A multi-vector community energy system integrating a heating network, electricity grid and PV production to manage an electrified community

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Abstract

Electrification in energy supply-demand plays a critical role in domestic heating and road transport, delivering an electrified community to reduce carbon emissions. This solution, however, places a significant power demand increase on the distribution networks. To ensure the security of electricity supply, an efficient energy system and energy demand reduction are essential. In this paper, a multi-vector community energy system, applying an electrified heating network, electric vehicle smart charging, community-scale peak shaving and photovoltaic (PV) generation, is demonstrated in three models to manage an electrified community. Firstly, a heating network model, comprising a central ground source heat pump, low-temperature district heating system, electric heaters and thermal storage, is established to measure the optimum distribution temperature. Next, an electrified community model illustrates hourly electricity demands and performances of a community energy system, which is then used to identify the required degree of housing thermal efficiency improvement (i.e., heating demand reduction). The third model evaluates decentralised PV/storage units to maintain the power demand below a targeted power. Modelling results show that the demand ratio of domestic hot water to space heating determines the distribution temperature, which indicates the temperature is increasing with growing housing thermal efficiency. Moreover, the electrification of a community could increase the peak power demand on the highest demand day by over five times, converting heating demands into electricity directly. This significant peak demand can be possibly reduced to only a 33% increase by employing a community energy system. The model of PV/storage units is validated through a 12-week assessment. Ultimately, a modelling tool is developed by assembling the mentioned models, providing four pathways to attain electrification. Users can adjust specific parameters and database to align with the local conditions. The results indicate the requirements of building a community energy system and electricity demands in the highest consumption period.

Keywords

Electrified community

Community energy system

Distribution temperature

Modelling tool

Housing thermal efficiency

Peak demand

Nomenclature	
Abbreviations	
COP: Coefficient of performance	LTDH: Low temperature district heating
DHW: Domestic hot water	LV: Low voltage
DG: Decentralised generation	PV: Photovoltaic
EVs: Electric vehicles	SH: Space heating
GSHP: Ground source heat pump	ULTDH: Ultra-low-temperature district heating
HPs: Heat pumps	

1. Introduction

Electrification of domestic heating and road transport is identified to be feasible and effective for decreasing carbon emissions [1, 2]; however, the process gives rise to considerable electricity demand increase [3]. Studies have highlighted that the significant power demand will induce detrimental impacts, especially on distribution networks, and exacerbate the existing daily peak in the early evening [4, 5]. To progress in electrification, energy system modelling [6] plays an important role in evaluating future energy supply and demand, applications and management of various energy technologies, and feasibility and impacts of different pathways to achieve electrification. Energy system models related to heating and transport electrification are introduced below.

Using 100% renewable energy to supply the electricity demand, Brain et al. [7] design an energy system model and then illustrate its energy combination of different sources as well as benefits such as socio-economic savings, increasing employment, earnings on exports and health of the population. Similarly, Hannah et al. [8] evaluate the renewable energy transition on an island, suggesting that to enhance flexibility and interaction in energy systems, investment incentives and dynamic tariffs should be conducted. To illustrate the influence of weather on renewable electricity supply and growing demand, Iain et al. [3] develop an open framework using free and open data. The result points out the rising peak demand and seasonal demand gap of the British electricity system. For an efficient energy system integration, Danny et al. [9] propose a whole-system assessment model to evaluate the grid-scale electricity storage, which optimises investments, minimises system operation costs while considering security requirements. Fei et al. [10] utilise an advanced stochastic model to assess the benefits of smart electric vehicles (EVs) and heat pumps (HPs) on carbon emission reduction and cost reduction of renewable energy sources integration. Focusing on a low-voltage (LV) distribution network, Rakesh et al. [11] develop a model with an autonomous control system to meet customer's demands and manage grid congestions.

The aforementioned studies cover the modelling works of a country, island or distribution network scale, of which the results help developing roadmaps and policies for cost-effective development of carbon-neutral systems as well as selecting suitable energy technologies and system control methods. However, to establish an energy system linking up homes for the electrification, technical parameters such as electric powers of heating and electricity generation devices, capacities of thermal and electricity storage units, district heating layout design and pipe sizing (if district heating is employed) are necessary to be addressed. In Ref. [12], an integrated model is built based on urban districts. This provides the mentioned technical parameters but does not consider the electrified transport sector. Other studies, giving technical parameters under various circumstances, only focus on a few specific fields such as district heating [13, 14], electricity storage [15, 16], photovoltaic (PV) battery system [17].

In energy system modelling, smart management measures have been studied extensively and are expected to be an essential factor in balancing supply and demand [4, 10]. Within the context of 100% penetration of EVs, Constance et al. [5] indicate that using smart charging can eliminate the need for additional generation infrastructure whilst decreasing the percentage of electricity network reinforcement. Simulation result of assessing 100% EVs and HPs adoption shows that smart control can constrain daily system peak at a 29% increase in winter, which without the optimisation, reaches a 92% increase [4]. Employing smart management to enhance network operational performance is possible because of the application of energy storage. For example, EVs powered by electricity storage units (batteries) can be charged during off-peak hours [18], likewise as an electrified heating supply applying thermal energy storage [19]. Moreover, peak shaving [20] (as a smart control approach to mitigate demand peaks) is enabled by installing electricity storage units on electric power networks. A study, evaluating residential heating demands met by HPs, indicates that using batteries for peak shaving could keep demand peaks at the current level [15].

The effectiveness of applying energy storage to alleviate electric demand peaks has been evidenced in studies. However, the increases in total electricity demand and seasonal demand gap caused by heat electrification are difficult to manage by only the deployment of energy storage due to the significant cost of very large-scale storage systems [21]. A study investigating national electricity supply and demand concludes that if heat electrification is the approach to deliver a secure and clean energy future, heating demand reduction must be attained [22]. Currently, improving the thermal performance of the built environment (i.e., decreasing SH demand) is one of the national strategies for carbon reduction in the UK [23].

According to the reviewed literature, an energy system model that considers both the electrified heating and road transport, assembles various energy technologies (covering generation, distribution and storage) and provides technical parameters for building an energy system under various scales is currently not well established. This paper manages to fill in this research gap, starting by tackling the residential demands using a multi-vector community energy system. This energy system model integrates smart management measures whilst estimates the improvement degree of housing thermal efficiency. The idea of a community energy system is similar to Microgrids that denotes a control approach within the distribution networks, which not only optimises distributed energy resources but also responds to the central power systems [24]. In this circumstance, energy systems can be modelled and optimised at different geographical levels, then assembled. This character provides nations with a great opportunity to manage highly digital and electrified smart cities.

In conclusion, this paper designs a community energy system to manage an electrified community delivered through 100% utilisation of EVs and electrified heating supply. The system is elaborated by three mapping studies; an electrified heating network, an electrified community, and the deployment of PV generation coupled with storage units, and demonstrated on a commercial software energyPRO [25]. These models utilise the conditions in the UK for demonstration, such as energy demands, the distribution network, etc. Ultimately, a modelling tool is developed by applying the concepts of the three models, providing four different pathways to attain an electrified community. The approaches are connected with different improvement levels of housing thermal efficiency. Based on this, the modelling tool analyses electric power demands in the highest consumption period (i.e., the coldest period), performs smart management measures, considers constraints of the distribution network and indicates capacities of generation and storage units. Also, the modelling tool is enabled to be flexible about community scale, amount of EVs, energy demands, geographical location, etc. This tool is an open-source software established in an Excel workbook and attached to this paper as supplementary material. The development process follows the flow chart in Figure 1.

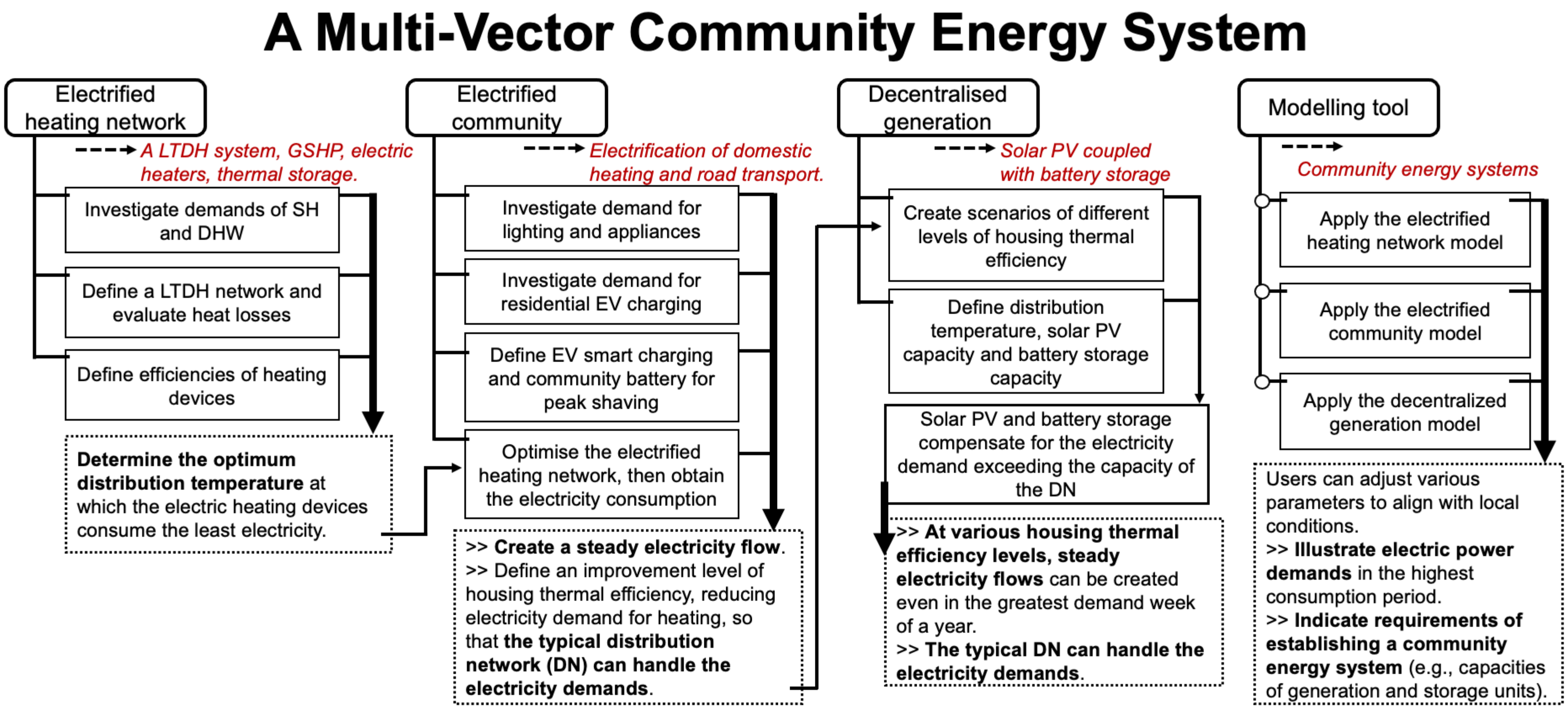

Figure 1: The development flow of a multi-vector community energy system.

1.1. An electrified heating network

A community energy system comprises an electrified heating network utilising a central ground source heat pump (GSHP) to generate heat, which is then distributed through a low-temperature district heating (LTDH) system. This LTDH system supplies households with domestic space heating (SH) demand and a heat source for domestic hot water (DHW) storage. Thermal storage units for DHW (i.e., household tanks) use electric heaters to meet the hygiene requirement.

District heating has been indicated to be a viable heat supply in a future world [26], estimated to provide 50% of entire heating demand by 2050 [27]. The development of this heat distribution technology is categorised by the supply temperature, from first-generation over 200°C to the present LTDH (fourth generation) defined to control the supply and return temperatures at 50°C and 20°C as annual averages [28]. Ultra-low-temperature district heating (ULTDH), proposed to be the fifth generation, applies a supply temperature lower than the general definition of the LTDH (50°C) [29]. This low-temperature approach decreases heat losses and makes greater uses of available low-temperature heat sources. The concern of using a low temperature in district heating is the preparation of DHW. To prevent the proliferation of legionella, water temperature should be greater than 50°C in a DHW system with circulation and heated up to 60°C in DHW storage units [30].

Briefly, employing a low temperature for heat distribution is an important measure. Most of researches adopt this idea to design systems that can be integrated with the electricity grid [31, 32], recycle waste heat [33-35], increase the utilisation of renewable sources [36, 37], and meet the hygiene requirement [38]. In this paper, an electrified heating network, meeting the domestic heating demands, consists of a highly efficient GSHP and low efficient electric heaters. This heating network, when using a lower distribution temperature, can reduce heat losses and increase the coefficient of performance (COP) of the GSHP [39]. However, due to the hygiene requirement, the low-efficiency electric heaters are utilised to boost the storage temperature of DHW, which may result in greater overall electricity consumption. This phenomenon is expected to be observed if the thermal performance of buildings is improved; DHW consumption accounts for a larger share in the domestic heating demand. Thus, a higher distribution temperature may be conducted for reducing the usage of electric heaters and thereby increasing the electricity saving. This hypothesis is addressed using a scalable model determining the optimum distribution temperature according to the least electricity consumption condition.

1.2. An electrified community

To create an electrified community model, electricity demands are investigated and indicated in an hour-by-hour form, including heating, EVs and Electricity (i.e., lighting and appliances). The consumptions of EVs and Electricity are obtained by utilising national statistical data and consumption profiles from validated simulation tool or real-world physical studies. The electricity demand of heating supply is illustrated through the electrified heating network model. Subsequently, the power demands are managed by a community energy system that performs smart management of EVs and heating supply, and a community-scale peak shaving enabled by an integration of the heating network, electricity grid and a community battery (section 2.2).

The smart control measures will be demonstrated to flatten the overall consumption power in the greatest demand week. Based on this greatest power, the required improvement level of housing thermal efficiency is estimated by factoring in the constraint of a LV substation within the typical UK distribution network [40]. Consequently, by conducting a community energy system and housing thermal efficiency improvement, the typical distribution network can handle the electricity demands.

1.3. The deployment of PV/storage units

In an electrified community, the electricity demand in the highest consumption period could exceed the capacity of a LV substation. To prevent potential faults to the distribution network, an improvement of housing thermal efficiency (reducing SH consumption) and/or an installation of PV coupled with storage units (providing extra electricity supply) are required.

Solar PV, the selected decentralised generation (DG) in this research, has been indicated to be a key technology that will produce clean energy in the UK [41]. In this paper, unlike studies that optimise the size of DG by considering the overall annual cost [42], the line losses of a power system [43] and the voltage stability with network losses [44], the capacity of DG is sized to offset the power demand exceeding the targeted maximum power within the distribution network and varied with the improvement level of thermal efficiency in buildings.

2. The multi-vector community energy system

2.1. System configuration

A community energy system, presented in Figure 2, can be categorised into heating and electricity networks. The linkages between these two networks are created by the GSHP and electric heaters placed in the community substation and household tanks, respectively.

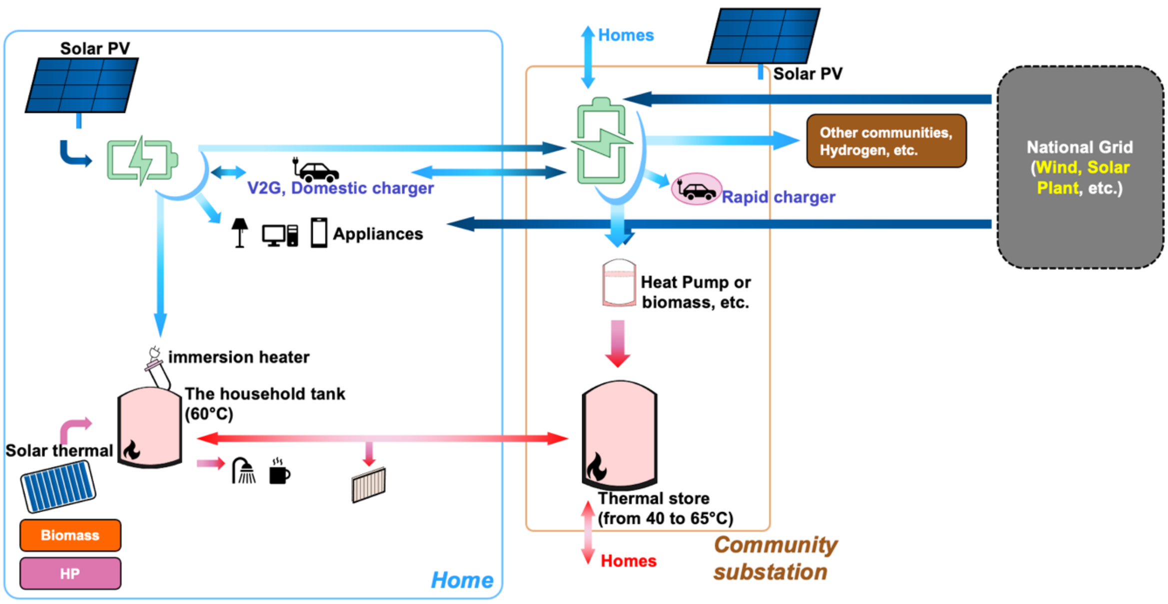

Figure 2: The multi-vector community energy system integrating a heating network, electricity grid and decentralised generation.

In Figure 2, the community substation receives the electricity supply from the electric power network and subsequently distributes the electricity to the GSHP and homes for domestic consumptions. The PV modules are placed at both community substation and homes. The battery storage in the community substation is designed to have a high enough capacity to power the GSHP during peak hours and perform rapid charging of EVs. The battery storage at home can interact with EVs and power appliances and the immersion heater in the household tank. Furthermore, EV charging at home utilises a domestic charger for slow charging with the application to deliver electricity back to the distribution network through vehicle-to-grid (V2G) technology.

Within the heating network, a GSHP is selected because of the ability to perform a COP of 4 that supplies hot water at around 50°C [39]. The community thermal store reserves hot water at a temperature range from 40°C to 65°C. A specific storage temperature is defined by the scalable model of an electrified heating network according to the network electricity consumption. For DHW storage (household tanks), a 60°C water temperature is advisable, which is supplied by the LTDH system and electric heaters. Unlike the GSHP, the electric heaters have a maximum efficiency of 100%, assumed to have a COP of 1 within models. The thermal storage units can mitigate peak demand and allow the system to adopt a GSHP and electric heaters with lower electric powers [4]. In addition, the storage units can be operated with other renewable technologies such as solar thermal, biomass, etc. for reducing electricity consumption.

2.2. The community-scale peak shaving

Commonly, within a distribution network, the output capacity of transformers and thermal limits of power lines constrain the maximum electric power supplied to homes [45]. Installing a community battery cannot boost this network capacity. Therefore, when the power consumption is greater than the network constraint, the utilisation of a community battery cannot be a solution to meet the demands.

In a community energy system, the integration of storage units, heating and distribution networks enables the community-scale peak shaving, illustrated in Figure 3. In this example, the maximum output power of the distribution network and the electric power of the GSHP are assumed to be 0.4 MW and 0.12 MW, respectively. Figure 3 (a) shows the electricity flows during off-peak hours. The community substation supplies electricity with an electric power of 0.28 MW to homes and the community battery whilst conveying an electric power of 0.12 MW to the GSHP. In Figure 3 (b), during peak hours, the distribution network constantly supplies the maximum power of 0.4 MW. At the same time, the community battery discharges its stored electricity with a power of 0.12 MW to the GSHP. From the consumers' perspective, the community substation with a 0.4 MW network capacity provides an electric power of 0.52 MW during peak hours. A steady electricity flow (0.4 MW) throughout a day attains the ideal of peak shaving.

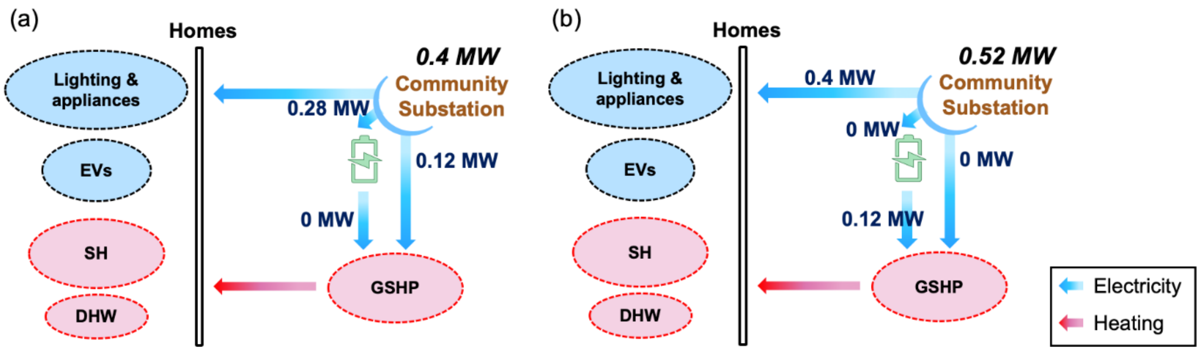

Figure 3: The illustration of the community-scale peak shaving in the multi-vector community energy system, (a) off-peak hours and (b) peak hours.

The concept of community-scale peak shaving enables a community to consume the electric power greater than the designed capacity of the electricity grid, employing the community battery (the battery placed at the community substation in Figure **2**) to supply the power demand for heating. Nonetheless, this approach still has its limitation because the maximum output power of the electricity grid is still 0.4 MW. Thus, when the power demands of the EVs, lighting and appliances in Figure **3** exceeds 0.4 MW, a home-based power supply is required, which is the battery located at home in Figure **2**.

3. An electrified heating network

This section illustrates the electrified heating network model, including modelling methodology (subsection 3.1) and results (subsection 3.2). The methodology section investigates monthly consumptions of DHW and SH in an average UK dwelling in 2018. Also, the formulas for calculating electricity demands of the GSHP and electric heaters are described. The heat losses in a LTDH system are then assessed, followed by defining the COP of a GSHP. The results section presents the key factor determining the optimum distribution temperature, temperature variation under different improvement levels of housing thermal efficiency, and scalability by evaluating various scales of communities.

3.1. Modelling methodology

3.1.1. Domestic hot water consumption

The energy consumption for DHW is related to the water volume, cold inlet temperature, hot water delivery temperature, and mainly determined by the number of occupants. In average UK dwelling, the number of occupants is 2.4 [46], which combines with a survey [47] to obtain monthly hot water consumption volumes in Figure 4. The month with the greatest hot water demand is December, attaining 3,676 litres. Figure 4 also shows the cold inlet temperature and hot water delivery temperature. The lowest and highest cold inlet temperatures are around 10.7°C in February and 20.5°C in July. The hot water delivery temperature is relatively stable, around 52°C. Accordingly, the annual energy consumption of DHW is 1649.1 kWh.

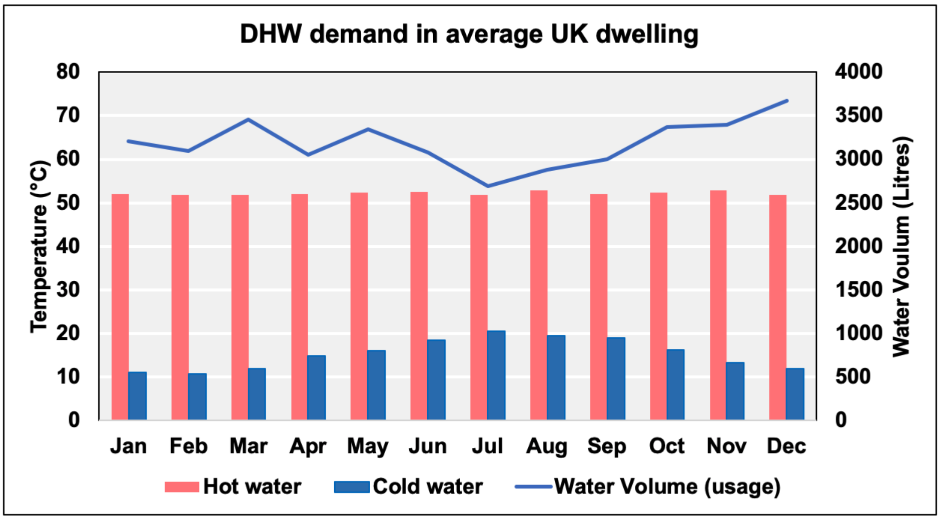

Figure 4: The monthly hot water consumption volume, cold water inlet temperature and hot water delivery temperature in an average UK dwelling [47].

The DHW consumption is supplied by two sources: LTDH system and electric heaters. The heat provided by electric heaters is calculated by Eq. (1), where $Q_{heaters}$ is the heat supply from electric heaters (kJ), $\vartheta_{setting}$ is the setting temperature on household tanks, ϑ_{tank} is the actual water temperature delivered to household tanks (°C), C_p is the specific heat (kJ/kg°C) and m_{tank} is the mass of water in household tanks (kg). The actual water temperature delivered to household tanks is gained by testing a LTDH system in the University of Nottingham [48].

$$Q_{heaters} = (\vartheta_{setting} - \vartheta_{tank}) * C_p * m_{tank} \tag{1}$$

The COP of electric heaters is 1 within models; hence, the electricity consumption of electric heaters is equal to their heat production. To gain the amount of heat supplied by the LTDH system (Q_{LTDH}), the DHW consumption (Q_{DHW}) is subtracted by the heat supply from electric heaters ($Q_{heaters}$), given by Eq. (2).

$$Q_{LTDH} = Q_{DHW} - Q_{heaters} \tag{2}$$

To factor in the heat loss of heat exchangers, the heat provided by the LTDH system (Q_{LTDH}) is divided by the efficiency ($\eta_{exchanger}$) of heat exchangers that is obtained by testing the system in the University of Nottingham [48]. The calculation formula is Eq. (3), where $Q_{DHW\ LTDH}$ is the final heat consumption of the DHW supplied by the LTDH system.

$$Q_{DHW\ LTDH} = \frac{Q_{LTDH}}{\eta_{exchanger}} \tag{3}$$

Finally, the electricity consumption of the GSHP (E_{GSHP}) generating heat to the LTDH system is calculated by dividing the final heat consumption with the COP of the GSHP (COP_{GSHP}), as described by Eq. (4).

$$E_{GSHP} = \frac{Q_{DHW\ LTDH}}{COP_{GSHP}} \tag{4}$$

3.1.2. Space heating consumption

In 2018, the SH consumption in average UK dwelling consumed 3.86 times more energy than DHW [49]. Thus, the annual consumption of the SH was 6365.4 kWh. Figure 5 illustrates the monthly consumptions of the SH and DHW in an average UK dwelling. The greatest consumption month of SH is the coldest month, February. This consumes 1,081 kWh. The lowest consumption month is July, reaching 40 kWh.

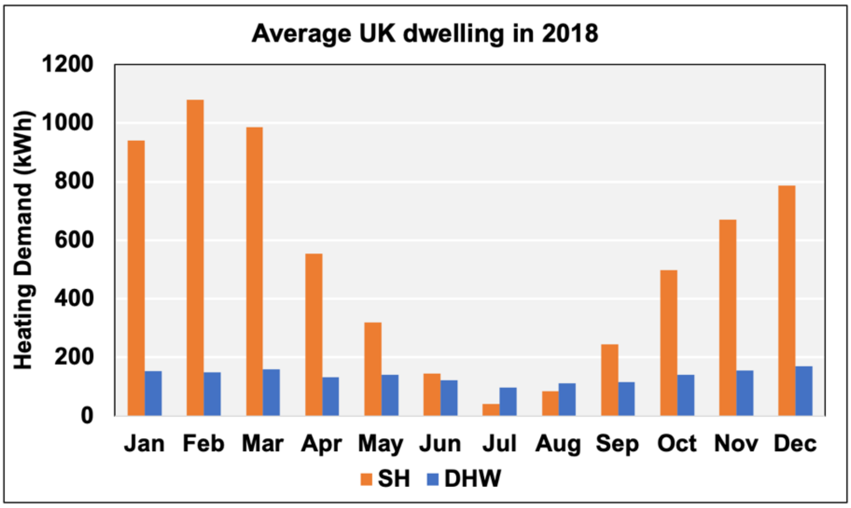

Figure 5: The monthly energy consumptions of the SH and DHW in an average UK dwelling in 2018 [47, 49].

The final consumption of the SH, considering the heat loss on heat exchangers, is calculated by dividing the SH demand with the efficiency of heat exchangers, Eq. (3). The SH demand is supplied by only the LTDH system. Therefore, dividing the final consumption with the COP of the GSHP obtains the electricity consumption for SH, Eq. (4).

3.1.3. Pipe heat loss assessment

In this paper, the evaluated distribution temperatures range between 40°C and 65°C. The return temperature is always 30°C. In a water distribution system, the size of distribution pipes correlates with the flow rate. The formula for calculating the flow rate is described by Eq. (5) [50].

$$V = \frac{Q_h}{C_p * (\vartheta_F - \vartheta_R) * \rho} \tag{5}$$

where V is the flow rate (l/s), Q_h is the heat flow (kW), ϑ_F and ϑ_R are the flow and 30°C return temperatures and ρ is the water density. The heat flow (Q_h) is the heating capacity, assumed to be 6 kW for each dwelling. Therefore, the flow rate (V) is determined by the lowest distribution temperature condition (40°C) due to resulting in the highest flow rate. The pipe sizes are then defined by applying the pressure loss table in Ref. [50] that also provides the thermal transfer coefficient (U value) of pipes for heat loss evaluation.

The layout of the heating network for pipe heat loss assessment is illustrated in Figure 6, applied as a double loop system in the models. This determines the lengths of pipes and is presented as units that one unit is comprised of one main pipe and two branch pipes. Only one branch pipe in a unit is also applicable.

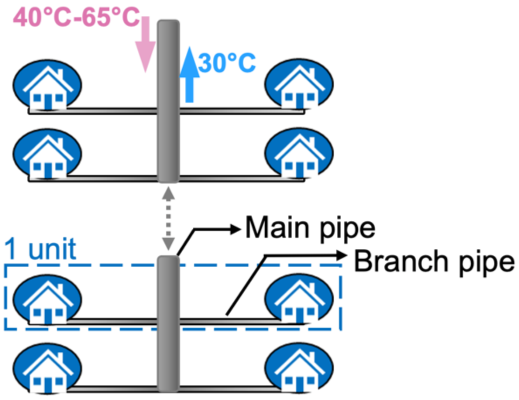

Figure 6: The layout of the heating network for pipe heat loss assessment.

The formula for heat loss evaluation is described by Eq. (6), where Q_{pipe} is the pipe heat loss per meter (W/m), U is the thermal transfer coefficient (W/m°C), ϑ_O is the average operating temperature (°C), and ϑ_S is the soil temperature.

$$Q_{pipe} = U * (\vartheta_o - \vartheta_s) \tag{6}$$

The calculation of heat losses (Q_{loss}) on branch and main pipes is given by Eq. (7).

$$[U_{branch} * (\vartheta_o - \vartheta_s) * l_{branch} * N_{branch} + U_{main} * (\vartheta_o - \vartheta_s) * l_{main} * N_{main}] * h_o = Q_{loss} \tag{7}$$

where l_{branch} and l_{main} are the lengths of a branch pipe and main pipe (m) in a unit, N_{branch} and N_{main} are the numbers of branch pipes and main pipes in a heating network and h_o is the annual operation hours (i.e., 8,760 hours). In the demonstration models, the l_{branch} and l_{main}

are assumed to be 5m and 10m. The N_{branch} aligns with the number of dwellings, while the N_{main} is the N_{branch} divided by two due to one main pipe connecting with two branch pipes. These values are adjustable in the developed modelling tool to meet various conditions, detailed in section 6.

The pipe heat loss is induced in the LTDH system utilising GSHP to provide heat. Thus, by dividing the heat loss (Q_{loss}) with the COP of the GSHP obtains the electricity consumption, as described by Eq. (4).

3.1.4. Ground source heat pump

The COP of a GSHP is correlated with the source temperature and supply temperature. The source temperature (i.e., soil temperature) is assumed to be 10°C, which results in COPs at various supply temperatures in Table 1 [39].

Table 1: COPs of a GSHP at various supply temperatures [39].

Supply temperature (°C)	40	50	60	65	70
COP	4.66	4	3.52	3.33	3.16

Soil temperature: 10°C

3.2. Results

An electrified heating network model calculates the electricity demand and then determines the optimum distribution temperature. This analysis can illustrate the temperature variation with various thermal performances in buildings, thereby applying it to an electrified community model. This section will indicate the factor defining the distribution temperature and identify the scalability.

The correlation between the DHW and SH is represented as demand ratios of DHW to SH such as 1 to 0.5, 1 to 1.2, 1 to 2, 1 to 2.7, 1 to 3.86, and 1 to 4.5. The various rates of SH can be reflected in thermal efficiency levels. The ratio of 1 to 3.86 is the DHW to SH demand ratio in 2018. SH consumption has a high likelihood to be reduced gradually [51]. Therefore, this paper selects only one condition as an example when the SH demand is increased in the future. The other conditions including 1 to 1.2, 1 to 2, and 1 to 2.7 are viewed as the thermal efficiency improved by around 70%, 50%, and 30%, respectively. To form a comprehensive analysis, two other DHW demand levels are evaluated, including 25% more and 25% fewer consumptions than the 2018 level. The scalability is shown by evaluating community scales of 50, 150 and 384 dwellings.

Figure 7 (a) illustrates the result with the increased 25% DHW consumption, consuming the annual DHW demand of 2.06 MWh in an average dwelling. When the SH rate is higher or equal to 2.7, the optimum distribution temperature is 40°C. This temperature is increased to 55°C if the demand ratio of DHW to SH is 1 to 2. The optimum temperature reaches 60°C with the SH rate lower than 1.2. As a result, a reduction in SH demand promotes greater distribution temperature.

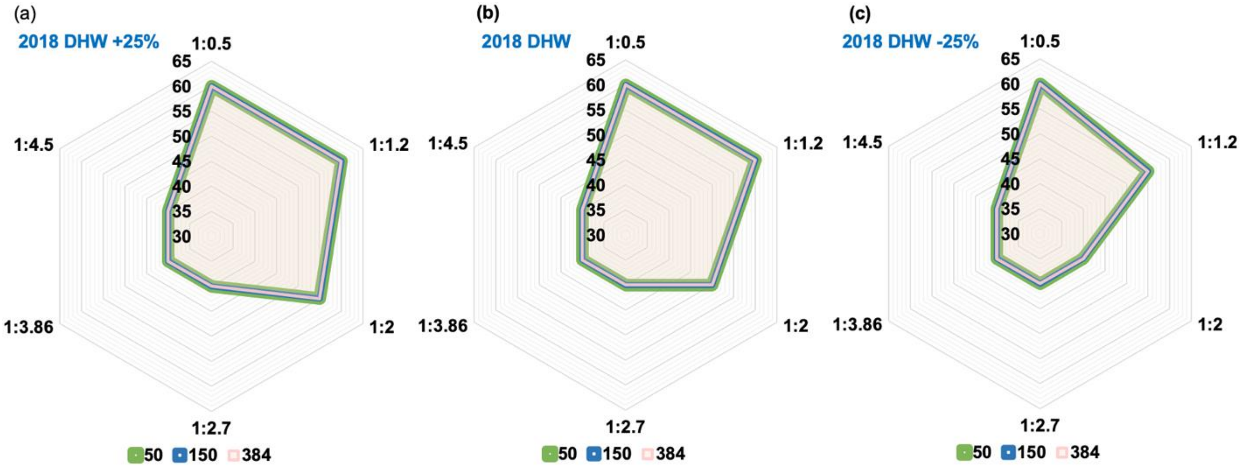

Figure 7: The distribution temperature selection in various demand ratios of DHW to SH and community scales. (a) The DHW demand is 25% greater than the 2018 level. (b) The DHW demand is the 2018 level. (c) The DHW demand is 25% less than the 2018 level.

The optimum distribution temperatures with the same DHW consumption at the 2018 level is indicated in Figure 7 (b). The rated SH conditions equal or over 2.7 should select a 40°C distribution temperature to achieve the best electricity saving. When the demand ratio of DHW to SH is 1 to 2, the temperature is increased to only 50°C. Based on the results, the total heating demand including DHW and SH is not the factor to define the distribution temperature. Comparing with the figure (a), the total heating demand of the figure (b) at the 1 to 2 condition is lower because of the fewer DHW consumption. Nevertheless, the optimum temperature in figure (a), 55°C, is greater than in figure (b), 50°C. In contrast, communities with the same DHW consumption apply a lower supply temperature for electricity saving when the total heating demand is greater. For example, in the figure (a), the ratio of 1 to 2.7 consumes more heating energy than the ratio of 1 to 2, but a lower supply temperature (i.e., 40°C) is indicated.

Figure 7 (c) presents the temperature selection with the DHW demand 25% lower than the 2018 level in an average dwelling (1.24 MWh). The distribution temperature should be 40°C in most of the conditions. The temperature reaches 55°C when the demand ratio is 1 to 1.2. Comparing the same demand ratio conditions in Figure 7 (a), (b) and (c) shows that reducing DHW demand enhances the benefit of applying a lower distribution temperature.

Figure 8 illustrates the detailed electricity consumptions of the heating network, covering the heating demands at the 2018 level and the condition with the SH demand reduced by 70%. The total power demand for DHW (i.e., the DHW_Heater and DHW_GSHP) is greater at a lower distribution temperature due to the increasing usage of low-efficiency electric heaters. Supplying a higher temperature to households raises the consumption of the GSHP; nevertheless, the efficiency of GSHP providing a greater temperature is still higher than the efficiency of electric heaters. This phenomenon dominates the network consumption if the SH demand is decreased (i.e., the housing thermal efficiency is improved; Figure 8 (b)). As a result, employing a 60°C distribution temperature can save around 37.8 MWh electricity annually in a 384-dwelling community if the SH demand is reduced by 70%.

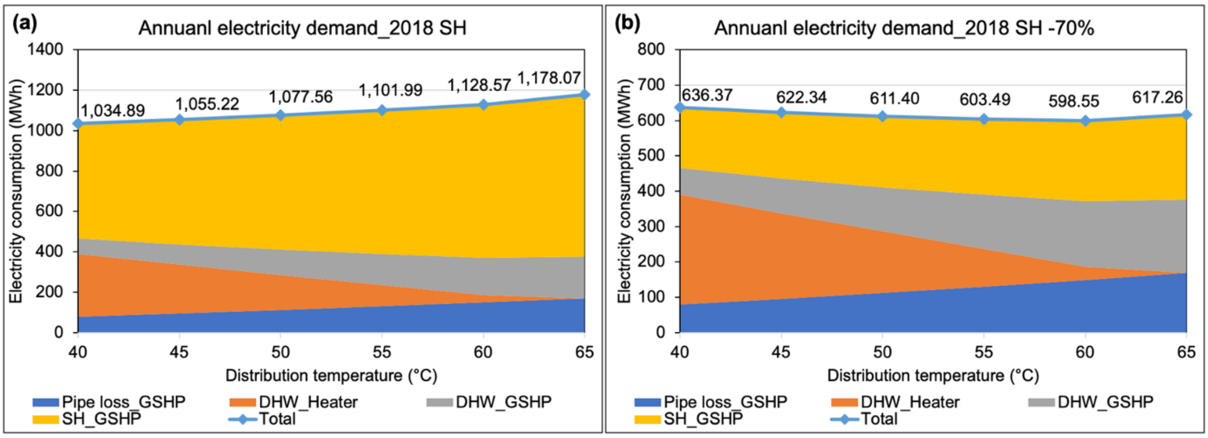

Figure 8: The electricity consumptions of the heating network under various distribution temperatures, including (a) the DHW and SH demands are at the 2018 level and (b) the DHW demand is at the 2018 level, and the SH demand is reduced by 70%.

4. An electrified community

This section elaborates the electrified community model. Subsection 4.1 (modelling methodology) firstly illustrates the typical UK distribution network and defines the scale of an electrified community. Subsequently, the electricity demands including Electricity (i.e., lighting and appliances), EV charging and electrified heating network are investigated. Next, the percentage of EV smart charging and capacity of a community battery for peak shaving are defined. Subsection 4.2 (results) shows the performance of a community energy system implementing smart management measures as well as a community energy system model with housing thermal efficiency improvement.

4.1. Modelling methodology

4.1.1. The typical UK distribution network

In the UK, a typical distribution network can be characterised as medium voltage and low voltage [40, 52]. The medium voltage substation (i.e., the 33/11 kV substation; primary substation) can output a maximum apparent power of 15 MVA, which exports electricity through six 11 kV feeders. Each feeder is connected to eight LV substations (i.e., the 11/0.433 kV substation; secondary substation). One LV substation, providing 384 houses with electricity, can output a maximum apparent power of 500 kVA [40]. Accordingly, the number of households for evaluation in an electrified community is 384. The instantaneous electric power is restricted to 500 kW (assumed power factor is 1).

4.1.2. Electricity demand for lighting and appliances

In this paper, hourly electricity demands are generated by utilising monthly consumptions and electric load curves. Figure 9 illustrates monthly consumptions in an average UK dwelling in 2018 [53]. The highest and lowest consumption months were in January and July, consuming around 393.5 kWh and 233.7 kWh. This data is then used to produce monthly consumptions in a community with 384 dwellings. On the other hand, an open-source software named CREST [54] is utilised to produce electric load curves of a community.

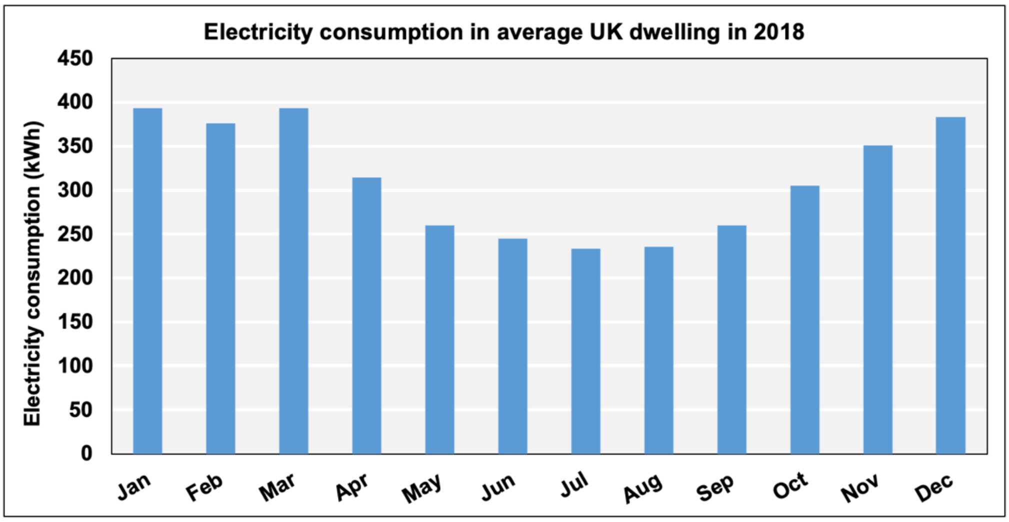

Figure 9: The monthly electricity consumptions of the Electricity (i.e., lighting and appliances) in an average UK dwelling in 2018 [53].

4.1.3. Residential charging demand of EVs

A study of EV charging behaviour in the UK [55] indicates the load curve of residential charging and the daily demand across a full year. The average annual charging demand per EV is 1,760 kWh that 75% (1,320 kWh) is supplied by residential charging points [55]. The monthly consumptions of an EV, illustrated in Figure 10, show that the consumption in January is around 130.2 kWh, the highest. The lowest consumption month, August, consumes around 88.4 kWh.

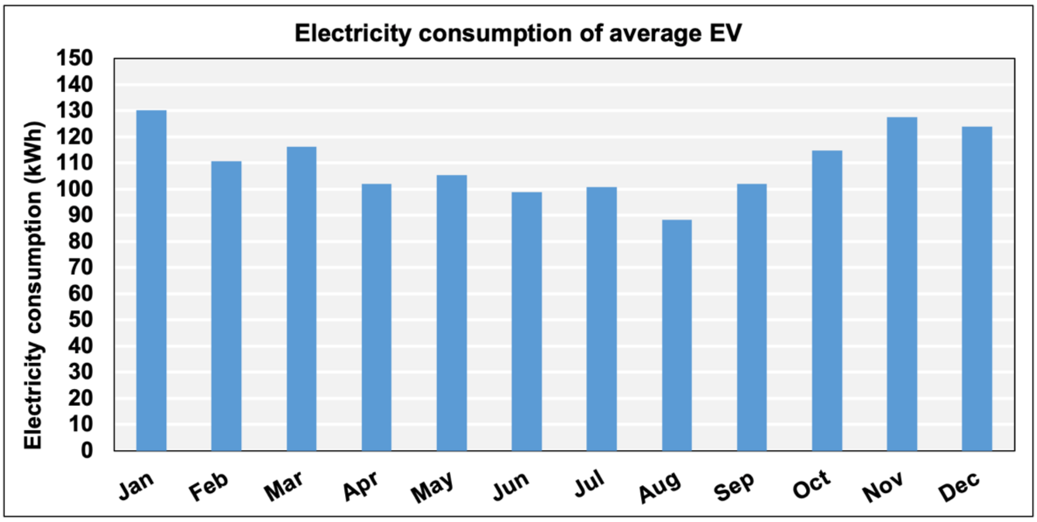

Figure 10: The monthly electricity consumptions for residential charging per EV [55].

In 2018, the average number of cars or vans per household is 1.21 in the UK [56]. Therefore, the number of EVs in an electrified community with 384 households is determined to be 465.

4.1.4. Electricity demand and operation of an electrified heating network

In a 384-dwelling community, the annual SH and DHW demands are 2444.3 MWh and 633.2 MWh, respectively, according to the consumptions per dwelling (subsection 3.1.2). The electricity demands of the GSHP and electric heaters, therefore, can be obtained using the methods depicted in section 3.1.

For the heating network operation, this paper employs an optimised approach, defined as the ideal heating supply, which is to operate the GSHP and electric heaters constantly in the greatest consumption week (i.e., the coldest week). The collective electric powers of the GSHP and electric heaters are around 220 kW and 41 kW. These power values will be illustrated in an electricity consumption curve in section 4.2.1. Furthermore, the community thermal store, is determined to store half of an average daily demand in the coldest month because of the constant operation. The daily demand per dwelling, derived from the February consumption in Figure 5, is 43.9 kWh. To enable a 20% consumption buffer, the capacity of the community thermal store, then, is 10.5 MWh.

4.1.5. EV smart charging and battery storage for peak shaving

The electricity consumptions in the greatest overall demand day (i.e., the coldest day) are illustrated in Figure 11, including 384 dwellings and 465 EVs. Figure **11** (a) without EV smart charging shows that the highest demand peak exceeding the 0.5 MW capacity of a LV substation is 0.59 MW. The mean electric power is 0.29 MW.

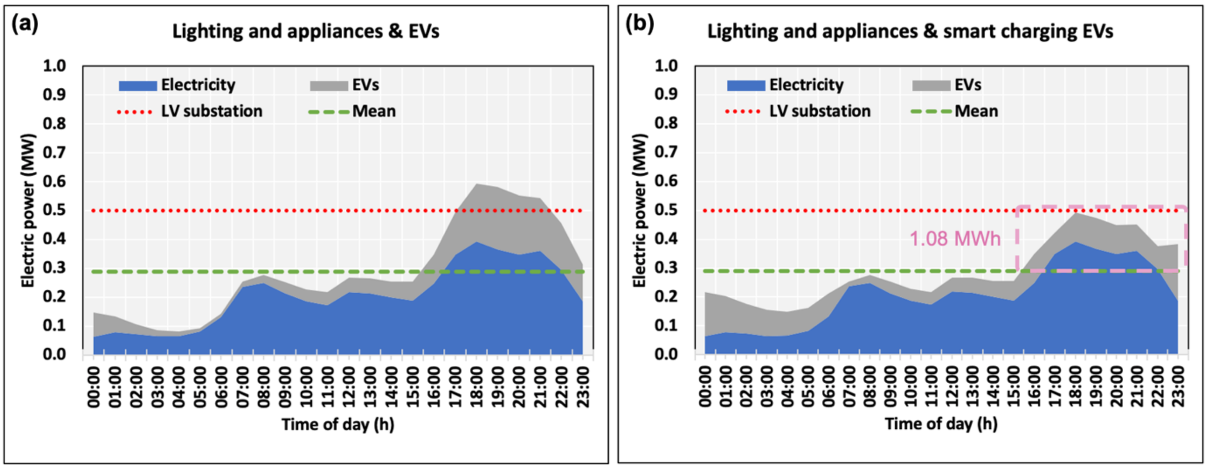

Figure 11: The Electricity (i.e., lighting and appliances) demand in 384 dwellings and the residential charging demand of 465 EVs, including (a) without EV smart charging and (b) applying EV smart charging.

A study indicates that the percentage of EVs adopting smart charging by 2050 could be over 75% in the UK [57]. For demonstration, EVs utilising smart charging is 50%. The demand profile with 50% smart charging is shown in Figure 11 (b). The peak consumption power lower than the maximum capacity of a LV substation is 0.49 MW. The method of applying the 50% smart charging is reducing the consumption of EVs from 17:00 to 23:00 in Figure 11 (a) by 50% and then allocating the removed consumption to 8 hours from 23:00 to 07:00. Furthermore, the Electricity demand in Figure **11**, representing the condition without the electrification, indicates the highest demand peak is 0.4 MW. This paper, therefore, sets the target as utilising a community energy system to control the power demand on the electricity grid not over 0.4 MW.

In an electrified community, the electricity demand profile can be flattened by applying the community-scale peak shaving. The capacity of battery storage for the peak shaving is defined according to the demand data in Figure 11 (b) that indicates a 1.08 MWh storage capacity is required to supply the demand exceeding the mean electric power. The battery capacity in a community energy system, then, is determined to be 1.27 MWh with an 85% utilisation rate. This battery storage is grouped into the community and home batteries in a community energy system (Figure **2**). The capacities of each battery category are defined by the maximum output power of the electricity grid (section 2.2). In this paper, the targeted maximum power is 0.4 MW. Thus, the power demand exceeding 0.4 MW in Figure **11** (b) should be met by the home-based batteries, while the demand higher than the mean power but lower than 0.4 MW is supplied by the community battery.

This section 4.1 addresses the conditions in an electrified community and parameters of a community energy system, summarised in Table 2. These conditions are input to energyPRO for modelling and illustrated in next section.

Table 2: The parameters of the multi-vector community energy system and demand data in the electrified community.

Conditions	
Number of dwellings	384
Number of EVs	465
Battery capacity (MWh)	1.27
Percentage of smart charging (%)	50
Electric power of GSHP (kW)	220
Thermal store capacity (MWh)	10.5
Temperature of heating network (°C)	40
Annual demand	
SH (MWh)	2444.3
DHW (MWh)	633.2
Lighting and appliances (MWh)	1439.6
EVs (MWh)	614.1

4.2. Results

4.2.1. An electrified community without/with a community energy system

To investigate the impact of electrification, the electric power demands on the highest consumption day are indicated in Figure 12. The conditions are evaluated with different COPs of heat generation to meet the SH demand. The COP 1 condition (Figure 12 (a)) can be viewed as the SH demand supplied by electric heaters. The maximum and mean consumption powers are 2.14 MW and 1.35 MW, respectively. Comparing with the maximum power created by the Elec. (i.e., without the electrification; the Electricity), the COP 1 condition increases the peak demand by 5.4 times. The mean consumption of the Elec. is 0.21 MW, indicating that the mean power is increased by 6.4 times with the COP 1 condition.

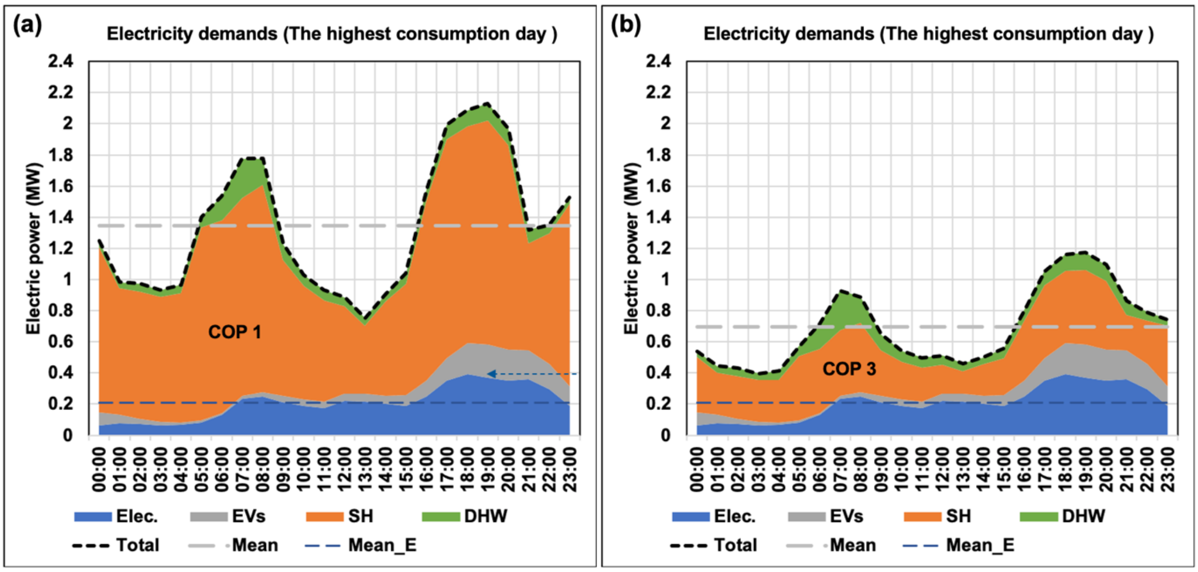

Figure 12: The electricity consumptions of a 384-dwelling community under different COPs for SH demand.

The COP 3 condition (Figure 12 (b)) is reflected in the utilisation of air source heat pumps [58]. The maximum power, compared to the COP 1 condition, is reduced to 1.17 MW while the average demand is decreased to 0.7 MW. In contrast to the Elec., the COP 3 condition raises the peak demand by 2.9 times and the mean consumption by 3.3 times.

Figure 13 illustrates the electricity demands in the highest demand week in which the heating demands are supplied by an electrified heating network employing the ideal heating supply. This stacked area figure shows that the maximum hourly demand power is 0.85 MW. The electric power of the GSHP operated constantly should be at least 213 kW.

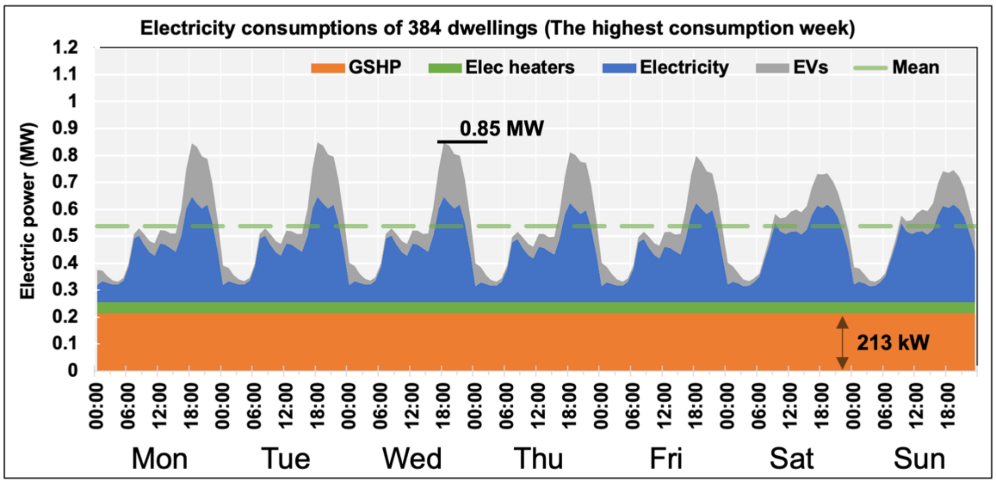

Figure 13: The electricity consumptions of an electrified community in the highest consumption week. An electrified heating network is employed.

A community energy system applying the ideal heating supply, smart charging of 50% EVs and peak shaving is demonstrated on energyPRO in Figure 14. The electricity grid (i.e., New Fixed tariff market) connects with the electrified heating network, battery and demands of EVs and Electricity. This model aggregates the community and home batteries as a battery unit to manage the electric power demand. The heating network utilises the GSHP and electric heaters to supply heat for the SH and DHW demands and heat losses. The heat produced by the GSHP can be reserved in the thermal store or delivered to homes directly. The DHW demand is separated into two sites due to the software constraint. Based on Figure 13, the electric power of the GSHP is determined to be 220 kW. The detailed conditions are summarised in Table 2.

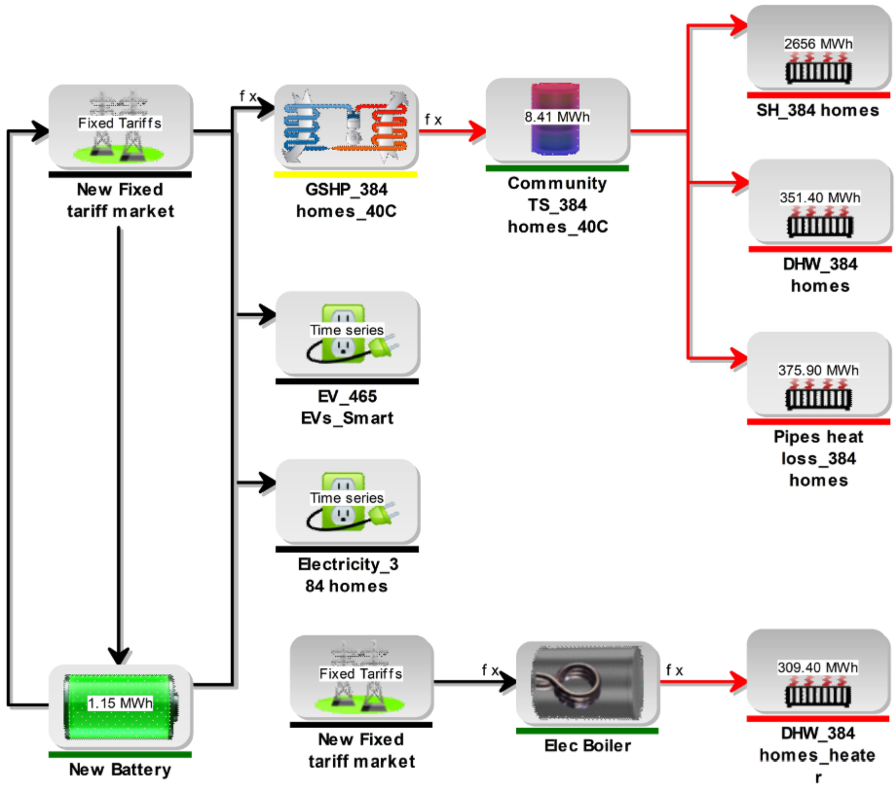

Figure 14: The modelling configuration of the multi-vector community energy system with the ideal heating supply, smart charging and peak shaving.

The modelling result in Figure 15 (a) shows the heat production and consumption, indicating that the GSHP (yellow colour) produces heat constantly during the highest consumption week (i.e., the middle of the graph). The heating power generated by the GSHP is not adequate to meet the instantaneous heating demand (red line). Nevertheless, the utilisation of thermal storage (Figure **15** (c)) successfully compensates for the insufficient supply. In figure (b), the collective electricity consumption for heating, EVs and Electricity is illustrated. Figure (d) presents the charging and discharging cycles of the battery, while the stored electricity capacity in the battery is indicated in figure (e).

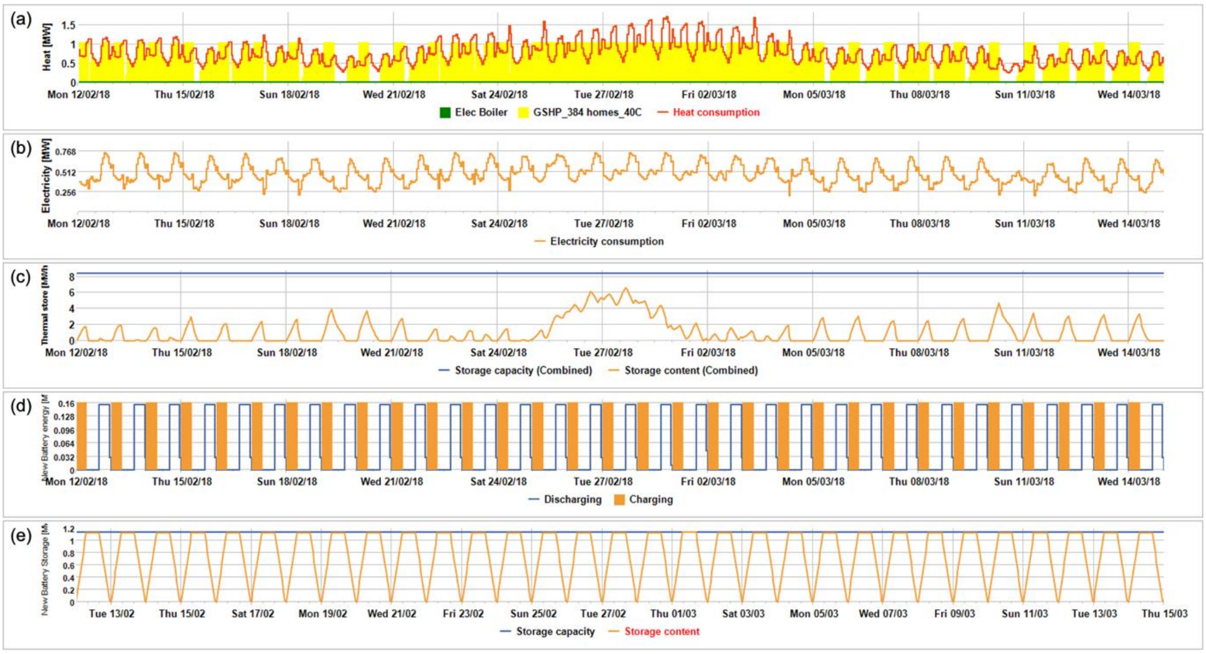

Figure 15: The modelling result of the community energy system with the ideal heating supply, smart charging and peak shaving. (a) heat consumption and heat production of the electric heaters and GSHP, (b) electricity consumption of the electrified community, (c) heat stored in the thermal store, (d) charging and discharging cycles of the battery and (e) electricity stored in the battery.

For a detailed analysis, the data in the greatest consumption week in Figure 15 is transferred to Figure 16. The maximum power of the stacked area is 0.75 MW on Wednesday. The mean power demand is 0.53 MW. Moreover, using the battery to perform peak shaving indicates that the highest demand peak (black line) is reduced to 0.64 MW. The charging period of the battery is from midnight to 7 am, that the charging power is set at 175 kW. The discharging period is from 16:00 to midnight, which has a discharging power of 170 kW. The battery is operated by a simple control method (the two black dash lines), implying that the total consumption power can be further decreased with a better battery control system and potentially constrained at around the Mean.

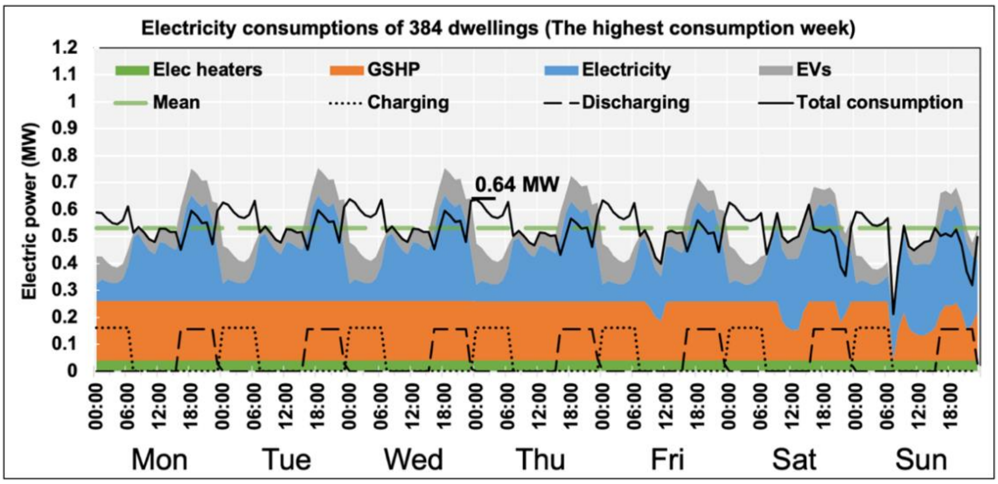

Figure 16: The electricity consumptions with the multi-vector community energy system with the ideal heating supply, smart charging and peak shaving.

4.2.2. A community energy system with housing thermal efficiency improvement

This section evaluates a community energy system with the typical UK distribution network, thereby indicating the required degree of thermal efficiency improvement in buildings.

The electricity consumptions within the greatest demand week, Figure 16, are converted into a bar chart in Figure 17. This chart assumes that the electricity flows are steady, attainable by utilising a community energy system. The electric power demand of the GSHP is split into SH and DHW with pipe heat loss, based on the model of an electrified heating network. The consumption of the GSHP for the DHW with pipe heat loss is added to the consumption of electric heaters that supply partial DHW, presented as the DHW + Heat loss in Figure 17. The electric powers of the Electricity, EVs, DHW + Heat loss and SH are 0.21 MW, 0.08 MW, 0.06 MW and 0.05 MW. To meet the target (0.4 MW), the exceeding demands are required to be reduced, which is represented by the ‘SH reduction’ and ‘PV (generation), Storage’ at the negative y-axis.

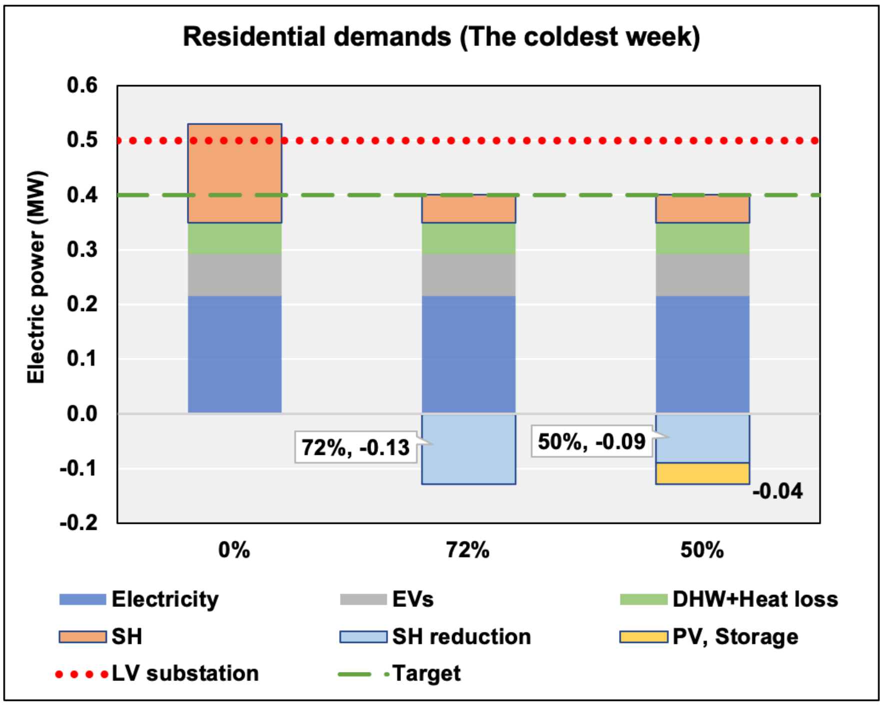

Figure 17: The average electric power consumptions in the highest demand week with different improvement levels of thermal efficiency in buildings.

In Figure 17, three levels of thermal efficiency improvement, compared with the housing thermal efficiency in 2018, are evaluated. The powers of SH reduction from the middle bar to the right bar are 0.13 MW and 0.09 MW. The middle bar illustrates that the target can be achieved by a 72% SH demand reduction, equivalent to a thermal efficiency improvement of 72%. This bar chart also indicates the maximum electric power of the GSHP by the addition of the DHW + Heat loss and SH powers (0.11 MW). The condition, requiring the utilisation of PV/storage units, is illustrated in next section.

The 72% improvement scenario is demonstrated on energyPRO, utilising the same modelling configuration as Figure 14. The differences are: (1) The SH demand is reduced by 72%. (2) The electric power of the GSHP is decreased from 0.22 MW to 0.11 MW. (3) The distribution temperature is increased from 40°C to 60°C (section 3.2). (4) The capacity of thermal storage is reduced from 10.5 MWh to 3.89 MWh.

Figure 18 indicates the modelling result in the greatest demand week. The maximum power of the stacked area attains 0.61 MW. The mean consumption power meets the target at 0.4 MW. Besides, the battery utilising a simple control method (two black dash lines) manages the total consumption power (black line) at a power range lower than the LV substation. The total consumption can be potentially constrained at the target power with a better battery control system.

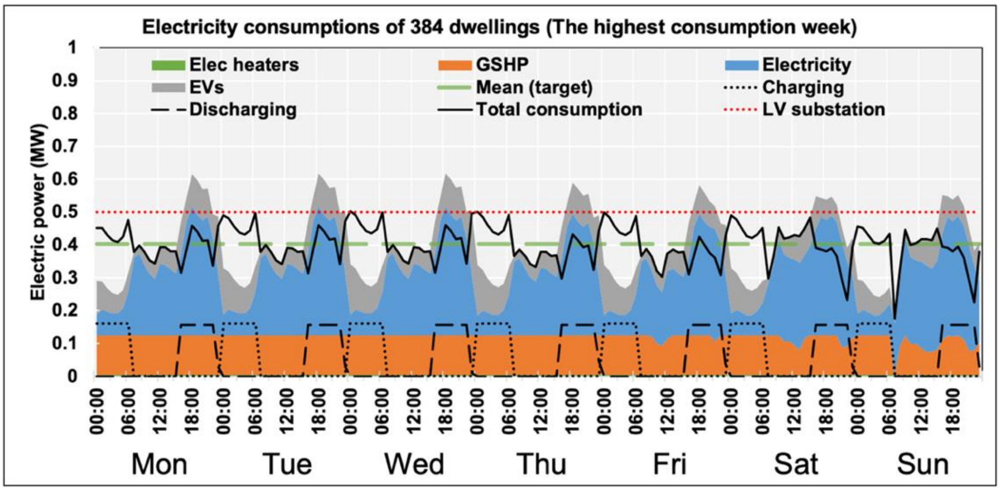

Figure 18: The 72% housing thermal efficiency improvement with the community energy system performing the ideal heating supply, smart charging and peak shaving.

5. The deployment of PV/storage units

This section evaluates decentralised PV/storage units within a community energy system by conducting the 50% thermal efficiency improvement in Figure 17. This assessment employs both PV and electricity storage systems to ensure that the distribution network is operated at safe conditions, even if the scenario of having no PV production occurred in the greatest demand week. Subsection 5.1 (modelling methodology) indicates system parameters of an electrified heating network, PV modules and electricity storage units (battery). The parameters are input to energyPRO for modelling. Subsection 5.2 (results) illustrates the result of utilising PV/storage units to offset the power demand exceeding the targeted maximum power.

5.1. Modelling methodology

5.1.1. An electrified heating network

This subsection illustrates the electric power of a GSHP and distribution temperature of a LTDH system. Comparing with the 72% improvement scenario in Figure 17, the 50% improvement scenario requires the power supply from PV/storage units for the greater SH demand. The electric power of a GSHP, therefore, is 0.15 MW (defined by the DHW + Heat loss, SH and PV, Storage powers).

The demand ratio of DHW to SH has been identified to be the factor determining the optimum distribution temperature. In Figure 7 (b), the scenario with 50% thermal efficiency improvement is described in the ratio of 1 to 2, indicating that the distribution temperature is 50°C.

5.1.2. Photovoltaic modules

PV generation is aimed at compensating for the power demand exceeding the targeted import electricity. The formula for scaling the PV modules is described by Eq. (8)

$$P_{PV} = \frac{P_r * h_D}{h_{sun}} \quad (8)$$

, where P_{PV} is the peak power generated by the PV modules, P_r is the required power that offsets the electricity demand over the target power, h_D is the hours in a day and h_{sun} is the daily peak sun hours. The highest consumption month in 2018 was February, which has daily peak sun-hours of around 2.7 hours [59]. As a result, the peak power of PV modules is 349 kWp in the 50% improvement level.

5.1.3. Battery storage

The function of battery storage is performing peak shaving and storing adequate electricity for the greatest demand week. The required capacity for implementing peak shaving is 1.27 MWh (subsection 4.1.5).

The required storage capacity for the greatest demand week is defined by the improvement level of housing thermal efficiency. In Figure 17, the 50% improvement scenario requires a battery capacity of 6.56 MWh, derived from the multiplication of the PV, Storage power and hours per week. Thus, the installed battery capacity is 7.72 MWh with an 85% utilisation rate. Table 3 summarises the conditions in the 50% and 72% thermal efficiency improvements.

Table 3: The conditions in the 50% and 72% thermal efficiency improvement scenarios.

Thermal efficiency improvement	50%	72%
Annual SH demand (MWh)	1219.2	688.5
GSHP electrical capacity (MW)	0.15	0.11
LTDH supply temperature (°C)	50	60
TES capacity (MWh)	5.90	3.89
Battery capacity (MWh)	7.72	1.27
Peak power of PV systems (kWp)	349	-

5.2. Results

A 12-week assessment in winter is conducted for showing reliability whilst validating the concept of applying housing thermal efficiency improvement and PV/storage units. The 72% improvement scenario has been demonstrated that even in the highest demand week, the electric power can be managed under the capacity of a LV substation by utilising a community energy system without PV modules (Figure 18).

Figure 19 indicates the modelling result of the 50% improvement scenario, including the PV generation and power demands within 12 weeks. The weekly consumptions less than the target are only week 4, week 10 and week 12. The electricity supplied by PV modules is illustrated with the secondary axis, which offsets the power demand exceeding the target, except for the week 2. Nonetheless, the demand in week 2 is only 0.9 kW higher than the target power after subtracting the PV generation from the total electricity consumption. The exceeding power demand, then, is 0.15 MWh, which can be met by the battery storage having 7.72 MWh capacity.

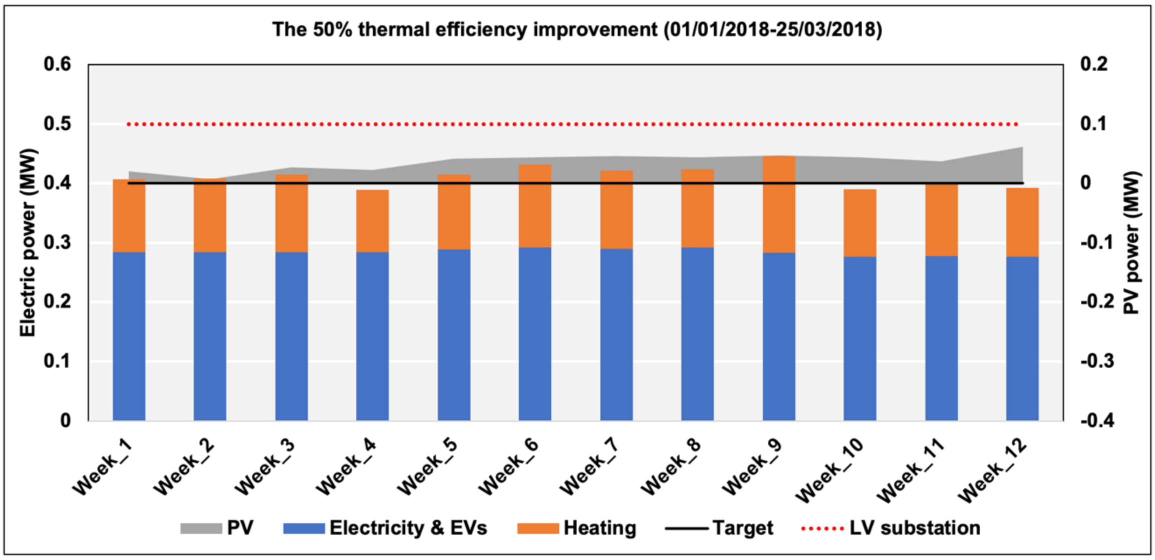

Figure 19: The electricity demands of a 384-dwelling community with the 50% thermal efficiency improvement and PV generation in 12 weeks.

In previous sections, a community energy system has been illustrated and demonstrated by utilising the conditions in the UK. A developed modelling tool based on the demonstration models is introduced in the next section, which enables the flexibility of applying a community energy system to match different geographical locations.

6. The modelling tool of multi-vector community energy systems

Subsection 6.1 outlines adjustable parameters in the modelling tool for users to align with local conditions. The modelling results are then illustrated in subsection 6.2.

6.1. Demand settings of the modelling tool

Demand setting is a worksheet of the modelling tool, categorising variables as the Community, District heating and Annual demands per unit. In Figure 20, the values of this example are the data from previous sections. In the Community category, users can adjust the maximum output power and targeted power of a LV substation. The numbers of dwellings and EVs in a community and the percentage of EVs participating in smart charging are also adjustable.

Community	LV substation	0.5	MW
	Targeted power on LV substation	0.4	MW
	Homes	384	numbers
	EVs	465	numbers
	Smart charging	50	%
District heating	Return temperature	30	°C
	Soil temperature	10	°C
	Length per branch pipe	5	m
	Number of branch pipes	384	numbers
	Length per main pipe	10	m
	Number of main pipes	192	numbers
Annual demands per unit	Space heating	6.365	MWh
	Plan to improve	50	%
	COP (efficiency)	1	
	Domestic hot water	1.649	MWh
	Household tank temperature	60	°C
	Lighting and appliances	3.749	MWh
	EVs	1.321	MWh

Figure 20: Screenshot of the modelling tool - The variables that users can adjust on the demand setting sheet.

The District heating category includes the return temperature, soil temperature, lengths and numbers of pipes. The temperature values are input as annual averages. The supply temperature is not a variable because its optimum temperature is defined by the electrified heating network model.

The Annual demands per unit is the energy demands in an average dwelling in a community, covering SH, DHW, lighting and appliances, and EVs. In the same category, the Plan to improve describes the desired improvement level of housing thermal efficiency, which defines the SH demand in one of the compliant scenarios as an electrified community. In Figure **20**, the input value of Plan to improve is 50%, meaning that the SH demand, 6.365 MWh, is reduced by 50%. Furthermore, the COP represents the efficiency of heat generation for SH consumption in the scenario without employing the community energy system. The household tank temperature as DHW storage temperature connects with the electrified heating network.

This subsection introduces basic parameters for meeting users' requirements, which connects to the database based on the conditions in the UK, such as heating and electric demand profiles, weather conditions and the electricity grid configuration. The database can be adjusted to align with local conditions, which, in the modelling tool, is highlighted with the green colour of Figure **20**.

6.2. Outcomes of the modelling tool

The modelling results are illustrated in four options in Figure 21. The first option is developing an electrified community without a community energy system and housing thermal efficiency improvement. By the utilisation of a community energy system is defined to be the second option. The third and fourth options, factoring in the targeted power on a LV substation, apply both a community energy system and the thermal efficiency improvement. The third option uses the thermal efficiency improvement to meet the target. For the fourth option, the level of thermal efficiency improvement is determined by the Plan to improve (Figure 20), which may require extra PV/storage units to support the energy system.

An electrified community	Energy system	Housing thermal efficiency	
Opt. 1	X	X	
Opt. 2	V	X	
Opt. 3	V	Condition 1	72%
Opt. 4	V	Condition 2	50%

Figure 21: Screenshot of the modelling tool - The four options of an electrified community.

Figure 22 shows the requirements of establishing a community energy system. The electric power, supply temperature and COP of a GSHP, and capacities of thermal storage units are indicated for the heating network. The capacities of PV modules and battery storage units are illustrated for providing decentralised electricity generation and storage, respectively. The Battery_1, operating the community-scale peak shaving, is split according to the capacity of a LV substation and then installed at the community substation and homes. Furthermore, Opt. 4 shows that the PV generation and Battery_2 are required due to the lower level of housing thermal efficiency.

By applying the system parameters in Figure 22, outcome results of an electrified community are demonstrated by Figure 11, Figure 12 and Figure 17.

	Heating_GSHP			Thermal storage		
An electrified community	Electrical power	Supply temperature	COP (efficiency)	Tank	Tank	**1** household tank
Opt. 1	**0**	**0**	**0**	**0**	**0**	**0**
Opt. 2	**0.24**	**40**	**4.67**	**907.02**	**10.53**	**0.116**
Opt. 3	**0.11**	**60**	**3.52**	**111.54**	**3.89**	**0.116**
Opt. 4	**0.15**	**50**	**4.00**	**254.10**	**5.90**	**0.116**
	MW	°C		m3	MWh	m3 *One dwelling*

DG	Electricity storage			
PV	Battery_1	B1_Substation	B1_Homes	Battery_2
0	**0**	**0**	**0**	**0**
0	**1.27**	**0.93**	**0.34**	**0**
0	**1.27**	**0.93**	**0.34**	**0**
349.37	**1.27**	**0.93**	**0.34**	**6.45**
kWp	MWh			MWh

Figure 22: Screenshot of the modelling tool - The requirements of establishing a community energy system

7. Discussion and conclusion

This paper designs a multi-vector community energy system, integrating heating network, electricity grid and PV generation, to address the management of electric power supply and demand in an electrified community.

In an electrified heating network model using a LTDH system, the supply temperature determines the system performance. This paper analyses heating demands, heat losses and efficiencies of heating devices to illustrate electricity consumptions under various supply temperatures. The demand ratio of DHW to SH is identified as the critical factor defining the optimum distribution temperature. This model demonstrates that a higher distribution temperature is enabled to reduces electricity consumption, when improving the housing thermal efficiency of a community.

To illustrate the impact of an electrified community on the electricity grid, this paper investigates hourly electricity demands for lighting and appliances, EVs and residential heating. The result shows that the peak consumption power of an electrified community can be increased by over 5 times on the greatest demand day, converting the residential heating demand into electricity directly. Nevertheless, a community energy system, utilising the electrified heating network, EV smart charging and community-scale peak shaving, can possibly reduce the increased peak power to only a 33% increase. Along with this community energy system, a 72% thermal efficiency improvement in buildings, reducing the electricity demand for SH, allows the typical UK distribution network to accommodate an electrified community. The improved percentage is compared with the 2018 level.

Apart from improving the thermal efficiency to meet the distribution network constraint, PV production coupled with battery storage is suggested to be an alternative if the improvement degree is lower than 72%. This concept is validated through a 12-week assessment in winter using the 50% improvement scenario. It is noteworthy that the required battery storage for the highest demand week in the 50% improvement scenario can be replaced by EV storage; however, this accompanies the change in the current home-based EV charging behaviour. This means that EVs need to access public charging points for storing PV generation while PV production should be delivered to different communities, where the electricity is required or deposited. Besides, the utilisation of a community energy system can create steady power flows. If EVs cannot store the PV generation, EVs exporting electricity to the distribution network (i.e., V2G) may not have a practical purpose. In other words, a community energy system applying PV generation/EV storage can be the best practice in V2G technology, which is the next development topic of a community energy system.

Within this body of work, the simulation models of a multi-vector community energy system are depicted, demonstrated and ultimately assembled to build a modelling tool. By utilising this modelling tool, a customised result for developing an electrified community can be obtained, which provides four options for selection. Based on these options, the required capacities of each component of a community energy system and the electric load curves of the highest consumption period in a year are indicated. This modelling tool is expected to provide the government or planner with the information of establishing an electrified community at various geographical locations, thereby progressing the electrification for carbon emission reduction.

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