LCOE. The carbon emissions were reduced by using storage and energy sharing, but the largest benefit was from energy sharing (12.5% reduction when energy sharing is used, 6% reduction when energy storage is used).

This study investigated 16 distinct scenarios to assess the merits of an energy sharing network. Some of the key variables from the study were averaged across all scenarios and summarised in Figure 13 to easily identify the variables with largest impact on the sharing network. Across all scenarios and variables, thermal storage had the greatest impact. The scenarios show that thermal storage is the key variable when it comes to sharing energy. The tariff structure had almost no effect on the total quantity of energy shared. This is supported by Figure 11, which shows a critical point of energy sharing. This suggests a point above which energy sharing is no longer financially beneficial. For this study, around 60% of shared potential was utilised across all scenarios with storage, while 40% was utilised across all scenarios without storage.

The tariff (either time of use or fixed rate) granted benefit in some places. Using a TOUT, on average, showed benefit for the cold side heat pump diversity, but not for the hot side heat pump. In this scenario, it is because the hot side heat pump must operate at higher capacity during the low cost periods, without having the benefit of relying on the shared heating to reduce the peak. This is contrary to the cold side, which can be supplemented by the shared cooling all year round as there are few times when the heating demand drops to zero.

The carbon tariff offers almost negligible carbon savings across all scenarios. This is because the carbon tax is too low and can therefore be mitigated through marginally higher thermal store. This has been identified as an issue globally and is an ineffective method of reducing carbon emissions [48].

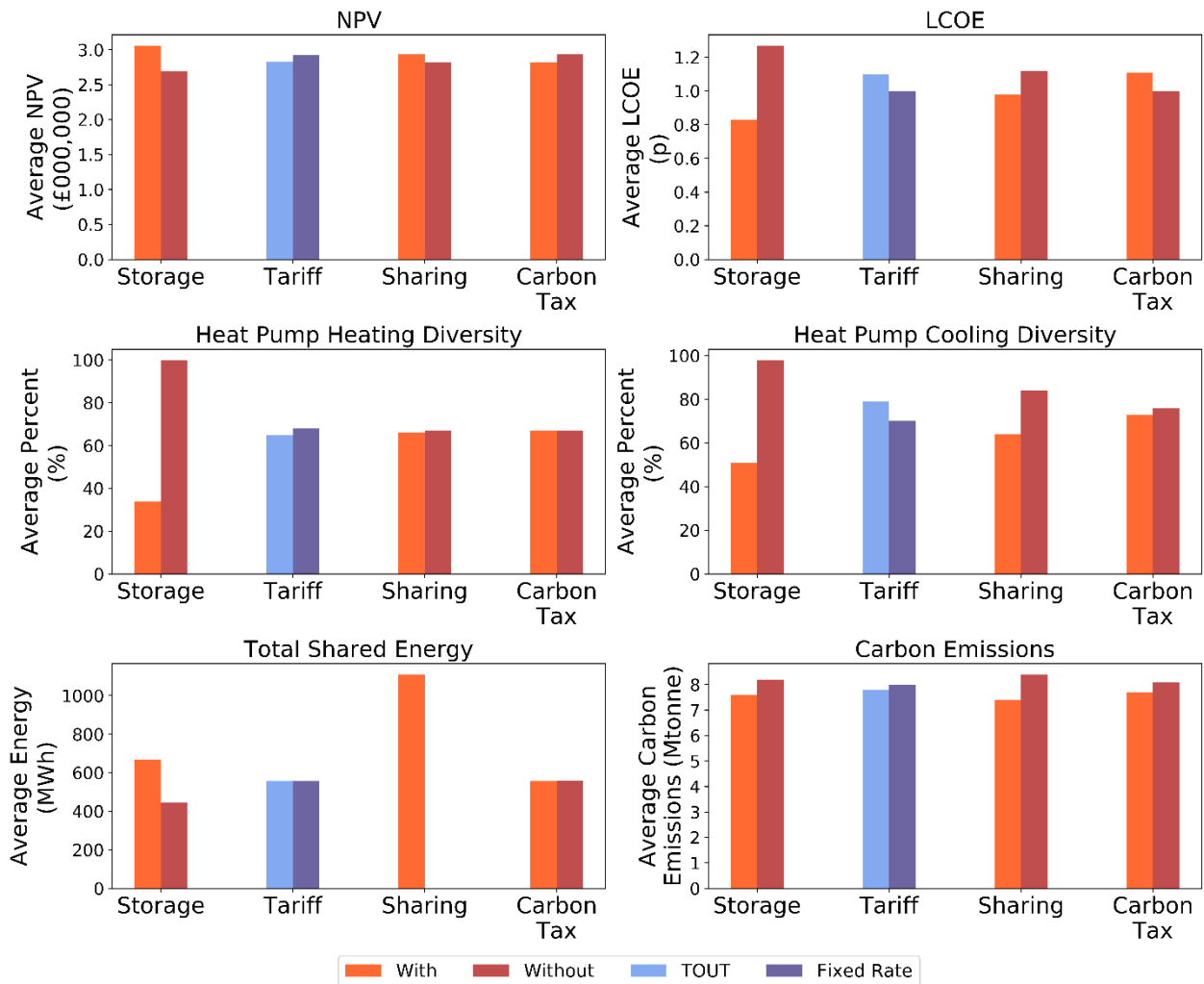


Figure 13. Aggregate Averages of key variables. The orange bars show the average of scenarios with the variable, the red bars show the average without the variable. Light blue bars are the average of TOUT, while dark blue is the average of the fixed rate tariffs.

5.5 Complimentary Heating and Cooling Loads

To fully appreciate the energy dynamics of an energy sharing system requires in depth, detailed analysis. This can be both time and financially expensive. It is therefore important to be able to draw generalisations from available data that can be used as a high-level tool to inform early stage design discussions, which is the intention of Figure 14.

Figure 14 shows the percentage of shared energy which is not economically viable to utilise. The best case scenarios are calculated via the method shown in 2.1 above and the total wasted shared heat ($Q_{\text{offset,H,k}} + Q_{\text{offset,C,k}}$) is calculated from these results. This is shown for 1156 different combinations of heating and cooling loads on a per m² basis. Where two of the same type are shown, this indicates a greater share of that type. For example, “Office, Office” would be twice as much office space. For example, the upper left corner is “Office heating and office cooling”. This shows that 92% of the potential shared energy is wasted when an office utilises the offset energy produced from heat pumps. The scenario below, “office heating and retail cooling” only wastes 86% of the energy, and is therefore a better choice.

Looking vertically, it is difficult to see any trends in shared heat usage, however there are clear trends horizontally with the chosen cooling loads. From the data, it would appear that there is little to no benefit to using residential or hotel cooling loads in an energy sharing network as the wasted shared energy is always close to 100%. This is expected as residential space in the UK does not have the facility for space cooling and the hotel cooling demand is negligible. As there is no sizable cooling load, there is no benefit of energy sharing. However, the heating loads could still be used and paired with a promising cooling load.

The best choice of heating load is office space. On average, this has the lowest wasted energy. The retail space was found to be the best option for a baseload cooling demand. These options can be understood by considering Table 3. The office and retail space both have a reasonable heating and cooling demand, while the other building types do not. This creates the potential for shared energy to be stored for later use in the building. If one building produces heat, the offset coolth that is produced can be stored for use in the same building at a later time because there is the demand. This suggests that there is benefit of using the offset energy in the one building, either between different space conditioned zones via smart management or potentially through energy storage. However, it is unclear if there is greater benefit from sharing energy between buildings or simply smarter internal usage. This approach may work for building types with mixed energy demands (e.g. retail/office) but will not offer benefit to those with a single large demand (e.g. residential/hotel).

On considering how wide to make connections to a network, there is a compromise on how many buildings to connect to the thermal demand density. As more buildings connect, the demand density has the potential to diminish leading to higher distribution losses. From Figure 14, the configuration with three building types had the lowest wasted energy. The largest cause of wasted energy comes from the shared coolth. The shared energy can be utilised because there is a significant amount of shared heat used immediately but also because there is always a heat demand across small time horizons; this is either from space heating or the year-round domestic hot water demand.

The analysis offers a first-pass guide intended for early stage design, not to replace detailed design and analysis. The limitations of the analysis must be acknowledged when considering the data in Figure 14.

The energy loads are for a very specific combination of building types. While this can be indicative of a typical urban street, variations may still occur which will vary largely depending on factors such as occupancy profile, location, building age/thermal performance and orientation.

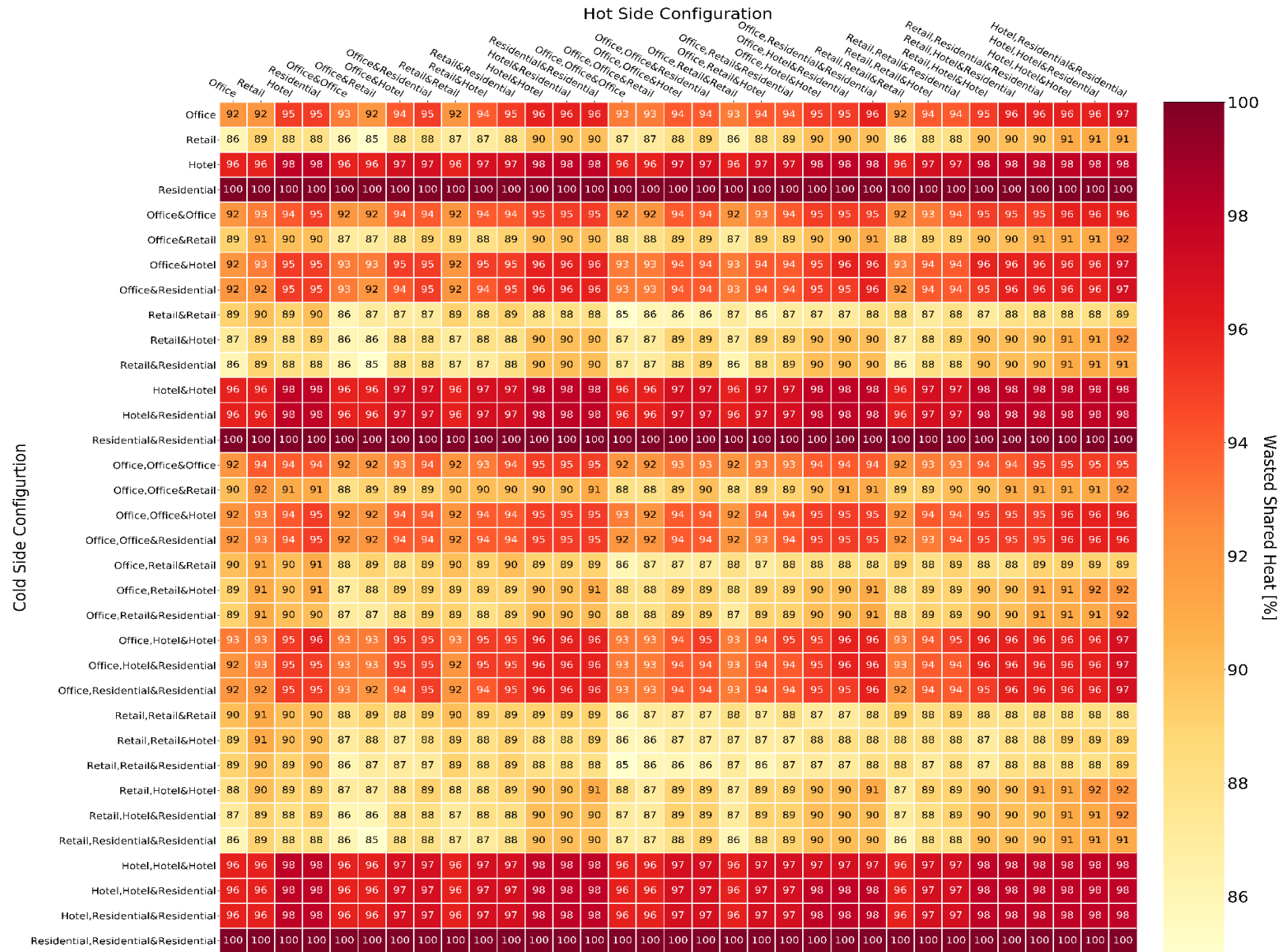


Figure 14. Heat Map of Wasted Shared Energy. Lighter colours show better scenarios (less wasted shared energy). Connected hot side demands are shown in the X-axis, while cold side demands are shown in the Y-axis.

6 Study Limitations

As with all computational projects, a number of assumptions have been used throughout the study which will introduce a degree of error.

The most significant error we can see is in reducing the model to a static input, rather than a full dynamic model of the distribution network. By taking a static model, we remove the need to consider system level dynamics (e.g. heat exchanger pinch points, internal thermal mass and inertia, secondary distribution) and therefore present a less detailed but cleaner comparison of the complimentary loads on the network. We believe this is suitable for a network level consideration (i.e. the point of network operator) as in practice, the network operator is only interested in meeting the demand. In a traditional heat network, the operator must maintain a minimum flow rate and temperature, but in a 5th generation network the deviation in grade of heat being supplied by the network is inconsequential as the secondary circuit is designed for low grade heat. Therefore, the operator is only concerned with the energy being absorbed/rejected from/to the network to remain within a much broader operating dead band.

However, from the perspective of the secondary distribution (i.e. from the heat pump) the difference between ambient loop temperature and heat emitter supply temperature is of greater importance. This can only be considered in detail with a dynamic simulation accounting for all loads and control response on the distribution network, therefore not considered here. As building fabric improves, it is likely the need for high temperature secondary loops will reduce, therefore minimising the errors of this assumption.

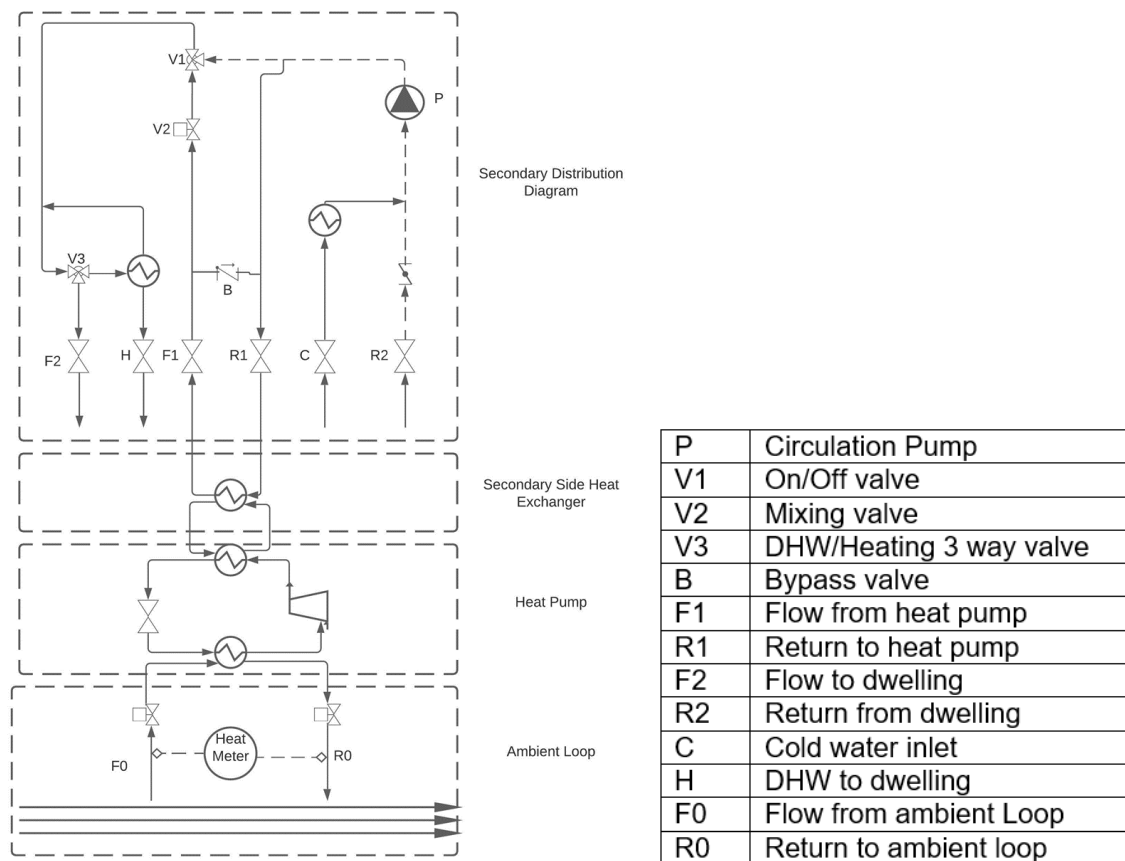


Figure 15. Suggested hydraulic circuit diagram of heat meter location and measurement points, showing heat metering taking place at the property boundary and interface between the ambient loop and end user.

7 Conclusions

This paper assesses the key performance indicators and metrics around 5th generation district energy sharing networks. A number of financial and technical metrics which are commonly used throughout design have been assessed for a European case study using dynamic building energy modelling, combined with linear programming. The network is assessed from the network operator perspective with the intention of providing novel research to support early stage design, and operation strategy. The optimisation algorithm is designed to select the most cost effective sizing of equipment (hot and cold side heat pump and thermal storage), and demand response approach. The demand response approach includes an optimal use of storage and capacity to maximise the Net Profit Value. In total, sixteen scenarios are tested and analysed in detail. These include scenarios using a fixed rate or time of use tariff, using thermal storage or no thermal storage, using energy sharing or no energy sharing, and using a carbon levy or no carbon levy.

We can conclude that:

- The largest promoter of energy sharing is the utilisation of thermal storage. Heating and cooling demands are rarely simultaneous and so it is necessary to store the shared potential for later usage. Some scenarios tested showed 82% shared energy utilisation with energy storage, compared with only 40% shared energy utilisation without. The Levelised Cost of Energy was 50% higher without thermal storage.
- Energy sharing did not have a significant impact on any of the metrics assessed. While energy sharing did offer improvements, these improvements were dwarfed by the benefit provided by utilising a time of use tariff or a thermal store. Energy sharing was able to show a 12.5% reduction in the Levelised Cost of Energy.
- Some building types are inherently better suited to sharing energy between users. The more users are connected to the network, the more likely shared energy is able to be utilised. From the energy demands assessed, a 14% increase in utilised shared energy can be achieved from connecting complimentary loads. Some demands are inherently poor matches for sharing (e.g. hotels and residential) where the energy demand is particularly heavy in one side. In this case, the heating demand was much greater than the cooling demand. Others are inherently much better, such as office space, where there is a year round mix of heating and cooling demands
- Tariff structures have a significant impact on operating strategy, operating cost, and therefore profitability. In some tested scenarios, the levelized cost was more than 33% less when using a time of use tariff, compared to the equivalent scenario with the fixed rate tariff. However, if there is no means of demand side management, the time of use tariff can be 69% more expensive than the equivalent scenario with demand side management.
- The rate of carbon levy is significantly too low to have any significant impact on either the operating strategy or the equipment sizing and selection. Energy sharing showed a 13% improvement on carbon emissions when compared with an equivalent non-sharing network, but this is un-related to the carbon levy. The cost per tonne of carbon dioxide would need to be significantly higher to force change in operation, and therefore further reduce carbon emissions.

This study utilised a number of assumptions, primarily around the performance of the heat pumps and the operating temperatures of the ambient loop. Further research is needed to better understand the dynamic interaction of energy demands on the sharing network, the selection of ambient loop temperature, and the demand response needed for a well performing energy sharing network.

7.1 Future Work

It is acknowledged that this study has used a number of simplifications which can be improved upon in future work to improve the representation of physical characteristics. Most notably, the study assumes a static coefficient of performance for the heat pumps. This is only likely to be a close approximation for high performance buildings, with low temperature heat emitters and Legionella prevention which is not temperature dependent (e.g. chlorine dosing, UV treatment). For retrofit applications, the efficiency will vary across the year depending on set point temperatures.

The dynamics of the ambient loop have not been considered in detail here. We have assumed that any energy rejected into the loop can instantaneously be used anywhere else on the loop, which may not be true in practice due to hydraulic lag. It is expected that the energy rejected from a single user will not be significant enough to make drastic change to the loop temperature, but is yet to be shown in literature.

8 Acknowledgements

The authors would like to thank the support received from members of Hoare Lea who offered input to the article. This research was funded by the National Productivity and Investment Fund EPSRC Doctoral Scheme (EP/R512266/1), Hoare Lea, Clyde Gateway and received support from the EPSRC “Combi-Gen” project (EP/P028829/1) and the EU H2020 LCE “DESTRESS” project (EC-691728). The research was also funded by the Newton Fund (EP/R003122/1), research fund EP/N020472/1 and the National Productivity and Investment Fund Innovation Placement Scheme (EP/S515395/1).

- [1] Department for Business Energy and Industrial Strategy (BEIS). 2017 UK Greenhouse Gas Emissions, Final Figures. In: National Statistics, editor. London2019.
- [2] Climate Change Act 2008. c27. UK2008.
- [3] The Carbon Budgets Order 2009.
- [4] Change CoC. UK credibility on climate change rests on Government action over next 18 months. 2019.
- [5] The Carbon Plan:Delivering our low carbon future. In: Department of Energy and Climate Change, editor. London2011.
- [6] The Association for Decentralised Energy (ADE). Market Report: Heat Networks in the UK. 2018.
- [7] grid n. Future Energy Scenarios. 2018.
- [8] Li H, Nord N. Transition to the 4 th generation district heating - Possibilities, bottlenecks, and challenges. *Energy Procedia*2018. p. 483-98.
- [9] Assessment of the Costs, Performance, and Characteristics of Heat UK Networks. In: Change DoEaC, editor. London2015.
- [10] Research into barriers to deployment of district heating networks. In: Department of Energy and Climate Change, editor. London2013.
- [11] (BRE); BRE. Distribution loss factors for heat networks supplying dwellings in SAP. 2016.
- [12] Cole C. Heat loss headaches. 2017.
- [13] Chen S, Friedrich D, Yu Z, Yu J. District Heating Network Demand Prediction Using a Physics-Based Energy Model with a Bayesian Approach for Parameter Calibration. *Energies*. 2019;12:3408.
- [14] Guelpa E, Marincioni L, Verda V. Towards 4th generation district heating: Prediction of building thermal load for optimal management. *Energy*. 2019:510-22.
- [15] Li H, Nord N. Transition to the 4th generation district heating - possibilities, bottlenecks, and challenges. *Energy Procedia*. 2018;149:483-98.
- [16] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating: Research and results. *Energy*. 2018;164:147-59.
- [17] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. *Energy*. 2014;68:1-11.
- [18] Sameti M, Haghighat F. Optimization of 4th generation distributed district heating system: Design and planning of combined heat and power. *Renewable Energy*. 2019;130:371-87.
- [19] Soltero VM, Chacartegui R, Ortiz C, Quirosa G. Techno-economic analysis of rural 4th generation biomass district heating. *Energies*. 2018;11.
- [20] Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. *Applied Energy*. 2011;88:479-87.
- [21] Gadd H, Werner S. Achieving low return temperatures from district heating substations. *Applied Energy*. 2014;136:59-67.
- [22] Østergaard DS, Svendsen S. Replacing critical radiators to increase the potential to use low-temperature district heating – A case study of 4 Danish single-family houses from the 1930s. *Energy*. 2016;110:75-84.
- [23] Best I, Orozaliev J, Vajen K. Economic comparison of low-temperature and ultra-low-temperature district heating for new building developments with low heat demand densities in Germany. *International Journal of Sustainable Energy Planning and Management*. 2018;16:45-60.
- [24] Cai H, Ziras C, You S, Li R, Honoré K, Bindner HW. Demand side management in urban district heating networks. *Applied Energy*. 2018;230:506-18.
- [25] Wang D, Hu Qe, Jia H, Hou K, Du W, Chen N, et al. Integrated demand response in district electricity-heating network considering double auction retail energy market based on demand-side energy stations. *Applied Energy*. 2019;248:656-78.
- [26] Saletti C, Zimmerman N, Morini M, Kyprianidis K, Gambarotta A. Enabling smart control by optimally managing the State of Charge of district heating networks. *Applied Energy*. 2020:116286.
- [27] Bühler F, Petrović S, Karlsson K, Elmegaard B. Industrial excess heat for district heating in Denmark. *Applied Energy*. 2017;205:991-1001.

- [28] Broberg S, Backlund S, Karlsson M, Thollander P. Industrial excess heat deliveries to Swedish district heating networks: Drop it like it's hot. *Energy Policy*. 2012;51:332-9.
- [29] Weinberger G, Amiri S, Moshfegh B. On the benefit of integration of a district heating system with industrial excess heat: An economic and environmental analysis. *Applied Energy*. 2017;191:454-68.
- [30] Wirtz M, Kivilip L, Remmen P, Müller D. 5th Generation District Heating: A novel design approach based on mathematical optimization. *Applied Energy*. 2020;260:114158.
- [31] Bünning F, Wetter M, Fuchs M, Müller D. Bidirectional low temperature district energy systems with agent-based control: Performance comparison and operation optimization. *Applied Energy*. 2018;209:502-15.
- [32] Langer L. An optimal peer-to-peer market considering modulating heat pumps and photovoltaic systems under the German levy regime. *Energies*. 2020;13.
- [33] Boesten S, Ivens W, Dekker SC, Eijdens H. 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. *Advances in Geosciences*. 2019;49:129-36.
- [34] Revesz A, Jones P, Dunham C, Davies G, Marques C, Matabuena R, et al. Developing novel 5th generation district energy networks. *Energy*. 2020;201:117389.
- [35] Murphy AR, Fung AS. Techno-economic study of an energy sharing network comprised of a data centre and multi-unit residential buildings for cold climate. *Energy and Buildings*. 2019;186:261-75.
- [36] Song WH, Wang Y, Gillich A, Ford A, Hewitt M. Modelling development and analysis on the Balanced Energy Networks (BEN) in London. *Applied Energy*. 2019;233-234:114-25.
- [37] Bui V-H, Hussain A, Im Y-H, Kim H-M. An internal trading strategy for optimal energy management of combined cooling, heat and power in building microgrids. *Applied Energy*. 2019;239:536-48.
- [38] Huang P, Lovati M, Zhang X, Bales C, Hallbeck S, Becker A, et al. Transforming a residential building cluster into electricity prosumers in Sweden: Optimal design of a coupled PV-heat pump-thermal storage-electric vehicle system. *Applied Energy*. 2019;255:113864.
- [39] Aunedi M, Pantaleo AM, Kuriyan K, Strbac G, Shah N. Modelling of national and local interactions between heat and electricity networks in low-carbon energy systems. *Applied Energy*. 2020;276:115522.
- [40] Heitkoetter W, Medjroubi W, Vogt T, Agert C. Regionalised heat demand and power-to-heat capacities in Germany – An open dataset for assessing renewable energy integration. *Applied Energy*. 2020;259:114161.
- [41] Akter MN, Mahmud MA, Haque ME, Oo AMT. An optimal distributed energy management scheme for solving transactive energy sharing problems in residential microgrids. *Applied Energy*. 2020;270:115133.
- [42] The Government's Standard Assessment Procedure for Energy Rating of Dwellings. In: Change DoEaC, editor. Watford 2014.
- [43] Logenthiran T, Srinivasan D, Shun TZ. Demand side management in smart grid using heuristic optimization. *IEEE Transactions on Smart Grid*. 2012;3:1244-52.
- [44] Gellings CW, Chamberlin JH. Demand-side management: Concepts and methods: The Fairmont Press Inc., Lilburn, GA; 1987.
- [45] Saffari M, De Gracia A, Fernandez C, Belusko M, Boer D, Cabeza LF. Price-based demand side management (DSM) coupled with cold thermal energy storage (TES) and solar PV for peak-load reduction. *ISES Solar World Congress 2017 - IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2017, Proceedings 2017*. p. 1-11.
- [46] Mendaza IDdC, Bak-Jensen B, Chen Z, Jensen A. Stochastic impact assessment of the heating and transportation systems electrification on LV grids. *IEEE PES Innovative Smart Grid Technologies, Europe 2014*. p. 1-6.
- [47] Baruah PJ, Eyre N, Qadrdan M, Chaudry M, Blainey S, Hall JW, et al. Energy system impacts from heat and transport electrification. *Proceedings of the Institution of Civil Engineers - Energy*. 2014;167:139-51.
- [48] Laing T, Sato M, Grubb M, Combetti C. Assessing the effectiveness of the EU Emissions Trading System. 2017.