Optimisation of a theoretical 4th generation district heating network located at the town of Loughborough, UK

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Abstract

A cost and efficiency optimization for a net zero district heat (DH) network providing hot water and space heating for a specific urban area in the town of Loughborough, UK, was performed using a previously developed model. The model simulates a DH system with heat provided from i) renewable heat sources (RHS), i.e. heat pumps powered by PV and/or Wind and evacuated tube solar thermal collectors (ETSTCs), and ii) stored heat from centralized long duration (namely long-term water tank, LTWT) and decentralized thermal energy storage (TES) systems. Based on hourly weather data, building specifications and occupancies the model calculates a) hourly domestic heat demands for both space and domestic hot water, b) the hourly heat production from the specified RHS and c) losses from TES and pipes. The DH network simulations were performed for an 18-month period from the 01/06/2018 00:00 to 31/12/2019 23:00. The effect of parameters affecting the performance of the decentralized short-term water tanks (STWT) used for heat stores including i) the average volume of the STWT (V_{STWT}) per dwelling and ii) the specified STWT charging temperatures ($T_{charging\ STWT}$), on a) the DH system cost per dwelling and b) the energy efficiency of the DH system (η_{DH}) were assessed. The predictions showed that increasing either the V_{STWT} and/or $T_{charging\ STWT}$ leads to i) an increase in the total cost of the DH system per dwelling, and ii) to a decrease in the η_{DH}. These results are mainly due to a reduced use of the LTWT, which results in a greater required installed Wind generation capacity and number of heat pumps to fully meet heat demands at certain periods of the year and as a consequence greater heat losses and increased amounts of heat being shed in the DH system.

Keywords: district heating; thermal energy storage; modelling; optimization; renewable; simulation

1. Introduction

The green deal recently approved by the European Union aims to reduce the greenhouse gas emission to 50% by 2030 relative to 1990 levels. In order to do this, reductions of greenhouse emissions originating in the residential sector [which was responsible for 26.1% of the final energy consumption of the European Union in 2018 (European Union, 2020)] are crucial. Different paths can be taken to accomplish this target including: i) replacing common fossil fuel heat sources by renewable heat sources, ii) increasing the efficiency of domestic heating systems and iii) implementation in urban areas of highly efficient 4th generation district heating (DH) networks. The recent increase in the costs of fuel together with the energy crisis in Europe resulting from Russia's invasion of Ukraine adds urgency to the transition to in-country local production of renewable energy instead of the importation of fossil fuels.

The 4th generation DH system approach aims to almost fully decarbonize the production of heat for domestic use by predominantly using renewable heat sources (RHS) and low/zero carbon heat sources (Lund et al., 2014). Due to the intermittent nature of renewable heat sources, the inclusion of thermal energy stores (TES) in 4th generation DH seems crucial. TES consist of a storage medium that stores thermal energy (heat or cold) produced at a time when heat production is greater than demand which can be released later when demand exceeds production. TES systems are classified depending on the storage approach used and may be sensible, latent or thermochemical. TES can also be classified based on storage duration: short-term and long-term storage. Short term stores for space heating are usually small devices located near or inside dwellings which are used to alleviate peak domestic heat requirements, whereas long term stores are generally larger stores which are charged during the summer months

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and discharged in winter months, providing backup in winter months for renewable heat generation and short-term stores.

One of the key parameters in the design of TES is to determine both the optimum volume and charging temperature that enables all domestic heat loads of dwellings connected to a DH network to be met all year round at minimum cost. Studies of how these parameters affect the cost and energy efficiency of a DH system are scarce, and most of the research publications in this area have focused on dynamic models of selected elements of a DH system rather than undertaking the simulation of a full DH system. The current simulations include i) different RHS available near a given urban area and ii) different short-term and long-term TES options (which include the three main types of TES systems used for storing heat, i.e. sensible, latent and thermochemical).

Allison et al. (Allison et al., 2018) calculated the theoretical maximum heat storage capacity required for different TES options to support load shifting. A hot water storage tank, concrete, high-temperature magnetite blocks, and a phase change material (PCM) (Paraffin C28) were the TES options considered. The results obtained showed that i) with low temperature heat storage, domestic load shifting is feasible over a few days (beyond this timescale, the very large storage volumes required makes integration in dwellings problematic); ii) supporting load shifting over 1–2 weeks is feasible with high temperature storage (retention of heat over periods longer than this is challenging, even with significant levels of insulation); iii) seasonal storage of heat in an encapsulated store appeared impractical in all cases modelled due to the volume of material required. The authors calculated the store heat capacities assuming that the heat load was to be fully met just using the stores with no additional heat input. Long-term large scale heat storage options, such as water tanks for seasonal heat storage and/or thermochemical storage (TCS) systems were not considered. Gaucher-Loksts et al. (Gaucher-Loksts et al., 2022) carried out the simulation of a system composed of air source heat pumps and building-integrated photovoltaic systems located in a solar house. Three different configurations of the system were evaluated, two of them including thermal storage (hot water). The authors determined that the tank volume and solarium size had the highest impact on the flexibility of the system. An optimal size for the store volume of between 300 and 600 L was determined for a house with a floor area of 116 m^2 (no seasonal heat stores were considered in the study). Schuetz et al. (Schuetz et al., 2017) carried a simulation of a system consisting of a combination of heat pumps and thermal storage systems for residential heating. The authors found that a larger heat pump size improves the system's flexibility while the size of the store had little impact. The authors also found also that the store volume, heat pump size, and load significantly impact the length of time the store remains charged and thus the flexibility of a system.

The present research aims to contribute to the development of designs for and future successful implementation of 4th generation DH systems in the UK and similar climates. The main objective of the reported research was to apply a novel model to simulate a theoretical 4th generation district heating system (which is fully described in (Pans et al., 2023) to determine the optimum operating conditions that i) minimises the cost of the DH network per dwelling and ii) maximises the energy efficiency of the network (by minimising heat shed in summer), while completely meeting domestic heat loads for the full simulation period. The proposed DH network modelled was based on the characteristics of two residential areas in Loughborough, UK. The effect of changing key parameters related to the decentralised TES system, [referred to as “short-term water tank” (STWT)], including the store charging temperature ($T_{charging\ STWT}$) and the store volume (V_{STWT}), on a) the total average cost per dwelling and b) energy efficiency of the DH system were assessed.

2. Methodology

2.1. Description of the proposed DH system

A detailed description of the model employed can be found in (Pans et al., 2023). Fig. 1 shows the general components and arrangement proposed for a DH system using only renewable heat sources and TES systems to meet annual hourly heat demands. As can be seen, in the model schematic presented in Fig. 1 the heat to meet domestic heat demands is produced using i) heat pumps (HPs) powered only by electricity produced by solar photovoltaic (PV) and Wind Turbines (it is assumed that there is no connection with the electricity grid) and ii) evacuated tube solar thermal collectors (ETSTCs) located on or very near the dwellings. In scenarios where the heat produced is higher than the heat demand, the extra heat is stored in domestic TES located inside or near the dwellings. In those scenarios where both the heat produced is higher than the demand and the domestic TES have reached their maximum storage capacity, the power not used from PV and Wind is used in another set of

HPs located near a seasonal TES - the long-term water tank (LTWT) - to increase the temperature of the water inside the LTWT to the required charging temperature. The extra heat generated by the ETSTCs not used to meet the domestic heat demands and/or to fill the stores is shed.

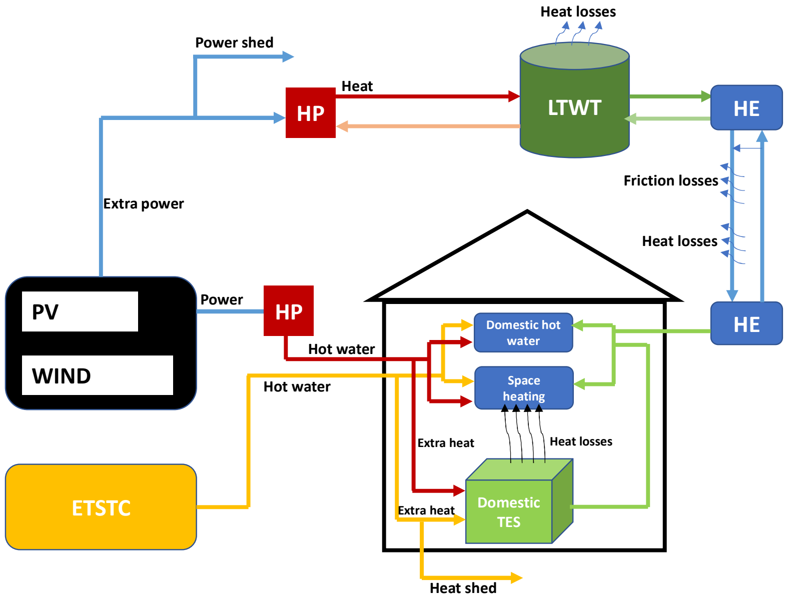

Fig. 1: A schematic diagram illustrating the components and operating mode proposed for a net zero DH network.

2.2. Methodology

The methodology used to carry out the simulation of the DH system described in detail in (Pans et al., 2023), can be split in to two different well-defined stages:

i) Calculation of hourly heat demand profiles for both space heating and domestic hot water by means of a) the number and type of buildings in a specified area and b) location specific hourly weather data. Four different building forms, detached, semi-detached, terraced and flats, were considered in this study. Key characteristics of the buildings such as floor areas, fabric form and U-values, glazing areas, orientation and occupancy were included in the model.

ii) Calculation of hourly energy/heat produced by the employed different RHS types. An online tool created by Pfenninger and Staffell (Pfenninger and Staffell, 2016) was used to estimate the hypothetical hourly capacity factor for both PV and Wind energy sources and the hourly ground-level solar irradiance (needed to calculate the efficiency of the ETSTCs).

Four different thermal storage systems were considered:

a) A centralized large long term heat store (water based, called long-term water tank, LTWT);

b) 3 types of decentralized small scale thermal stores located in the building stock: STWT, PCM-based stores and TCS-based stores.

Heat losses from stores and the distribution network in addition to pumping power requirements were calculated for each hour.

2.3. Application of the model to a residential area in Loughborough, UK

Fig. 2 shows the two urban areas in Loughborough, UK, considered in this simulation study (namely blue and red areas). The total number of dwellings is 262 (173 dwellings in the blue area and 89 in the red area). The two different areas were divided into different sub-areas with an average of ca.10 dwellings per sub-area. Data regarding the number of dwellings, type of dwelling and household type was exogenously obtained from the official labour market statistics for both residential areas (Pans et al., 2023).

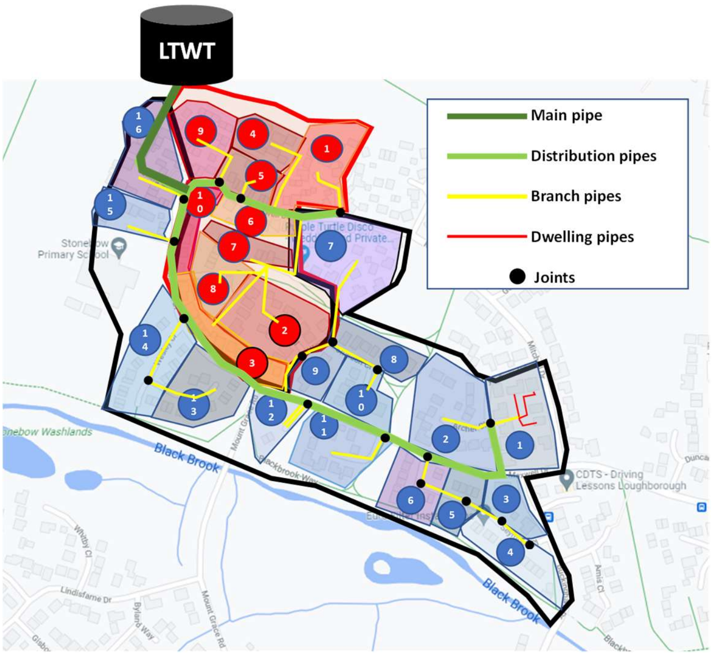

Fig. 2: Residential areas of the town of Loughborough considered for the simulations performed, illustrating the proposed layout of the DH network and the location of the LTWT

The piping network proposed for the DH system located in Loughborough is presented in Fig. 2. The location of the LTWT was assumed to be adjacent to the residential area. Four different types of pipes with different diameters were used: LTWT main (dark green), main distribution (light green), branch (yellow) and dwelling pipes (red). The LTWT main is the pipe that connects the LTWT with the main distribution pipes; the main distribution pipes connect the LTWT with the two different urban areas (red and blue); the branch pipes connect the main pipes to the different sub-areas; and finally, the dwelling pipes connect the branch pipes to the dwellings. The black dots indicate joints between two or more pipes. The distance between joints was calculated using Google maps. The total length of the modelled piping network was 3466 m. The pipes were assumed to be made of polyvinyl chloride with an insulation of foam (Aluflex type). The diameters of the different pipe sections were chosen to avoid maximum velocities of water inside the pipes greater than ca. 1.5 m/s. The thickness of the insulation material for the different pipes was chosen following manufacturers recommendations. The heat losses and friction losses in the piping network were calculated for each hour for every pipe section (sections of the pipe between two joints) based on the flow rate and dimensions of each specific pipe section (Pans et al., 2023). The time-period considered in the simulation of the DH system was from 01/06/2018 00:00 to 31/12/2019 23:00.

2.4. DH system optimization methodology

Tab. 1 shows the values used in the simulations for the main parameters of the DH network. Optimisation was performed by determining the mix of installed capacities of Wind ($Wind_{capacity}$) and solar PV ($PV_{capacity}$) required to fully meet domestic heat demands for the whole time period of the simulation for the minimum cost per dwelling. The model uses the hourly capacity factor for both PV and Wind in the town of Loughborough obtained exogenously from (“Renewables Ninja on-line tool,” n.d.), as explained in section 2.2. The Coefficient of Performance (COP) values for the two types of HPs were calculated for each hour in the simulation using the equation and parameters show in (Pans et al., 2023). The total number of heat pumps required to meet the loads was calculated at every hour by dividing i) the hourly power output from the combination of different amounts of PV and Wind (thus assuming that the HPs are not connected to the grid) by ii) the minimum power required to operate a heat pump, which was assumed 5 kW for domestic HPs and 15 kW for HPs used to boost the temperature of the water inside the LTWT. The sizes were chosen according to information regarding typical sizes for domestic

HPs, which range between 5 and 15 kW (Ecoexperts, n.d.; Evergreen energy, n.d.). In this work, a HP size of 5 kW was used to provide heat for dwellings and 15 kW to charge the LTWT, as the amount of extra heat to be stored in the latter is usually much higher than the amount of heat required in individual dwellings to meet demands and/or the amount of heat to be stored in individual domestic TES. Once the minimum number of heat pumps needed in each hour was determined, the minimum number of heat pumps required for to meet loads for the whole time-period considered in a simulation, was the maximum of all hourly minimum-number-of-heat-pump values. For the simulations half of the minimum number of heat pumps required were specified to be air-source heat pumps (ASHPs) and half ground-source heat pumps (GSHPs) (for heat pumps used for boosting the LTWT temperature the acronyms used are ASHP-LTWT and GSHP-LTWT). The mix of heat pump types can be varied based on local conditions. The average area of ETSTC per dwelling was set at 2 m^2. The size of the LTWT was determined taking into consideration the maximum monthly heat demand predicted for the proposed DH system and for the full time-period of the simulation, which in this case corresponds to the heat demands obtained for January 2019 (625875 kWh). A volume of 15000 m^3 was specified for the LTWT to provide sufficient capacity to store/discharge the heat needed to satisfy the heat demands of the DH system in the coldest month of the year (15000 m^3 provides 696666 kWh of heat storage, based on a charging temperature of 60°C and a return temperature of 20°C with a perfectly stratified store).

Tab. 1: Main fixed parameters specified for the simulation

TESsystem main parameters	
Deployment (% of dwellings with stores)	
STWT	50%
PCM	30%
TCS	20%
Charging temperature (°C)	
STWT	Variable (50 – 90°C)
PCM	50
TCS	120
LTWT	60
Volume	
STWT volume per dwelling (m^3)	Variable (0.1 – 0.4)
PCM volume per dwelling (m^3)	0.2
TCS volume per dwelling (m^3)	0.2
LTWT (m^3)	15000

The selected levels of deployment of different decentralised TES systems into dwellings was based on their current technology readiness levels. 0.2 m^3 per dwelling was specified for PCM and TCS systems. The effects of two key parameters in the design of the STWT systems, the volume (V_{STWT}) and charging temperature ($T_{charging\ STWT}$) on a) the average total cost per dwelling and b) energy efficiency of the DH system was assessed.

2.5. Assumed capital costs of the DH system components

Only initial capital costs were considered in this work. The capital costs for the different constituent parts of the simulated DH network obtained from a range of sources are detailed in Tab. 2. The cost of the piping network includes the cost of pipes, installation work, circulation pumps and heat exchangers in dwellings.

Tab. 2: Costs for the different constituent parts of the DH system

Energy and heat sources		Capital cost
Installed PV (£/MW)((STA), n.d.)		1000000
Installed Wind (£/MW)(Briefings for Britain, n.d.)		1290000
ETSTC (£/m^2)[1]		170
ASHPs (£/kW)(Staffell et al., 2012)	Capital cost (£/kW_{th})	$\frac{£}{kW_{th}} = 200 + \frac{4750}{{kW_{th}}^{1.25}}$
	Installation cost (£)	1500
GSHPs (£/unit)(Staffell et al., 2012)	Capital cost (£/kW_{th})	$\frac{£}{kW_{th}} = 200 + \frac{4750}{{kW_{th}}^{1.25}}$
	Installation cost (£/kW_{th})	800
TES		
TCS (£/kg)(Mahon et al., 2020)		0.2
PCM (£/kg)(Fadl and Eames, 2019)		6
STWT (£/0.2 m^3)(Guelpa and Verda, 2019)		200
LTWT (£/m^3)(Guelpa and Verda, 2019)		50
Network		
Piping network (£/dwelling) (Energy research partnership, 2016; Energy technologies institute, 2018)		800

[1]Obtained as an average of prices found online for different ETSTCs brands.

3. Results

3.1. Effect of V_{STWT} and $T_{charging\ STWT}$ on the average cost of DH system per dwelling.

The simulations show that for all different studied scenarios the minimum cost is always achieved when no PV is installed at the dwellings to power the domestic HPs and only wind turbines are used to generate power. The reason for this is that in the Loughborough area, the average capacity factor (i.e. the average power output divided by the maximum power capability) of wind turbines for the time-period considered in the simulations is more than double that for PV (as shown in Fig. 3), which results in an average higher cost required to produce the same amount of power when using PV compared to when using Wind turbines.

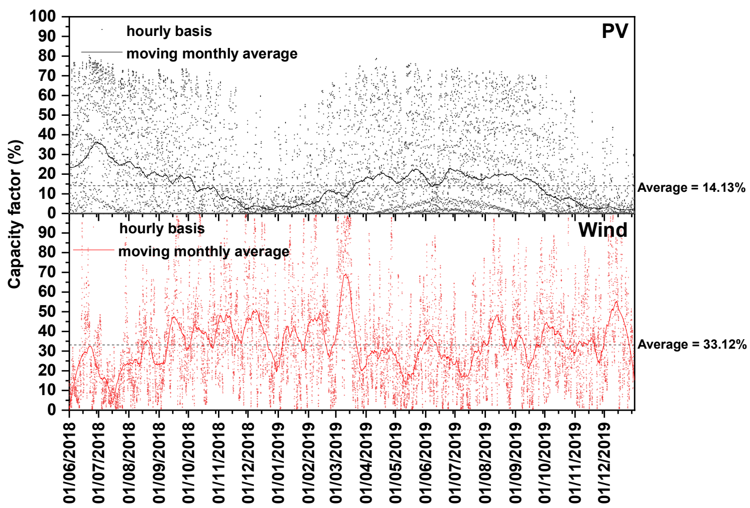

Fig. 3. Capacity factor for solar PV and Wind power generation from 01/06/2018 00:00 to 31/12/2019 23:00 in the Loughborough area. Hourly basis (dots) and moving monthly average (lines). Results obtained using weather date from the online simulation software www.renewables.ninja ("Renewables Ninja on-line tool," n.d.).

Fig. 4 shows the effect of V_{STWT} on the average cost of the DH system per dwelling for different $T_{charging\ STWT}$ values. As can be seen, higher values of V_{STWT} lead to an increase in the cost per dwelling. At $T_{charging\ STWT}$ = 50°C, the increase in the cost with increasing V_{STWT} is mainly due to an increase in the cost of the store, with the cost of the other components of the DH system remaining roughly constant, as can be seen in Fig. 5. As $T_{charging\ STWT}$ increases, the Wind capacity needed and number of HPs increases with $V_{STWT,}$ which leads to a further increase of the cost. This is because with increasing V_{STWT} more heat can be stored in the STWT and as a consequence less heat is stored in the LTWT, which leads to a shortage of available heat from the LTWT at certain times of the year and thus to a higher Wind capacity and, as a consequence, number of HPs needed to meet demands. This can be seen in more detail in Fig. 6, where the hourly heat stored in the LTWT is presented for different V_{STWT} values when operating at $T_{charging\ STWT}$ = 80°C with a set $Wind_{capacity}$ = 0.4277 MW (which is the minimum $Wind_{capacity}$ required in the simulations using the minimum V_{STWT} value used in this work, i.e., 0.1 m^3 per dwelling). As can be seen in Fig. 6, the increase of V_{STWT} reduces the amount of heat available in the LTWT between 15/01/2019 and 15/03/2019, as a consequence the domestic heat demands cannot be met at certain times of this period, as shown in Fig. 7. This results in a higher Wind capacity needed to meet the domestic heat demands for those specific times and dates.

The shortage of available heat from the LTWT when increasing V_{STWT} can be explained by the fact that the rate of heat losses from heat stored in the LTWT are smaller than the heat losses per unit of heat stored in the STWT (due to the greater surface area to volume ratio of the STWT). Thus, at higher V_{STWT} more heat can be stored in STWT, meaning higher heat losses in the system.

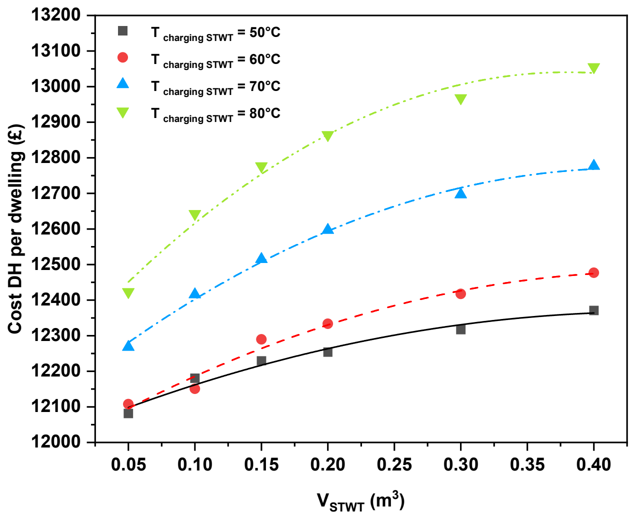

Fig. 4: Effect of V_{STWT} and $T_{charging\ STWT}$ on the average cost of the DH system per dwelling.

As can be seen in Fig. 4, the increase of $T_{charging\ STWT}$, leads to an increase in the cost of the system (for set volumes V_{STWT}) which is again due to the increase in both $Wind_{capacity}$ and minimum number of HPs required to meet fully domestic heat demands, as seen in Fig. 5. Similar explanations of that mentioned above when explained the effect of V_{STWT} on cost can be given here, i.e. the higher $T_{charging\ STWT}$ the higher storage capacity available in STWT which leads to less use of the LTWT and thus to a shortage of the heat stored in the LTWT in winter/autumn months. Further, when $T_{charging\ STWT}$ increases the efficiency of both HPs and ETSTC decreases which leads to less heat produced and stored in the STWT. Due to this, the charging of the STWT store is slower and consequently at certain dates and times higher $Wind_{capacity}$ is required, compared to the $Wind_{capacity}$ needed for simulations with low $T_{charging\ STWT}$ values, to meet the domestic heat demands.

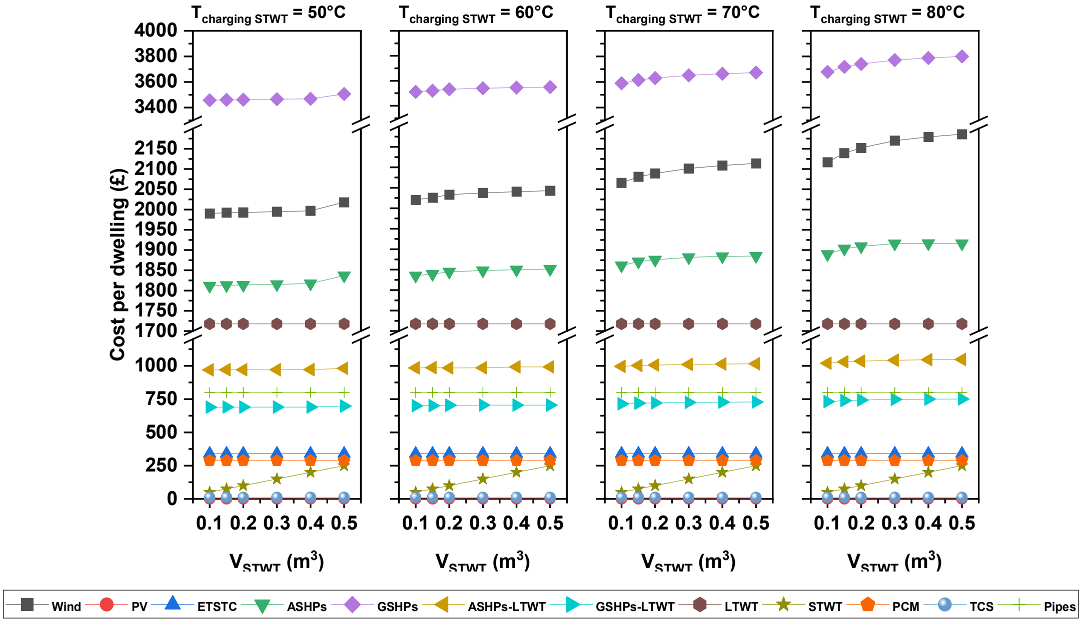

Fig. 5: The effect of V_{STWT} on the cost of the different parts of the DH system when operating at $T_{charging\ STWT}$ values of 50,60,70 and 80 °C.

A minimum cost of £12,103 per dwelling was obtained for V_{STWT} = 0.1 m^3 and $T_{charging\ LTWT}$ = 50°C, which is in the same range of cost obtained for DH networks by different authors (AECOM, 2017; Department of energy and climate change, 2015; Wang, 2018). Unlike these studies, the present study assumes only decentralised renewable heat sources, which it is assumed would result in a much higher costs than that of DH systems using centralized heat sources. However, the cost predicted was similar to those estimated by sources considering centralized heat sources which indicates the benefits of incorporating TES into DH networks supplied using only renewables in terms of cost and efficiency. The predicted average cost per dwelling is also less than the installation cost of a single GSHP and slightly higher than the cost of a single ASHP.

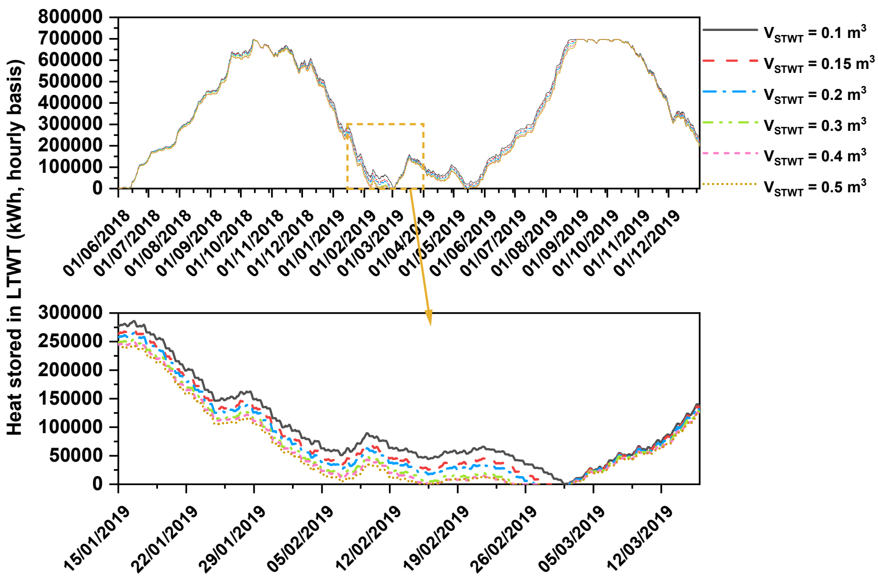

Fig. 6: The effect of V_{STWT} on the heat stored in the LTWT from 01/06/2018 00:00 to 31/12/2019 23:00 when operating at $T_{charging\ STWT}$ = 80°C and $Wind_{capacity}$ = 0.4277 MW.

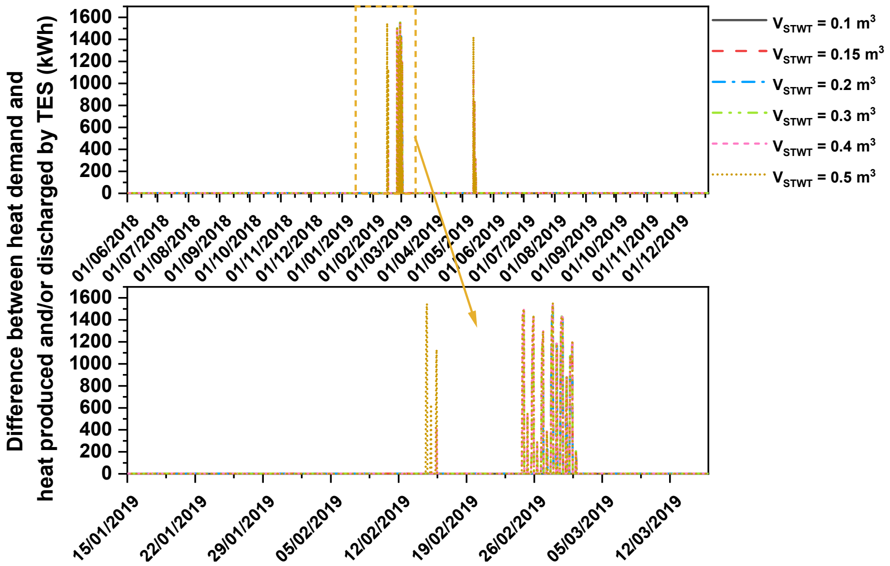

Fig. 7: The effect of V_{STWT} on the difference between i) heat demand and ii) heat produced and/or discharged by TES, from 01/06/2018 00:00 to 31/12/2019 23:00 when operating at $T_{charging\ STWT}$ = 80°C and $Wind_{capacity}$ = 0.4277 MW.

3.2. Effect of V_{STWT} and $T_{charging\ STWT}$ on η_{DH}.

The overall energy efficiency of the DH network (η_{DH}) was calculated using **Eq. 1**:

$$\textbf{Eq. 1}\quad \eta_{DH\,(t)}\,(\%) = \frac{Useful\ hea\ _{(t)}}{Energy\ delivered_{(t)}} \cdot 100$$

Where $Useful\ energy_{(t)}$ is the sum of the heat used in dwellings plus the heat stored in TES, and $Energy\ delivered_{(t)}$ is the sum of the i) heat produced by the different RHS ii) the heat discharged from TES and iii) the heat losses in STWT and PCM stores. The reason behind the inclusion of heat losses from both STWTs and PCM stores is that as these devices were assumed to be located inside the dwellings, the heat losses from these stores can act as heat gains to dwellings and be used to reduce the domestic space heat demand.

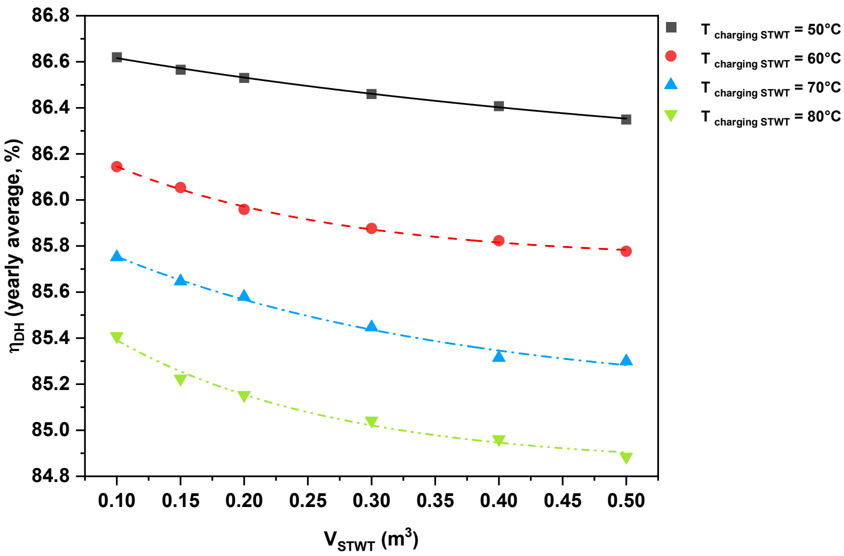

Fig. 8: Effect of V_{STWT} and $T_{charging\ STWT}$ on η_{DH}.

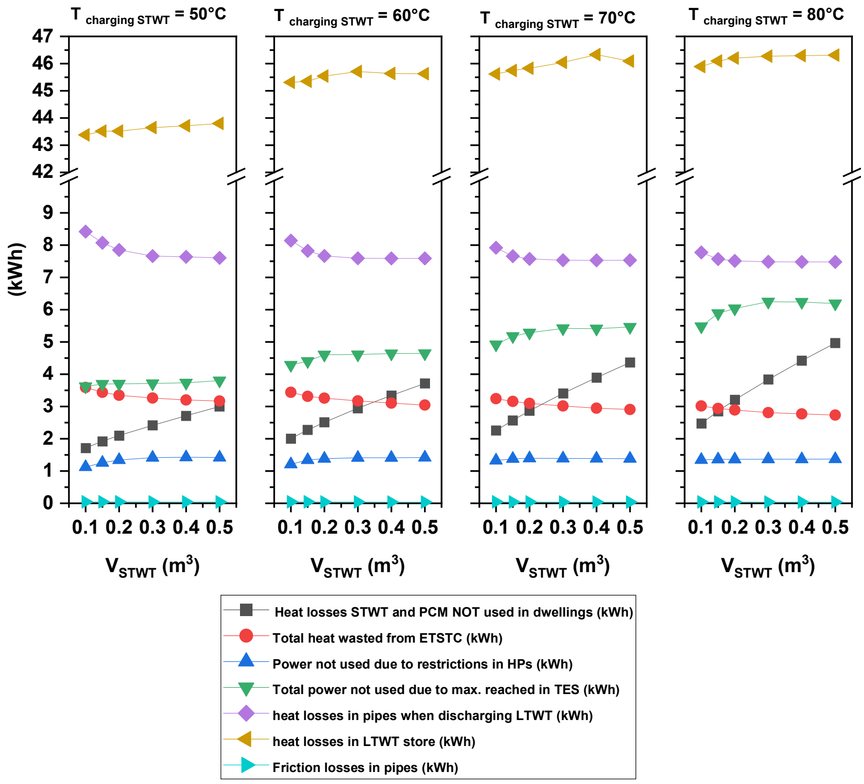

Fig. 9: The effect of V_{STWT} on the heat and power shed and heat losses from different parts of the DH system for different $T_{charging\ STWT}$ values (yearly average).

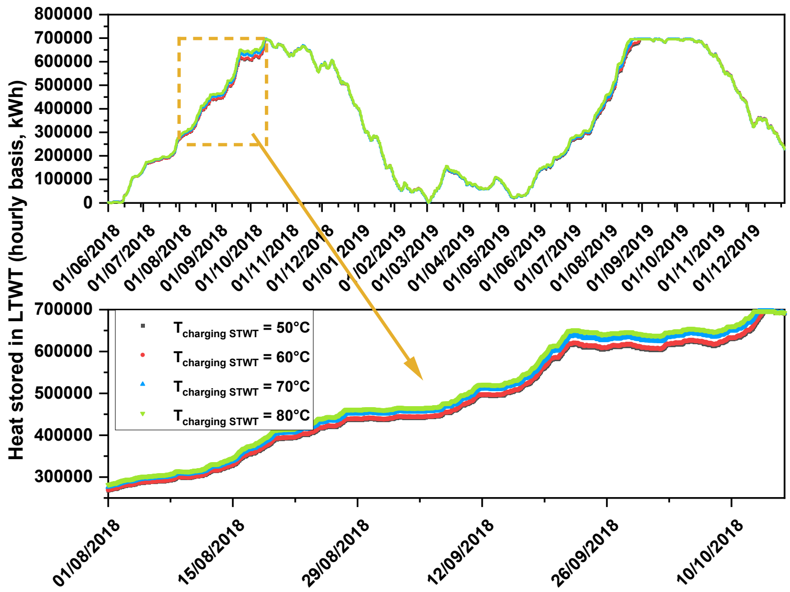

Fig. 10: The effect of $T_{charging\ STWT}$ on the heat stored in the LTWT for V_{STWT} = 0.5 m³.

The predicted effect of both $T_{charging\ STWT}$ and V_{STWT} on the yearly average DH network energy efficiency are presented in Fig. 8. From Fig, 7, it is clear that for the range simulated both V_{STWT} and/or $T_{charging\ STWT}$ have little effect on predicted η_{DH}, with a maximum difference of ca. 1.8 percent between the systems with the highest and lowest η_{DH} value. When V_{STWT} and/or $T_{charging\ STWT}$ increases the overall energy efficiency of the DH system decreases, due mainly to the increase in both the power shed and the heat losses from the STWT devices, as can be seen in Fig. 9. It is important to remark here two aspects: i) first, the heat losses from STWT that affect the energy efficiency are heat losses that cannot be used to alleviate heat loads at certain hours, due to the absence of heat demands at these hours; the power shed is power not used in HPs, but in real applications this power could be used somewhere else in the buildings or to be sold, so it would not be shed (so the efficiency would be higher).The increase in the power shed with increasing either V_{STWT} and/or $T_{charging\ STWT}$ is due to the increase in the minimum $Wind_{capacity}$ needed to fully meet the domestic heat demands. This means that, at certain times of the year, the amount of power generated that is not used despite the higher STWT storage capacity available and thus shed will be high (at those times when the LTWT is also fully charged). The greater heat losses from the LTWT obtained when increasing $T_{charging\ STWT}$ can be explained again by the higher $Wind_{capacity}$ needed at higher $T_{charging\ STWT}$, which results in higher levels of heat stored in the LTWT at certain times of the year, as can be seen in Fig. 10. The predicted yearly average η_{DH} obtained for the minimum-cost case-scenario, i.e. V_{STWT} = 0.1 m^3 and/or $T_{charging\ STWT}$ = 50°C, was 86.62%, which is in the same range as those obtained in other studies (Li and Svendsen, 2012; Zhang et al., 2021).

4. Conclusions

In the present work, an optimisation study of a simulated DH network for two areas in the town of Loughborough, UK, for the time period from the 01/06/2018 00:00 to 31/12/2019 23:00 was undertaken. This was achieved by a parametric analysis of the effect of operating parameters for the DH network, V_{STWT} and $T_{charging\ STWT}$ on the DH system cost per dwelling and the overall energy efficiency of the DH system. For each simulated case the results were obtained by modifying the installed capacity of both Wind and PV in order to ensure domestic heat loads were met for the whole time-period at the minimum cost. The predictions show that the increase of both V_{STWT} and $T_{charging\ STWT}$ lead to an increase in the total cost per dwelling and a decrease in the overall η_{DH} value, due to the greater amount of heat stored in the STWT which leads to a reduction in heat stored in the LTWT. This results in ii) more heat losses and ii) a shortage of heat from storage in the winter months and thus more $Wind_{capacity}$ needed to meet demands (meaning more power shed).

A predicted minimum cost of £12,103 per dwelling and DH network energy efficiency of 86.62% was obtained at the optimum conditions found.

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