Optimisation of a Theoretical District Heating System with Seasonal Thermal Energy Storage

Miguel Angel Pans Castillo*, Philip Eames

Centre for Renewable Energy Systems Technologies (CREST), Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Leicestershire LE11 3TU, UK
**Corresponding author. Email:* m.pans-castillo@lboro.ac.uk

ABSTRACT

A novel model was used to simulate how an existing district heating (DH) network for Holywell Park, Loughborough University (Loughborough, UK) could be transitioned to low/zero carbon heat. A simulation which includes heat pumps (HPs) and evacuated-tube solar thermal collectors (ETSTCs) to both provide heat for buildings and charge a potential seasonal thermal energy storage (STES) system was performed. Both a) real historic half-hourly CO_2 emissions per kWh of electricity and b) real historic half-hourly heat demands for Holywell Park for the year 2021 were used in the simulations. The model assumes that HPs can only be used to charge STES systems at those times when the CO_2 emissions associated with grid electricity are zero. A parametric analysis was used to investigate the effect of a) the inclusion of STES in the DH system and b) when including the STES 1) the volume of STES system and 2) maximum amount of zero-emissions electricity available to charge STES ($E_{CO2 = 0, STES}$) on the levelised cost of heat (LCOH) for a 23 year simulation period.

Keywords: *district heating, thermal energy storage, modelling, optimization, zero-carbon sources, CO_2 emissions.*

1. INTRODUCTION

In June 2019, the UK government committed to achieve ‘net zero’ emissions of greenhouse gases by 2050, compared to 1990 levels [1]. The implementation in urban areas of district heating (DH) networks is a possible solution to reduce/minimise the CO_2 emissions coming from the residential sector, which in the UK represents 16% [2] of total emissions. DH systems are based on the idea of providing heat to multiple users by means of a centralised high-efficiency heating unit, replacing low- efficiency distributed in-building heating units, which increases the overall efficiency [3]. Low-temperature DH networks allow easier replacement of common fossil fuel heat sources by renewables, which is key to eliminate CO_2 emissions associated with heating.

To address the mismatch between heat demand and production when using renewable heat sources, thermal energy storage (TES) systems are included in DH systems. Thermal energy storage systems act as a buffer between demand and supply, improving both the flexibility and the performance of DH systems and enabling the increased integration of renewable energy sources into heat networks.

The environmental and economic benefits of including TES in DH have been studied by different authors. Pakere et al. [4] performed a simulation of an existing DH system, which uses as heat sources a solar field, biomass and natural gas boilers, integrated with a thermal storage tank. They found that increasing the thermal storage capacity, together with the inclusion of heat pumps and local waste heat as heat sources, leads to a significant decrease of the fossil fuel consumption, an increase in the energy efficiency and a reduction of heat production costs.

Li et al. [5] found that the application of a fifth-generation district heating and cooling system integrated with borehole thermal energy storage can achieve lower levelised costs of energy, lower greenhouse gas emission, higher exergy efficiency, and lower electricity peak load compared to decarbonisation of heat through individual heat pumps/air conditioning units in each building.

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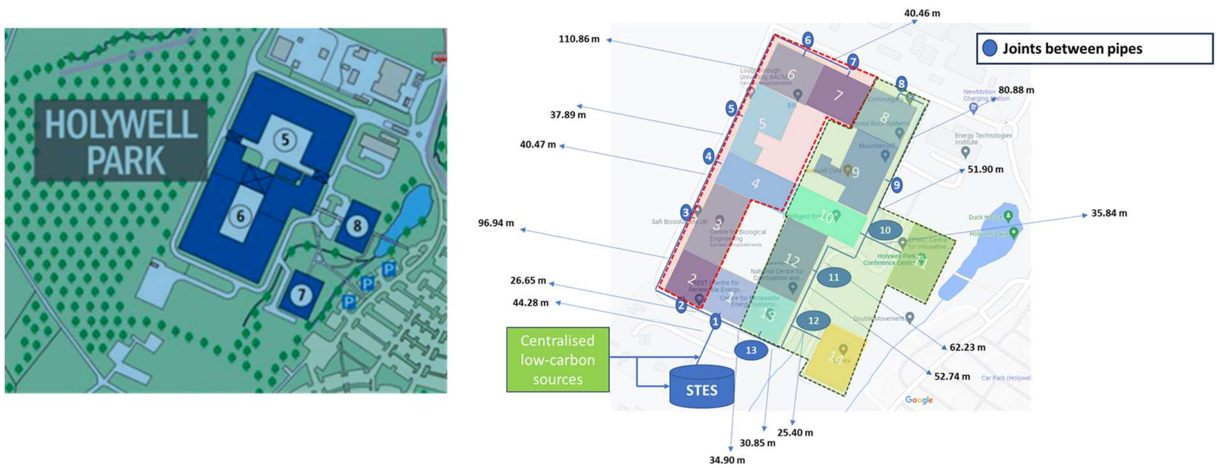

Fig. 1. Existing DH system with added low-carbon heat sources and STES.

Lerbinger et al [6] developed a methodology for determining optimal decarbonization strategies for existing DH networks while considering building-level energy supply and retrofitting investment decisions and the expansion of existing DH networks. They found that a combination of heat pumps, hot water thermal storage and solar PV reduces both total system costs and CO_2 emissions.

1.1. Aim of this study

The main goal of the current research work presented is to apply a novel model to simulate how an existing DH network for Holywell Park, Loughborough University (Loughborough, UK) could be transitioned to low/zero carbon heat. A simulation which includes heat pumps (HPs) and evacuated-tube solar thermal collectors (ETSTCs) to both provide heat for buildings and charge a potential centralised seasonal thermal energy storage (STES) system was performed. The main novelties of this work are:

i) STES are charged using HPs at times when the CO_2 emissions generated from electricity production are 0, i.e. times when all grid electricity is generated by zero-carbon sources. Simulations used real half-hourly CO_2 emissions data per kWh of electricity produced in the UK in 2021 in the North-west area;

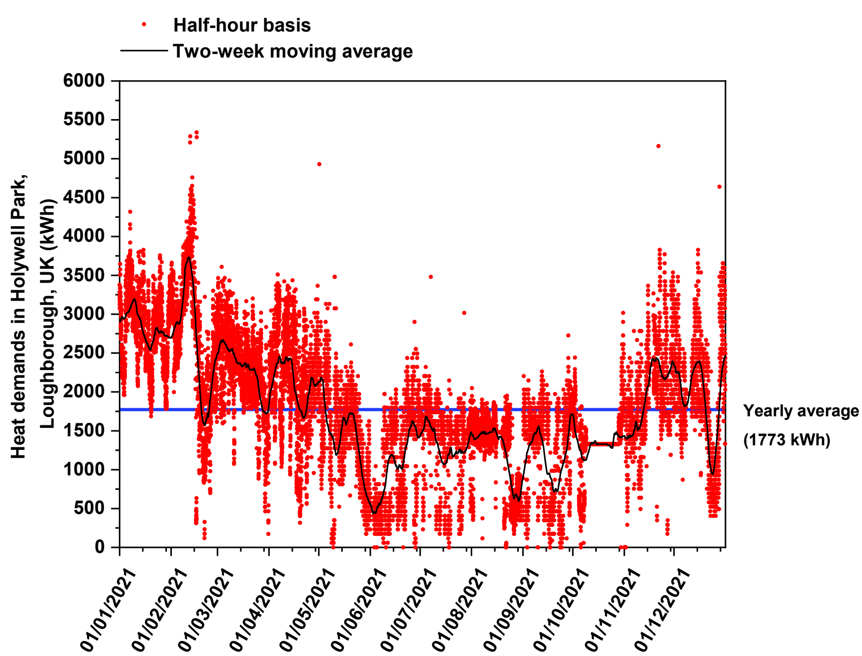

Fig. 2. Heat demands for Holywell Park, Loughborough University, Loughborough, UK.

ii) prediction of the effects of 1) including STES in the DH network and 2) assessment of the effect of both the volume of STES and the maximum amount of electricity produced by zero-carbon sources used in HPs to charge the STES, on the levelised cost of heat calculated for a simulated 23-year period.

2. METHODOLOGY

2.1. Proposed DH system

Fig. 1(left) shows a plan of Holywell Park in Loughborough University (Loughborough, UK). The park comprises three buildings: Holywell building, Holywell Park conference centre and Charnwood building. A DH system already serves the Holywell Park complex, using gas boilers to produce heat and a centralised combined heat and power unit. The proposed upgraded DH system includes HPs and ETSTCs as heat sources which in the simulations are assumed to be located near the south wing of the Holywell building. When considering the scenario with STES, the STES was assumed to be located adjacent to the centralised heat sources HPs and ETSTCs. To achieve greater precision in the calculation of both heat losses and friction losses from pipes the main building was divided in to 12 sub-areas, as shown in Fig. 1 (right). Half-hour heat demand data for the whole Holywell Park complex for the year 2021 was supplied by the Estates and Facilities Management team of Loughborough University and are shown in Fig. 2. Data for other years were not available at the time this study was undertaken. To estimate the half-hour heat demands for years from 2000 to 2023 inclusive, different correlations between the half-hourly heat demands and the outdoor temperature for the year 2021 were obtained and are presented in Fig. 3. Heat demands for other years were estimated using the asymptotic correlation shown in Fig. 3, and half-hourly outdoor temperature data sourced from the online tool Renewables.ninja [7].

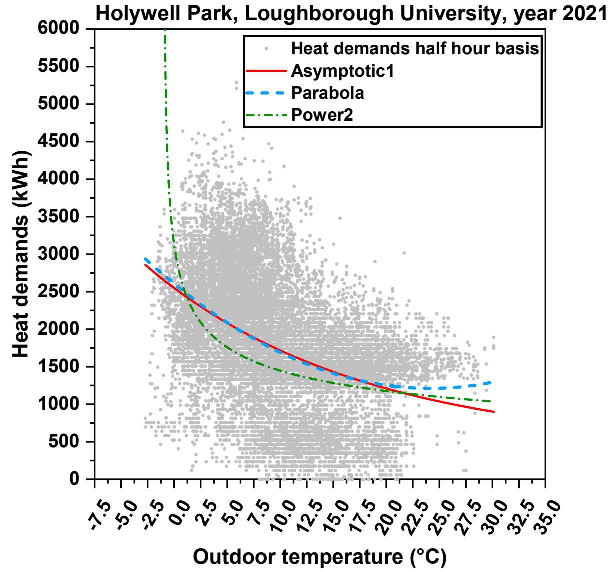

Fig. 3. Correlations between the outdoor temperature and the heat demands for Holywell Park, Loughborough University, UK, for the year 2021.

2.2. CO_2 emissions data

Real half-hourly historic CO_2 emissions data per kWh per half hour of electricity produced in the UK (7% transmission and distribution loss included) for the year 2021 was used in the simulations. The half hourly CO_2 emissions data was provided by SSE Energy Solutions for the North West region of England and is plotted in Fig. 4. Zero values in the data set indicate times ar which

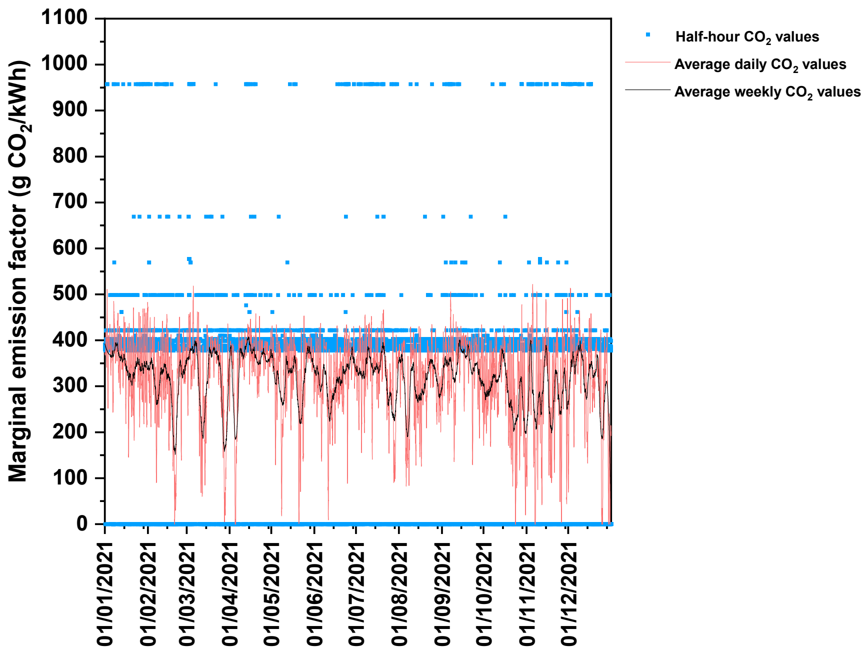

Fig. 4. Historic CO_2 emissions per kWh of grid electricity for the North West region of the UK, 2021 (7% transmission and distribution loss included).

electricity is generated only by zero-carbon sources such as biomass, hydro, pumped hydro, batteries, wind and solar PV, etc.

Fig. 5 shows the methodology followed when undertaking simulations for the scenario with STES. In the simulations the model ensures that the heat loads are

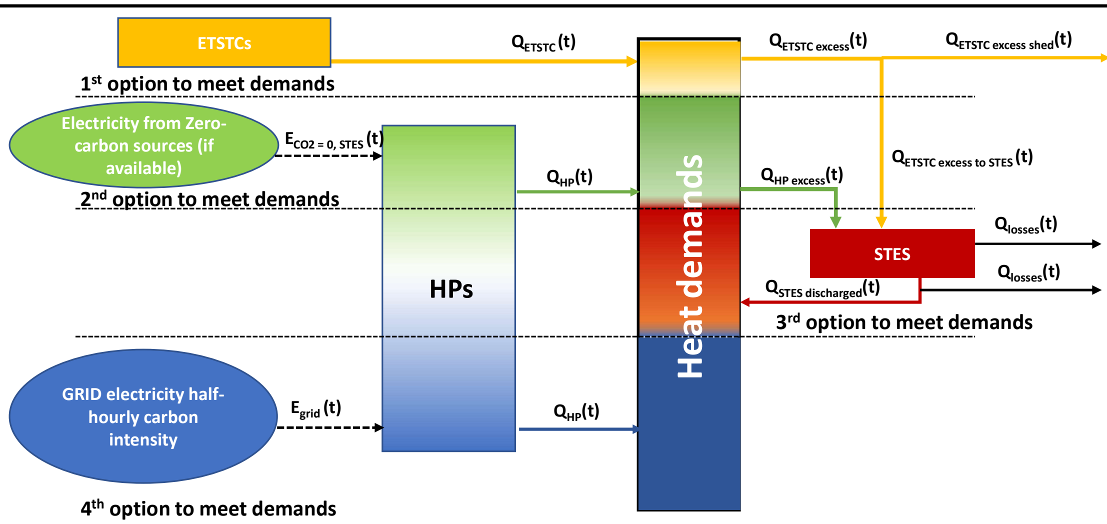

Fig. 5. Flow diagram illustrating the order of priority of heat supply when the DH system includes a mix of heat production systems.

met at every half hour time step using different heat sources in the following order of priority.

2.3. Scenarios studied

In this study two different scenarios were considered, which are described in Sections 2.3.1 and 2.3.2.

2.3.1. Scenario 1: DH with STES

1. *Option 1: ETSTCs*. ETSTCs are used as the first source to provide heat to buildings. The total area of ETSTC included in the simulation was set to an area of 10,000 m^2. If heat demands are met a) any extra heat produced by ETSTCs is stored in the STES and b) if there is electricity produced by zero-carbon sources available in the half hour period, HPs are

also used to charge the STES. The maximum amount of electricity produced by zero-carbon sources used in HPs to charge STES ($E_{CO2 = 0, STES}$) is a specified input variable in this study, with values ranging between 500 and 1500 kWh per half hour, inclusive. Any excess heat produced by the ETSTC that cannot be charged to the STES, when the STES is fully charged is shed, whereas any electricity produced by zero-carbon sources that cannot be used to charge STES for the same reason will be shed and/or used in other applications.

2. *Option 2: HP powered by zero-carbon electricity*. If heat demands cannot be met using only ETSTCs, heat is provided by heat pumps operating with electricity supplied from zero-carbon sources, if available in each specific time step. The maximum amount of electricity produced by zero-carbon sources that can be used in HPs to try to meet concurrent heat demands is $E_{CO2 = 0, STES}$. If demands can be met using HPs powered by zero carbon sources, any extra heat produced by HPs is stored in the STES. If the STES is full, the excess electricity produced by zero-carbon sources will be shed and/or used in other applications.

3. *Option 3 : STES.* If demands cannot be met using ETSTCs and HPs powered by zero-carbon sources, heat if available is discharged from the STES to meet demands.

4. *Option 4 to meet heat demands: HP powered by grid electricity.* If heat demands cannot be met using ETSTCs and HP powered by zero-carbon sources and STES, electricity from the grid with the time step half-hourly carbon intensity is used in HPs to meet fully concurrent heat demands.

It is important to stress that electricity produced from non-zero-carbon sources is used only to meet demands (if needed) but not to charge the STES: STES are charged by HPs only when electricity is available from zero-carbon sources and not required to meet concurrent heat demands in the half hour timestep.

2.3.2. Scenario 2: DH without STES (baseline scenario)

To determine the potential differences in costs that can be achieved with different levels of thermal storage, the counterfactual case with no storage was simulated. Fig. 6 shows the methodology followed to perform the simulations for the baseline scenario with no STES. Again, ETSTCs were considered as the first option to meet demands. If heat demands are met any excess heat produced by ETSTCs is shed. If demands are not met with ETSTCs, heat pumps will provide the necessary heat to fully meet demands. The electricity used in HPs to meet domestic heat demands for each half hour time step was calculated and grid electricity carbon intensity and cost for each half hour time step used.

2.4. Summary of the key details of the model used to simulate the DH system

The detailed methodology applied in the model is presented in [8] and is briefly summarised below:

i) The heat produced in each half hour period by the ETSTCs was calculated based on a) half-hourly ground-level solar irradiance data sourced from the online tool Renewables.ninja [7], b) the ETSTC efficiency (calculated with a ETSTC efficiency curve equation, which includes ground-level solar irradiance, ambient temperature and collector output temperature) and c) the specified area of ETSTC.

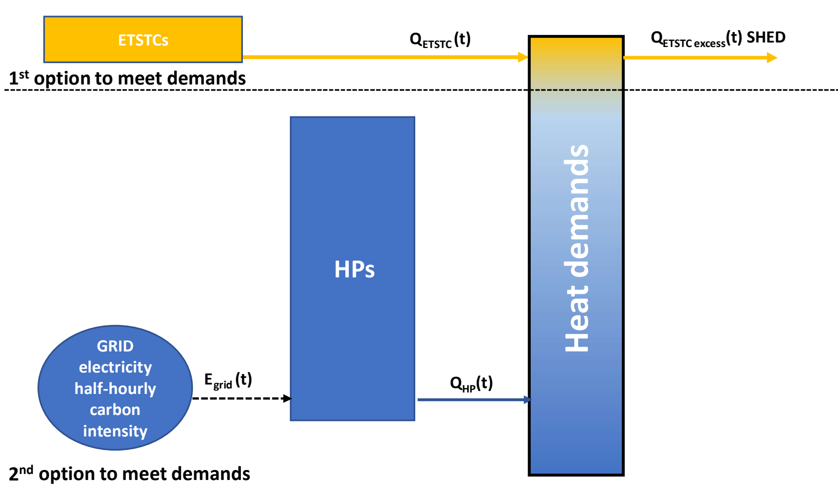

Fig. 6. Flow diagram of the process followed when not using STES (Baseline scenario, Scenario 1).

ii) The heat delivered in each half hour period by the air source and ground source HPs was determined by both 1) assuming/predicting the total amount of electricity used by HPs and 2) calculating the HP coefficient of performance for each half hour period. The model assumes that half of the electricity is used by air-source heat pumps (ASHP) and the other half in ground-source heat pumps (GSHP). The number of heat pumps required was calculated for each half hour period by dividing i) the total heat supplied by HPs by ii) the assumed heating capacity of a single heat pump. The number of heat pumps required for the DH for the full simulation period is the maximum of the number determined for each half hour time period. The heating capacity for a single HP was assumed to be 250 kW.

iii) The heat losses from the STES in each half hour period were calculated using sub-models developed and described in [8]. The initial temperature of the water inside the tank was set to 12°C which is the average ground temperature. The required charging temperatures for the STES was assumed to be 60 °C. A full description of the STES system considered in this simulation can be found in [8].

iv) The heat losses and friction losses in the piping network in each half hour period were calculated for each pipe section (between pipe intersections) based on the specific pipe section fluid flow rate and dimensions, as described in [8]. The diameters of the different pipes were selected to restrict maximum water flow velocities to less than 1.5 m/s [9]. The thickness of the foam insulation for the different pipes was based on manufacturers recommendations [10].The materials chosen for both pipes and insulation are specified in [11].

2.5. Calculation of LCOH

The economic indicator used to evaluate and compare the performance of the system is the levelised cost of heat (LCOH, pp/kWh) calculated using Eq. 1. LCOH is calculated as the ratio between i) the sum of all the costs incurred during the lifetime of the different elements that constitute the DH system (i.e. STES, HPs and ETSTCs) and ii) the total heat delivered by HPs and ETSTC during the same period:

$$LCOH = \frac{Inv + \sum_{t=1}^{n} \frac{(OC\&M)_t}{(1-r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1-r)^t}} \qquad (1)$$

Where:

Inv = investment cost, which includes cost of STES, HPs and ETSTCs (£). Values and equations used to calculate capital costs are shown in Table 1.

OC_t = Operational cost in the year *t*, i.e. cost of electricity needed to operate the heat pumps (£). The half-hourly electricity cost in the East Midlands region, UK, for the year 2021 used in this work was sourced from [12] and is shown in Fig. 7.

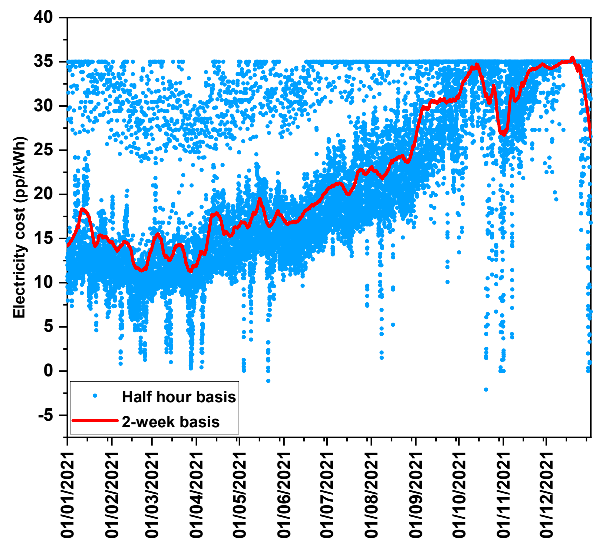

Fig. 7. Half-hourly electricity costs in the East Midlands region, UK, for the year 2021 (Source [12]).

M_t = Maintenance cost of STES, HPs and ETSTC in year *t* (£). Assumed values were obtained from different sources and are shown in Table 2.

r = discount rate (assumed 5%)

H_t = total heat produced by ETSTC and HPs in year *t* (kWh per half hour), which includes the heat used to meet demands and the heat charged to the STES (if applicable).

n = number of years (23 years in this study).

Table 1. Assumed capital costs of the different elements of the proposed DH system.

ETSTC (£/m^2) [8]	170
STES (£/m^3) [13]	50
Cost heat pumps (M£) = a + b MW$_{th}$ [14]	
ASHPs	a =0.1883 b = 0.6774
GSHPs	a =0.5054 b = 0.6398

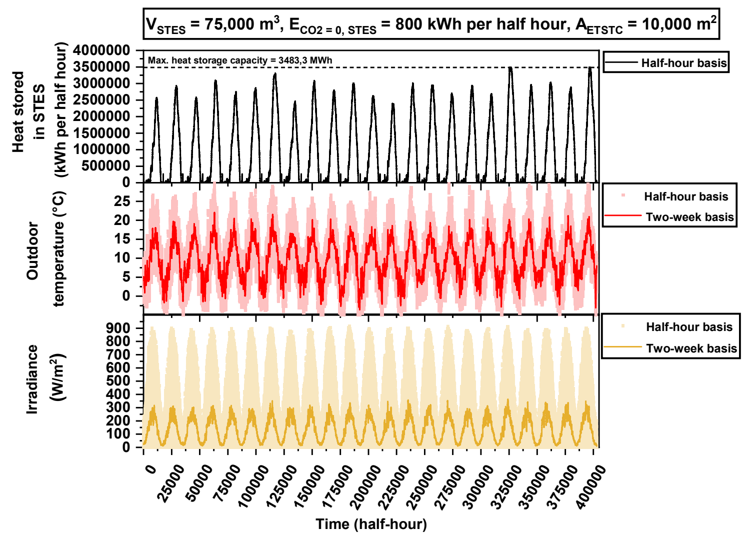

Fig. 8. Example of predicted heat stored in STES, outdoor temperature and irradiance vs. time.

Table 2. Assumed maintenance cost of the different elements of the proposed DH system.

ETSTC (£/m^2/year) [15]	13
HPs (% of the operating cost) [16]	20%
STES (% of the investment cost) [17]	1%
Salary of operator per year (£) [16]	12,300

3. RESULTS

3.1. The effect of weather conditions on the predicted heat stored in the STES

Fig. 8 shows the predicted heat stored in STES, outdoor temperature and irradiance versus time for the following operating conditions: V_{STES} = 75,000 m^3, $E_{CO2=0, STES}$ = 800 kWh and A_{ETSTC} = 10,000 m^2. As seen, the higher the outdoor temperature and/or irradiance in a year the higher the maximum amount of heat stored in the STES in the same year. This is due to lower heat demands and more heat produced by renewables because of both the higher coefficient of performance of the ASHPs and/or higher efficiency of the ETSTCs.

3.2. The effect of V_{STES} and $E_{CO2=0, STES}$ on LCOH

Fig. 9 shows the effect of $E_{CO2=0, STES}$ on LCOH, for V_{STES} = 50,000 and 75,000 m^3. For the same V_{STES}, similar values of LCOH were obtained for $E_{CO2=0, STES}$ values up to ~ 800 kWh per half hour. For $E_{CO2=0, STES}$ > 800 kWh per half hour LCOH increases substantially with $E_{CO2=0, STES}$, due mainly to the increase in the operational, investment and maintenance cost of HPs, as can be seen in Fig. 10.

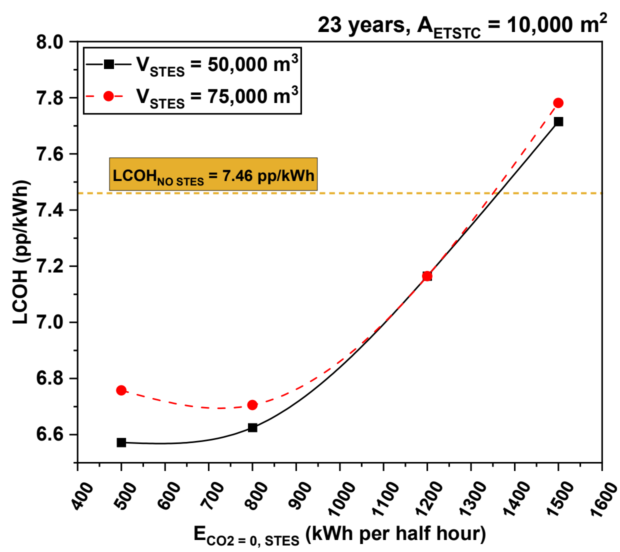

Fig. 9. Effect of V_{STES} and $E_{CO2=0, STES}$ on predicted LCOH.

When comparing the results obtained with the two different volumes, V_{STES}, higher LCOH values were obtained for $E_{CO2=0, STES}$ values up to ~ 800 kWh per half hour with a V_{STES} value of 75,000 m^3, as shown in Fig. 9. This is due to the higher investment cost in STES, which counteracts the savings achieved in the cost associated with HPs due to the greater heat capacity of the store, as observed in Fig. 10.

When comparing the predicted values of LCOH obtained with STES with those obtained without STES it can be observed that up to $E_{CO2=0, STES}$ = 1200 kWh per half hour, lower LCOH values were predicted when

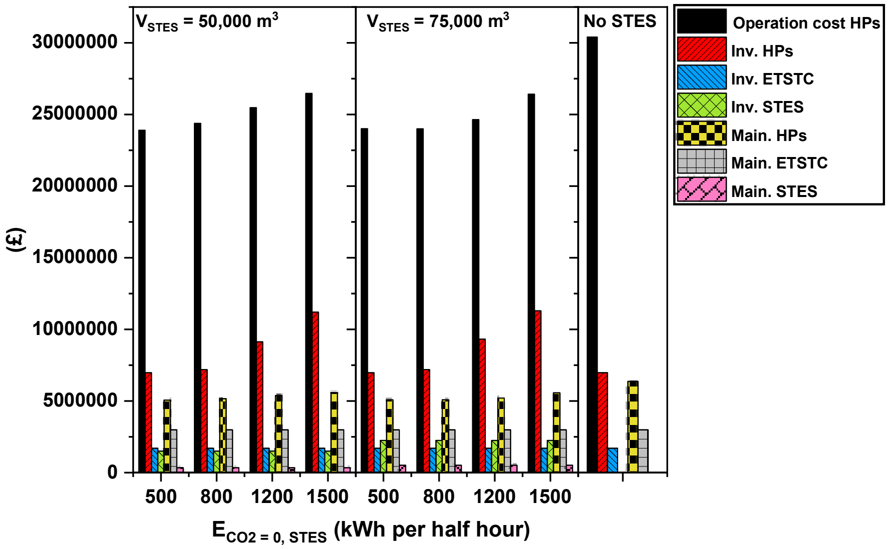

Fig. 10. Effect of V_{STES} and $E_{CO2 = 0, STES}$ on the different economic factors affecting LCOH.

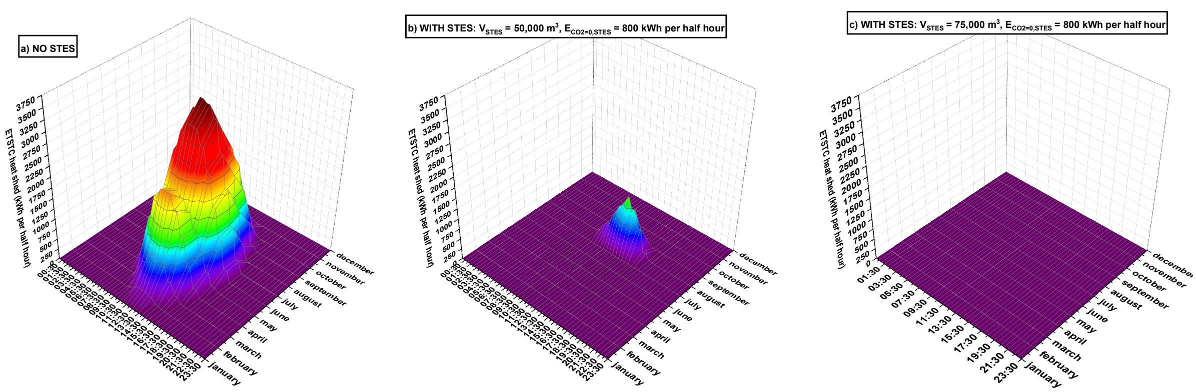

Fig. 11. effect of V_{STES} on the monthly average heat shed from ETSTC for year 2021.

including STES in the DH system, due mainly to the much higher operational cost of HPs when not using STES, as can be seen in Fig. 10. This is mainly due to the decreased heat that is shed from the ETSTCs when using STES, as shown in Fig. 11. The greater use of heat produced by ETSTCs leads to a reduction in electricity use, as shown in Fig. 12, which reduces the operational cost by ca. 15% when using STES. Using STES also allows increased electricity use at off-peak hours (as shown in Fig. 12), when the cost of electricity is cheaper. Using STES allows HPs to operate at night, storing any heat produced excess to concurrent demands in the STES. Heat for the STES can be subsequently used during the day to meet demands when electricity costs are high.

4. CONCLUSIONS

A novel model was used to simulate how an existing district heating (DH) network for Holywell Park, Loughborough University (Loughborough, UK) could be transitioned to low/zero carbon heat. The proposed DH system includes heat pumps and evacuated-tube solar thermal collectors to provide heat for buildings. Simulations used both a) real historic half-hourly CO_2 emissions per kWh of grid electricity and b) real historic half-hourly heat demands for Holywell Park for the year 2021. A parametric analysis was used to investigate the effect of i) including a centralised STES and ii) when including STES the effect of a) the volume of STES system and b) the maximum amount of zero-carbon electricity available to charge STES, namely $E_{CO2 = 0, STES}$, on the levelised cost of heat for a 23 year simulation period. The predictions indicated that for Holywell Park using $E_{CO2 = 0, STES} > 800$ kWh per half hour increases the operational cost, investment and maintenance of HPs, which leads to an increase in the LCOH. The use of STES reduces the LCOH by up to 1.74 pp/kWh, due to the reduced operational and maintenance costs of HPs, which is due to both the greater use of the heat produced by ETSTC to meet demands and the greater use of electricity at off-peak times. A minimum value of LCOH of 6.57

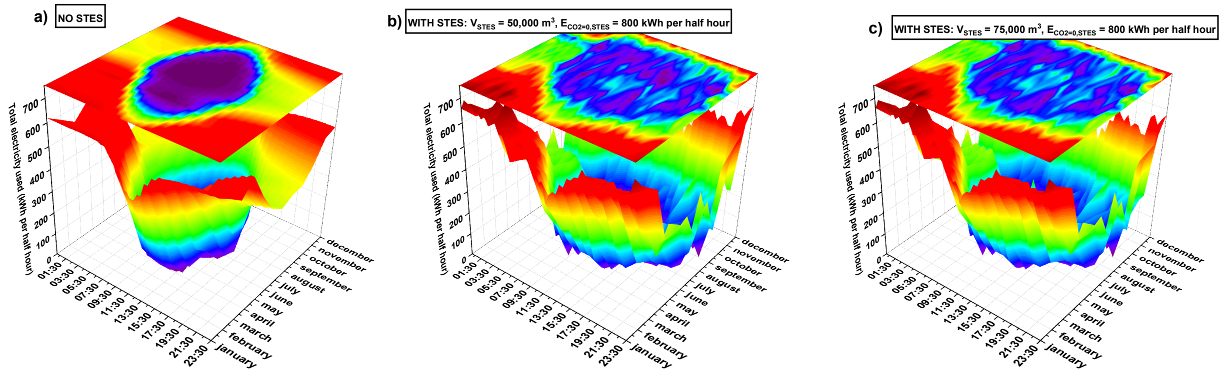

Fig. 12. effect of using STES on the monthly average electricity used for year 2021.

pp/kWh was predicted for V_{STES} = 50,000 m^3 and $E_{CO2=0, STES}$ = 800 kWh per half hour.

AUTHORS' CONTRIBUTIONS

M. A. Pans: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft. P. C. Eames: Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition.

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