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Data-driven modelling of operational district energy networks

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ABSTRACT

There has been a resurgence of interest in district energy networks due to the cost, energy and emission reductions they can deliver. The prohibitively large computational cost of estimating thermal energy demand based on district- and urban-scale energy simulations is a major barrier to the wide-scale use of modeling in design and operation of district energy networks and in feasibility studies of technologies such as thermal energy storage. In this paper, a simple, computationally efficient modelling approach is proposed where operational data from the district energy network is used to construct temporal load profiles and thereby eliminate the need for building energy simulations. The proposed model is validated against data from a newly developed natural-gas powered district energy network in British Columbia, Canada. The utility of this data-driven approach is demonstrated through case studies on the feasibility and effectiveness of hourly thermal energy storage. It is shown that hourly thermal energy storage in a water tank can reduce the daily peak loads on the boilers by as much as 20%. Furthermore, using thermal energy storage, the highly fluctuating demand can be met with a constant-power supply, which would facilitate the use of biomass as an alternative energy source.

1. Introduction

1.1 District energy networks and urban sustainability

Buildings account for more than 40% of the total primary energy consumption in most developed countries [1,2], with space and water heating responsible for approximately 70% of the buildings' energy demand [1,2]. In Canada, residential buildings are responsible for 17% of the nation's total energy use, of which more than 80% goes to space and water heating [2]. Water and space heating in residential buildings in Canada produces more than 60 $MtCO_2$ annually, 9% of the nation's GHG emissions [2]. Given Canada's dominantly cold climate and large use of fossil fuels for heating buildings, 57% in 2015 [2], reducing the greenhouse gas emissions due to space and water heating is key to meeting the country's national targets and international commitments.

In addition to the conservation measures aimed at reducing demand, cities around the world are implementing various sustainable energy initiatives to supply energy to buildings more efficiently, decarbonize the urban energy infrastructure and build capacity for resilience against and adaptation to climate change. District energy networks (DEN) are one of those initiatives. Although the basic concept and technology are not new, there has been a resurgence of interest in DEN due to the cost, energy and emissions reductions they can deliver. DEN can be also used to address the intermittency of renewable energy sources through the great flexibility they provide for orchestrating various renewable energy sources to meet demand, especially at times of peak demand. Moreover, DEN provide the opportunity to connect and/or integrate the thermal energy network with other sectors, e.g. the power grid and transportation.

1.2. Thermal energy storage for district energy networks

Thermal energy storage (TES) is a key technology for decarbonizing district energy networks. TES facilitates a more efficient supply of energy during demand peaks, as well as transition to lower-temperature operation of the network and integration of alternative energy sources such as solar and geothermal. Furthermore, peak shifting through TES is essential in model-predictive control of advanced DEN. See for instance [3]. TES is also important for higher-efficiency operation of DEN since it can absorb fluctuations in demand and smooth the load on boilers [4,5]. Furthermore, baseload plants burning renewable e.g. biofuel are, in general, cheaper than peak-load plants which mostly rely on fossil fuels, e.g. natural gas [4,6]. A basic application of TES in district heating is therefore to reduce (shave) and/or shift the peak load to times of lower

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energy price and/or higher availability of renewable energy. See Fig. 1. Reduced peak loads bring savings in both capital and operating costs of the network while facilitating the integration of alternative energy sources, particularly bioenergy.

DEN have "built-in" storage capacity in the working fluid and, to a lesser extent, in the piping network, which can be used as a buffer to meet small load fluctuations with a relatively smooth supply [7,8]. This storage capacity depends on the size and configuration of the network. In the case of smaller networks, e.g., the pilot network studied here, the network's storage capacity is too small to enable considerable peak shaving. Centralised storage in hot water tanks is a simple, effective, and therefore popular storage solution. In addition to peak shaving/shifting, simple TES solutions such as water tanks are essential in the implementation of waste-heat recovery [9,10], integration of renewable sources [6,11], and mobile thermal energy storage [12,13]. More detailed reviews on various TES technologies and applications can be found in [14,15].

1.3. District energy models

Urban-scale energy models are needed to optimize the design and operation of the urban energy infrastructure, particularly DEN, and assess the feasibility and effectiveness of technologies such as thermal energy storage. An extensive review of modelling studies of DEN and the different modelling approaches can be found in [16]. The existing DEN models generally rely on building energy simulations to determine the space conditioning demand of individual buildings or building archetypes and aggregating or scaling those loads to district levels. While energy models for individual buildings have been well-established and many of the existing models offer a remarkable degree of detail and accuracy [17], the extension of single-building energy models to urban-scale models remains an outstanding challenge [18], mainly due to the high computational cost, which is especially prohibitive for early-stage feasibility and decision-making studies. Furthermore, the uncertainties introduced by the compilation and application of building archetypes to represent neighbourhoods may detract from the reliability of modelling results.

1.4. Scope

The present work proposes a simple, computationally efficient approach to modelling the thermal performance of DEN using the flow-rate and temperature data that is readily available from operational networks. The proposed model is validated based on the operational data collected in the pilot phase of a recently developed DEN in British Columbia, Canada. The model is then used to study the feasibility and effectiveness of hourly thermal storage in water tanks, particularly for peak shaving.

2. City of Surrey's district energy Network: *Surrey City energy*

Buildings in Surrey, British Columbia, Canada, emit more than 40% of the city's total emissions [19]. *Surrey City Energy*, the district energy network owned and operated by the City, is part of Surrey's plan to drastically cut emissions from the building sector. The plan is for the network to service more than 1,600,000 m^2 of built area by 2040, reducing the per unit area GHG emissions ($kgCO_2/m^2$) from its service area by more than 70% compared to a 2007 baseline [20]. The first phase of the network (2017–2019), which is the subject of the present study, comprised two generation sites where natural gas boilers produced hot water that was supplied to several high-rise buildings in the city centre area for space and domestic hot water heating. The City of Surrey did not pursue cogeneration due to the small size and the temporary nature of the pilot facility in particular, and the low cost of natural gas in British Columbia in general.

Fig. 2 shows a schematic of the network layout, including boilers in a generation site, *Temporary Energy Centre,* supplying hot water at temperature T_{supp} to two delivery heat exchangers in each building for space (HX) and water (DHX) heating. The pressure and temperature at several points in the network as well as the flow rate in the network were recorded throughout the pilot phase. The secondary side, i.e. distribution system past the delivery heat exchangers in each building, is beyond the operation of the network and was hence not included in the present study; only the supply ("primary") side was considered.

3. Model development & validation

3.1. The general thermal network

The thermal network representing the primary side of the DEN was modeled as a physical network in MATLAB Simulink [20]. The built-in elements of the Simscape library [21] were used to represent the components of the system. The boilers in the energy centre were represented by a variable heat source that supplied hot water at the desired temperature T_{supp}. A variable-speed pump was used to maintain the flow rate, $\dot{m}$, in the network. A reservoir was used to represent the expansion tank. The delivery heat exchangers were represented by a short pipe from which the instantaneous load was extracted. The piping network was divided to two sections, each 100 m in length, representing the supply and return legs of the network**.** Table 1 summarizes the components used in the Simulink model.

3.2. Heat loss from the pipes

A thermal resistor–capacitor model was used to represent the piping network, as depicted in Fig. 3, where T_{fluid} is the bulk temperature of the fluid at a given axial location. Conduction across the pipe wall is characterized by R_{pipe}, R_{ins} and $R_{coating}$ which were estimated based on analytical relations for the thermal resistance of a cylindrical shell. Thermal contact resistance between the pipe wall layers was ignored. Convection inside the pipe is represented by R_{conv} which was estimated based on the correlation from [21]. Finally, heat loss from the outer surface of the pipe to soil was represented by R_{soil}, evaluated based on the analytical solution to conduction from a long cylinder in a semi-infinite medium [22]. C_{water} is the thermal mass of the water in the pipe; the thermal mass of the pipe has been ignored in the transient energy balance. Specifications of the pipes are reproduced from the manufacturer's catalogue [23] in Table 2. Pressure drop in the pipes was

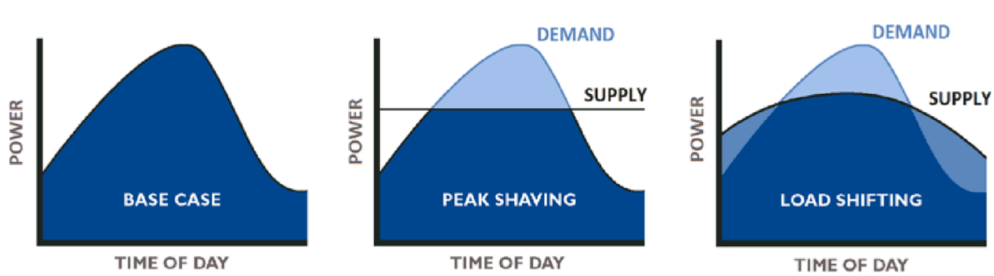

Fig. 1. Load management strategies: Peak shaving vs. load shifting [30].

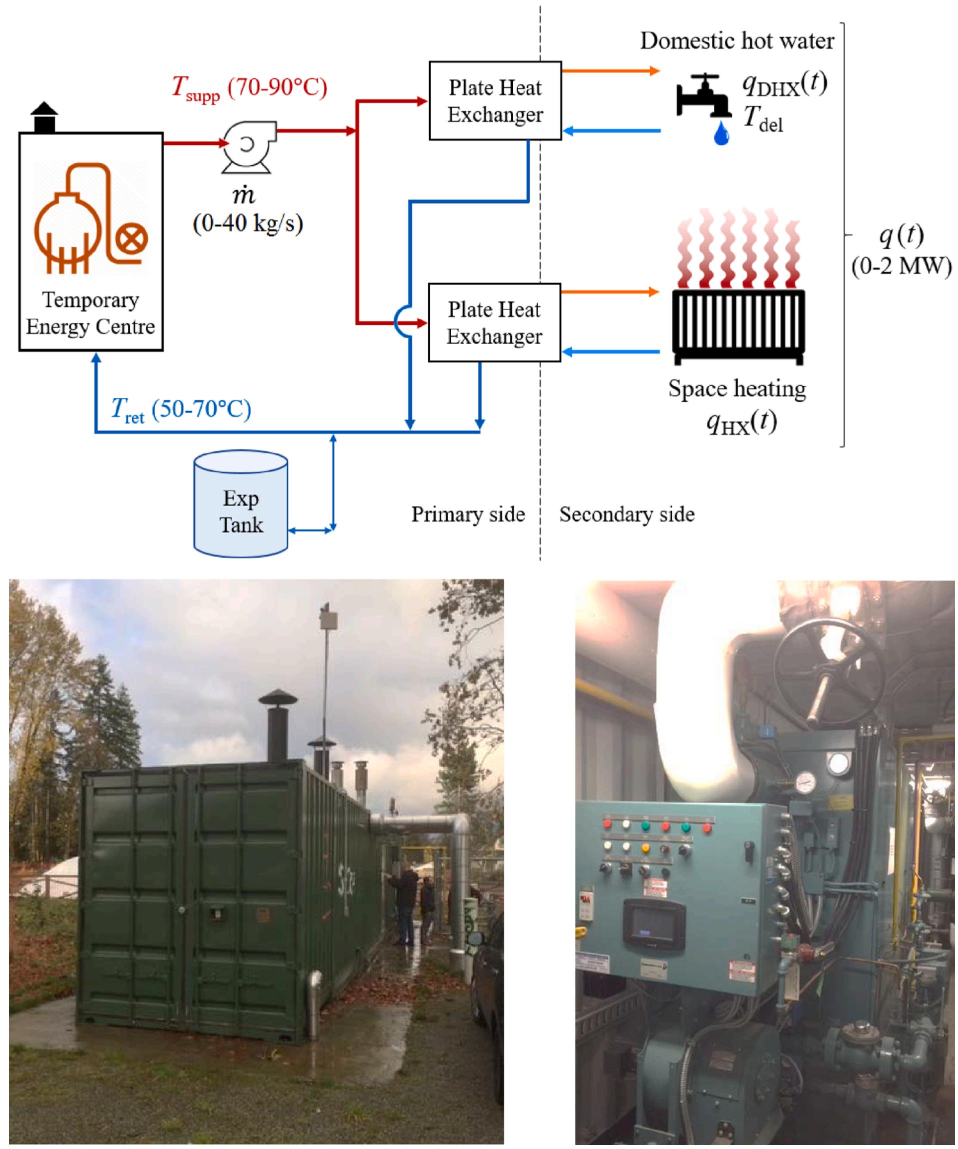

Fig. 2. Top: Layout of the *Surrey City Energy* thermal network (pilot phase) Bottom: A temporary generation site of *Surrey City Energy* (left) and its boilers (right).

not modelled.

3.3. Boundary conditions

The total instantaneous load, $q(t)$, was calculated based on the energy balance of the delivery heat exchangers using the flow rate and inlet and outlet temperatures measured at a typical sampling rate of 30 min. The temporal load profile thus obtained was applied as boundary condition in the Simulink model. The flow rate and supply temperature profiles were obtained either from operational data or the desired alternative supply scenarios (see Section 4). The intermediate points were interpolated.

Given that pipes are not far from the surface of the ground, the soil temperature was assumed to be equal to the ambient temperature which was imposed based on local weather data [24].

3.4. Solution method

In order to calculate the return temperature, T_{ret}, a transient energy balance was performed on the loop and the resulting ODE was solved using a variable-step, continuous implicit solver, based on the trapezoidal rule and with a maximum time step of 1 s, chosen for stability.

The computational efficiency of the present model must be emphasized. For instance, monthly simulations of the network took around three hours to complete on a PC. The computational efficiency of the model facilitates its expansion to larger networks, as well as simulations over extended periods and optimization of various components using computational methods.

3.5. Validation

In Fig. 4, simulation results for T_{ret} are compared to data from January 2017. The RMS error of the modeling results is 1.8 °C, while the uncertainty in the temperature data is 0.2 °C. Further comparisons with data from other intervals during years 2017 and 2018 were also performed; similar results were obtained. The close agreement with the measurements indicates the validity of the model.

4. Case Study: Hourly thermal energy storage in water tank

The validated model was used to simulate "what-if" scenarios to study the effectiveness of thermal energy storage in a water tank for peak shaving. The tank was added to the main DEN loop in parallel, as shown schematically in Fig. 5. After several iterations, a 40 m^3 tank was

Table 1
Summary of Simulink model elements and parameters.

Physical element	Simulink element	Parameters/comments
boiler	controlled heat flow rate source	rate determined based on T_{supp} data, desired T_{supp} or desired q_{supp}
	pipe [Thermal-Liquid (TL)]	$L = 0.1$ m, $A = 0.07065$ m^2, $D_H = 0.160$ m; equivalent resistance length = 0
pump	pump (centrifugal)	flow rate determined based on data or desired value
expansion/ overflow tank	tank (TL)	$V = 40$ m^3, Pressurization: atmospheric
pipe	pipe (TL)	$L = 100$ m, $A = 0.07065$ m^2, $D_H = 0.160$ m; equivalent resistance length = 0
	conductive heat transfer	see Fig. 3, Table 2; $k_{soil} = 0.3$ W/(mK)
delivery heat exchanger	pipe (TL)	$L = 0.01$ m, $A = 0.01$ m^2, $D_H = 0.1128$ m; equivalent resistance length = 0
	controlled heat flow rate source	rate determined based on $q(t)$ data
	physical signal lookup table	data resolution: 15 min
TES tank	tank (TL)	$V = 40$ m^3, Pressurization: atmospheric
	controlled mass flow rate source	See Section 4

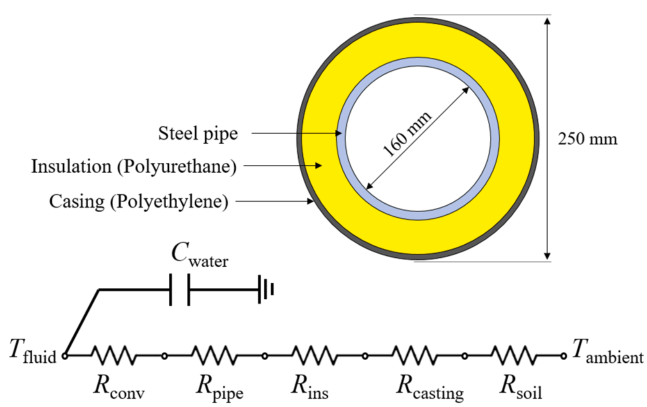

Fig. 3. Thermal resistor–capacitor model of transmission pipes.

Table 2
Pipe specifications [24].

Outer diameter [mm]	Outer casing :250 Steel pipe: 168.3
Wall thickness [mm]	Outer casting: 3.6 Steel pipe: 4.1
Pipe weight [kg/m]	21
Water content [l/m]	20

selected for the present case studies. Optimum sizing and control of the storage tank are topics of interest for future research. Heat loss from the tank was ignored.

4.1. Peak shaving

In the first alternative operation scenario, hot water was supplied at a constant flow rate of $\dot{m} = 14$ kg/s and a constant temperature of $T_{supp} = 75$ °C. Note that in the baseline case the flow rate is modulated to meet the instantaneous demand. The operational flow rate data has a wide range, 0–40 kg/s, averaging at around 14 kg/s. The supply temperature of 75 °C was chosen to satisfy the health requirement that domestic hot water (the secondary side) must be at 60 °C or higher.

The TES tank was charged or discharged based on the return temperature, T_{ret}, using a simple proportional controller, with the objective of maintaining the return temperature above 60 °C in order to avoid spikes in the load at times of peak demand. To add robustness, an additional proportional control signal was set up based on the deviation of the instantaneous load from the daily average value. See the Appendix for the control rules of charging and discharging the TES tank.

Simulation results for the instantaneous load on the boilers during a sample day in January are shown in Fig. 6. The baseline case (solid line) is the replication of the actual operation of the network where the supply and demand curves are almost identical, with the small heat loss from pipes being the only difference (less than 2%). With the boilers always supplying 75 °C water in the alternative scenario (dashed line), the TES tank was charged during times of lower demand (higher T_{ret}), e.g. 1-3am and 1–3 pm, and discharged at peak times (lower T_{ret}), around 12 pm and 7 pm. Comparing the two load curves, it is seen that by adding the TES tank, the two daily peaks were reduced by 12% and 20%, respectively. The stored energy (dotted line) is plotted against the axis on the right. During the second peak (around 7 pm) the TES tank was completely discharged.

Reduced peak loads can lead to savings in capital costs, e.g. by reducing the number of boilers, as well as higher efficiency operation of the boilers due to less frequent cycling and shutdown. Moreover, shaved peaks can reduce or eliminate the use of back-up fossil fuels in DEN where the baseload is supplied from renewable sources, e.g. geothermal.

4.2. Flattening the supply curve

A second scenario was studied to assess the feasibility of replacing natural gas boilers with biomass boilers. Replacing natural gas with biomass has a significant GHG reduction potential. The natural gas supply in British Columbia, Canada has an average emission factor of 49.87 kgCO_2/GJ [25], while biomass is considered carbon–neutral [26]. In the single day studied here when the total heating supply was 82 GJ, switching to biomass boilers could reduce the direct emissions of the DEN by as much as 4.09 tCO_2. Biomass as a low-carbon energy source is particularly attractive in British Columbia, Canada, where large amounts of waste wood are available from the forestry and construction industries [27,28]. Biomass boilers can also offer cost savings. See for instance [30]. Since biomass boilers operate best at a constant capacity, i.e. with minimal load fluctuation and cycling [29], peak shaving is essential for effective utilization of bioenergy in DEN.

The alternative supply scenario representing the use of biomass boilers was idealized as supply at a constant capacity of $q_{supp} = 0.95$ MW, roughly the daily average demand according to data from the sample day studied here (January 1, 2017). The TES was controlled using the same proportional controller described in Section 4.1, with the objective of maintaining $T_{ret} \geq 60$ °C. A constant flow of $\dot{m} = 14$ kg/s passed through the boilers. A main consideration was to avoid supply temperatures below 75 °C, to meet the health requirements for domestic hot water (see Section 4.1).

In Fig. 7, the supply temperature during the day of interest is plotted for the baseline case (actual operation of the network on January 1, 2017) and the alternative supply case (constant power) representing biomass boilers. It is seen that, with the help of the TES tank, biomass boilers operated at a constant rate can meet the highly fluctuating demand while satisfying the $T_{supp} > 75$ °C recruitment more frequently than the baseline case. Recall that demand is approximately the same as the load on boilers in the baseline case, shown in Fig. 6. The stored energy (dotted line) is plotted against the axis on the right.

It is noteworthy that in the alternative scenario, the supply

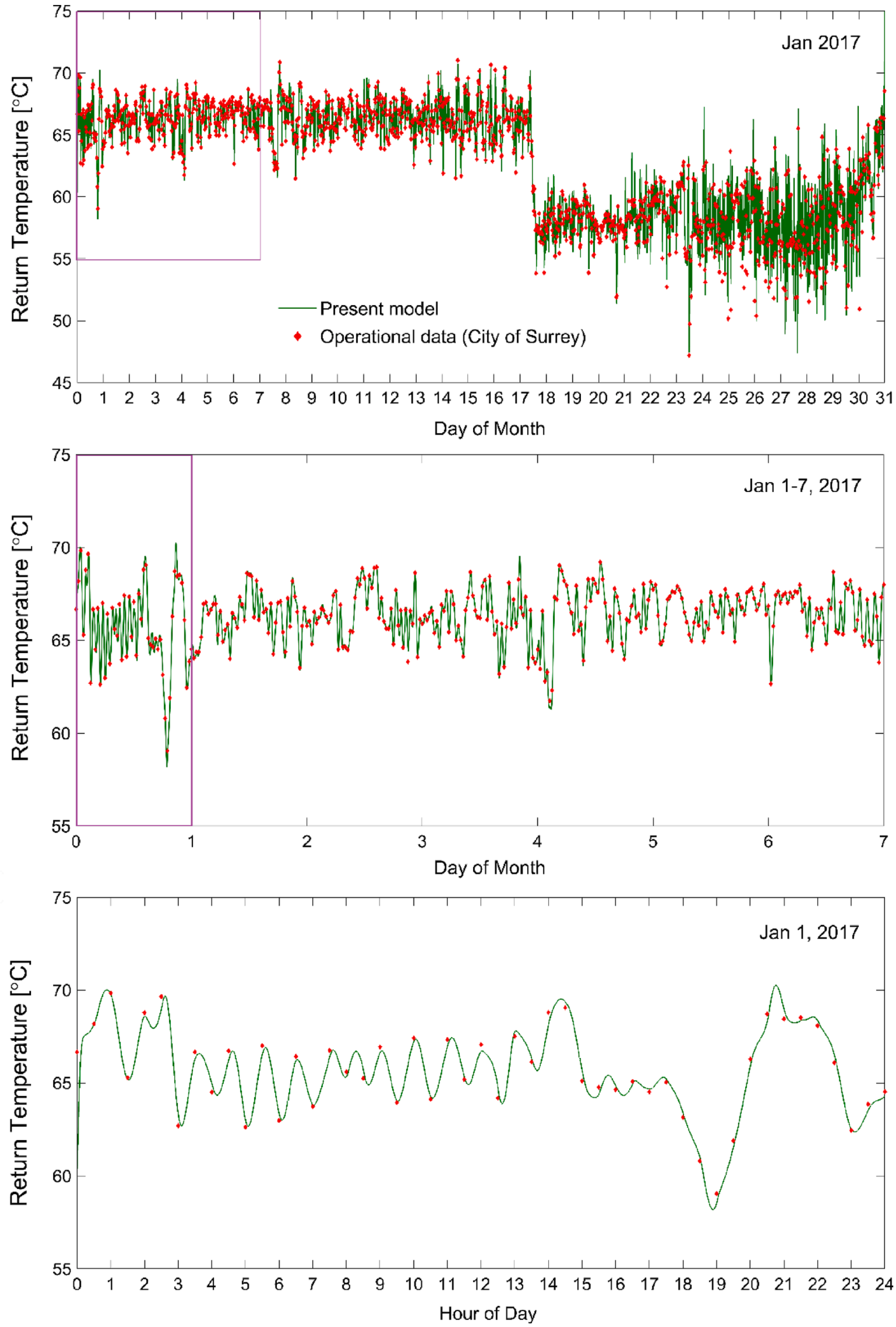

Fig. 4. Average daily return temperature (Jan 2017): Field data vs. model. Uncertainty of data: 0.2 °C, RMS error of model: 1.8 °C.

temperature is generally lower than in the baseline case, which decreases heat loss from the piping network. Although heat loss was not significant in this study due to the small size of the network, it can be notable in larger networks and in colder climates.

5. Conclusion

The thermal performance of district heating networks can be accurately simulated using a transient energy balance of the network where thermal loads calculated based on operational data of the network are applied as boundary conditions. By eliminating the need for building energy simulations to estimate demand, this approach significantly decreases the computational cost of district- and urban-scale energy modelling and provides a quick decision-making tool for feasibility studies and early-stage design. This was demonstrated for a recently developed district energy network in British Columbia, Canada.

Data from the pilot phase of the network was used in the proposed modelling approach to assess the feasibility and effectiveness of hourly thermal energy storage for peak shaving and integration of alternative energy sources. It was shown that introducing a relatively small TES water tank, daily peak loads could be reduced by as much as 20%. Furthermore, it was shown that short-term TES can essentially flatten

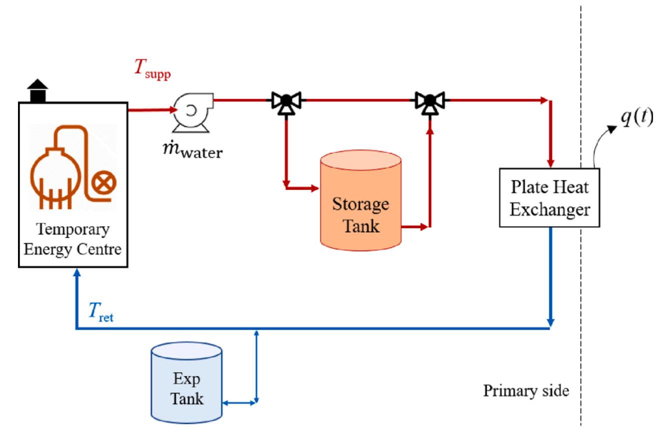

Fig. 5. Layout of the primary (supply) side of the network with water tank TES.

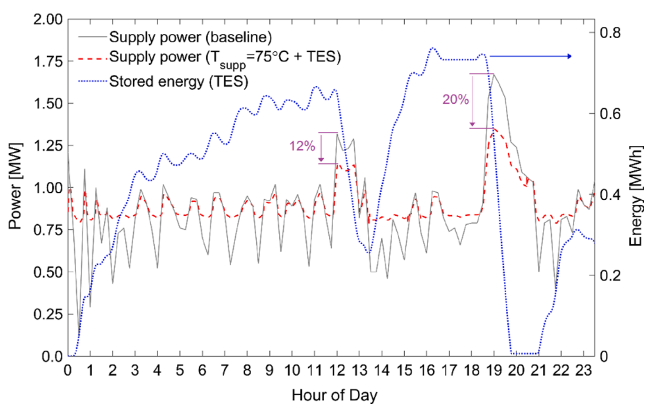

Fig. 6. Hourly load on boilers (sample day in Jan 2017): introduction of hourly TES in water tank can shave peaks by up to 20%

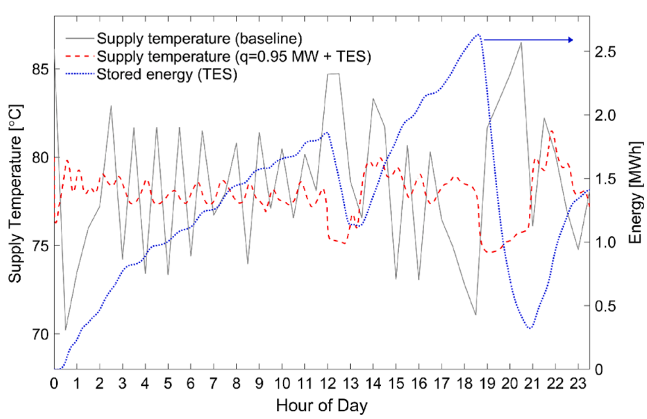

Fig. 7. Hourly supply temperature: Baseline case vs. constant-capacity (biomass) boilers with TES.

the load profile, paving the way for the introduction and efficient operation of biomass boilers. The City of Surrey is now considering the implementation of thermal energy storage at various scales in *Surrey City Energy*. Optimization of the storage tank size and charge/discharge control strategies will be explored in future work.

CRediT authorship contribution statement

Sepehr Foroushani: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft. **Jason Owen:** Resources, Validation, Data curation, Writing - review & editing. **Majid Bahrami:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix:. Storage tank controls

In the equations below, $\{\mathbf{A}\}$ denotes a Boolean operation returning 1 if statement A is true and 0 if A is false; V_{min} and V_{max} denote the minimum and maximum allowed volume of water in the TES tank, respectively.

a) Constant supply temperature (Section 4.1):

$$\dot{m}_{charge} = 2.0 \times \{V < V_{max}\} \times \{T_{ret} > 60\} \times (T_{ret} - 60)$$

$$\dot{m}_{\text{discharge}} = 0.7 \times \{V > V_{\min}\} \times \{T_{\text{ret}} < 60\} \times (60 - T_{\text{ret}}) + \frac{q}{10^7} \times \{q > 1.05 \times 10^7\}$$

b) Constant supply power (Section 4.2):

$$\dot{m}_{\text{charge}} = 0.8 \times \{V < V_{\max}\} \times \{T_{\text{ret}} > 60\} \times (T_{\text{ret}} - 60)$$

$$\dot{m}_{\text{discharge}} = 2.0 \times \{V > V_{\min}\} \times \{T_{\text{ret}} < 60\} \times (60 - T_{\text{ret}})$$

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