Advances in Applied Energy 5 (2022) 100088

Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapen

# Electrification with flexibility towards local energy decarbonization ☆

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ARTICLE INFO

*Keyword:*
Local energy system
Decarbonization
Electrification
Flexibility
Electricity network
Electric vehicle

ABSTRACT

On the way towards Net Zero and considering new disruptive technologies may not be ready at scale in the near term, we investigated the role that electrifying local energy systems (LES) could play via coordination across local electricity, heating, transport, and buildings sectors. A representative case in Wales was investigated as the UK recently set a near-term target to reduce 78% emissions compared to 1990 levels by 2035. To do so, we firstly developed a local energy emissions model to simulate whether an electrified LES could achieve the emission target. Then, we developed a local energy optimization model to address the induced significant increment of peak demand. The case study revealed that decarbonizing the local heating sector is vital and challenging based on the UK current initiatives while a greater effort to achieve at least 46% residence installing heat pumps is needed by 2035. Compared to the existing level, the peak electricity demand after electrification would be more than tripled without flexibility. In contrast, the peak electricity demand would only be less than doubled with flexibility. Overall, through the proposed two models, this study demonstrates electrification as a feasible solution to achieve deep decarbonization and further implies flexibility is the key in electrification with huge cost-saving potential in upgrading electricity networks.

## Introduction

The UK government recently announced the 78% greenhouse gas emissions reduction target by 2035 compared to the 1990 levels to bring the UK more than 3/4 of the way towards Net Zero by 2050 [1]. Achieving this decarbonization target requires lots of actions on our buildings, transport, and energy systems at a local level. Local renewables, storage, and decarbonization of heating and transport sectors all need to be delivered with significant involvement of local stakeholders to make sure local needs are met in a more cost-effective way. Plenty of projection models have been developed for exploring the national-level decarbonization pathway [2], for instance, the UK Times Model was used in the UK National Grid Future Energy Scenarios [3]. When it comes to the local-level, the emerging value of LES has been increasingly noticed, e.g., promoting local renewable energy production [4,5], bridging local stakeholders and national energy infrastructure by a whole system approach [6] or a nexus approach [7], enabling novel business modes [8], as well as achieving local balancing [9]. However, buildings and energy networks all vary among different local areas, and no clear consensus has emerged regarding the most appropriate pathway to decarbonization. Can electrifying local heating and transport be a feasible solution? How much additional electricity demand would be induced? Can the existing electricity network support that electrification without heavy investment? This paper gives evidence-based answers to the above questions by revealing the flexibility enhanced electrification as a possible solution for decarbonizing LES. Note that flexibility is an evolving concept that has been investigated from the supply-side perspective, e.g., fast ramping ability of generators; the network perspective, e.g., network reconfiguration; the demand-side perspective, e.g., building-level demand response [10] and multi-energy integration [11]; or the storage perspective, e.g., battery storage, thermal storage and power-to-gas seasonal storage [12,13]. Here, as we address LES, the flexibility here refers to the ability to modify local generation and consumption patterns in reaction to external signals (e.g., price signal or frequency signal) to provide a service within the energy system or achieve local supply-demand balance.

To do so, we firstly built a local energy emissions (LEE) model and applied it to a case study to simulate whether an electrified LES can achieve the 78% emission reduction target. Then, the benefit of flexibility for the electricity network to handle the challenge of significant induced electricity demand was demonstrated by developing a local energy optimization (LEO) model and applying it to the same case. The contribution of this study is offering a whole-system based modeling tool to explore feasible solutions for local energy decarbonization and revealing quantitative implications systemically for the local electricity,

☆ Information on the data underpinning the results presented here, inlcuding how to access them, can be found in the Cardiff University data catalogue at http://doi.org/10.17035/d.2022.0141909234.

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https://doi.org/10.1016/j.adapen.2022.100088
Received 5 January 2022; Received in revised form 10 February 2022; Accepted 11 February 2022
Available online 12 February 2022

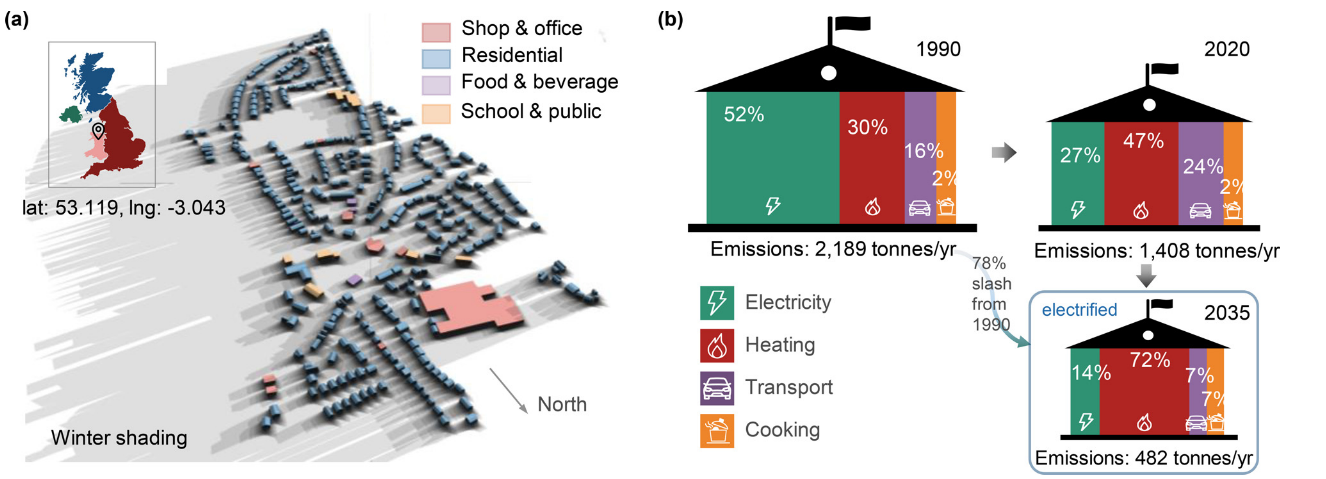


**Fig. 1.** The case county map and emissions breakdown. (a) various kinds of local buildings having the potential to develop rooftop PV panels without shading among each other; (b) total energy-related emissions and the four sectors' breakdown in 1990, 2020, and 2035 calculated by the LEE model with inputs listed in Method Table 2.

heating, transport, and building sectors by a comprehensive case. The local stakeholders, energy industry, policy makers, academia, and non-profit organizations, who wish to contribute to the decarbonization of LES but are uncertain how, would be interested in the findings.

*Electrification is feasible but needs greater efforts*

We developed the LEE model summing up the emissions of local energy-related activities at annual basis and applied it to a typical local district located in Flintshire County, Wales, UK as an example. The local district is mainly with residence, small businesses, and other essential services, e.g., food supply and school (see Fig. 1a). Most residents live in detached houses, where natural gas is used for cooking and heating. In Wales, roughly 76% of the population live in this kind of county accounting for 97% of Welsh land [14]. By inputting true data for both 1990 and 2020 and simulated data for 2035 into the LEE model (as listed in **Method Table 2**), local energy-related emissions for the three time periods were simulated, i.e., the 1990 emissions as the baseline, the emissions in 2020, and the emissions in 2035 satisfying the 78% reduction target by an electrified LES. The energy-related emissions and their breakdown in 1990, 2020, and 2035 for this district were obtained from the LEE model output as shown in Fig. 1b. In 1990, due to the relatively high emission factor of the electricity grid, 52% emissions of this district came from electricity. Thanks to the significant decarbonization progress of the electric power system, the electricity's emission share dropped to 27% in 2020. Though the amount of emissions from heating and transport did not change significantly in 2020 compared to that in 1990, their shares increased to 47% and 24%, respectively.

To meet the 2035 target, the local energy-related emissions have to drop 78% from 2189 tonnes/year (1990-level) to 482 tonnes/year by 2035. Whether the electrified LES could meet the 2035 target or not directly depends on the estimates of five critical parameters:

- ***Electricity grid emission factor***. Significant reduction in the emissions of the electricity grid makes electrification a possible solution for local energy decarbonization, i.e., the UK average electricity grid's emission factor drops from 0.718 kg/kWh (1990) to 0.233 kg/kWh (2020) [15] and it is expected to further dip to 0.041 kg/kWh by 2035 [16]. The electricity grid's emission factor for the local district is assumed identical to the UK average value.
- ***Local renewables installed capacity***. A 500 kW PV farm has been under construction in the district so far and the "rooftop PV + battery" system is prevailing; hence the local PV installed capacity could reach 2000 kW if all local rooftops are installed with PV panels. This is based on 200 houses with 8000 $m^2$ available rooftops, 20 non-residential buildings with 1000 $m^2$ available rooftops, and rule of thumb 1 kW per 6 $m^2$ [17]. Here we only consider rooftop PV and the under-construction PV farm; nevertheless, greater local PV potential does exist if more PV farms are planned.
- ***Transport electrification rate***. Adopting electric vehicles (EV) for electrification is considered a promising solution for decarbonization of the transport sector [18]. The transport electrification rate is defined as the proportion of EV among all vehicles on road. Based on the Climate Change Committee (CCC)'s forecast of 18,000,000 EVs on road in 2030 and the ban of new combustion-engine vehicles sales from 2030 in the UK [19], the local district's transport electrification rate is assumed identical to the UK average value, which is expected to be as high as 90% in 2035.
- ***Efficiency improvement by building fabric retrofit***. Considering the UK average household heating emissions is 2745 kg $CO_2$/year [20], the average gas boiler efficiency of 85%, and the gas emission factor of 0.184 kg/kWh [21], the annual household heating demand (spacing heating and domestic hot water included) is 12,680 kWh/year. In Wales, more than 80% of cavity walls, roofs, and lofts have been retrofitted locally, while insulation on solid walls and windows remains a retrofit opportunity indicating 15% heating savings [22].
- ***Heating electrification rate***. Gas boilers are widely applied for individual household heating so far. Electrifying the heating sector by heat pumps could significantly reduce the carbon emissions [23]. The heating electrification rate is defined as the proportion of residence installing heat pumps among all residence. Based on the current heating electrification scheme of the UK Department for Business, Energy and Industrial Strategy (BEIS)'s commitment to speeding up the installation of heat pumps from 30,000 per year to 600,000 per year by 2028 [24] and the industry's forecast of 1000,000 per year during 2028~2035 [25], on average 34% of the UK's 29 million residence would install heat pump by 2035. The local district is assumed with the same heating electrification rate.

Based on the above estimates of the five critical parameters, Table 1 summarizes the baseline values for the five critical parameters. To explore the impact of each parameter by performing sensitivity analysis, each baseline value is then assigned as the average value of corresponding lower and upper bound values, e.g., the baseline value (12,680 kWh/year) for the heating demand per residence is 15% higher than its lower bound value (10,780 kWh/year), and the upper bound value (14,580 kWh/year) is 15% higher than the baseline value (12,680 kWh/year). The same arithmetic sequence based value assign-

**Table 1**
Parameterization and scenario settings.

| Parameters and scenario settings | | Baseline value | Lower bound | Upper bound |
|---|---|---|---|---|
| Electricity grid emission factor (kg $CO_2$/kWh) | | 0.041 | 0.011 | 0.071 |
| Local PV installed capacity (kW) | | 1500 | 1000 | 2000 |
| Transport electrification rate | | 90% | 70% | 95% |
| Heating demand per residence (kWh/year) | | 12,680 | 10,780 | 14,580 |
| Heating electrification rate | Scenario-CS | 34% | 22% | 46% |
| | Scenario-TL | 46% | 34% | 58% |
| | Scenario-LW | 58% | 46% | 70% |

Note: Only heating electrification rate is set with 3 scenarios, the rest 4 parameters use the same values in the 3 heating electrification scenarios. The value of each parameter can vary between the lower and the upper bounds when performing sensitivity analysis.

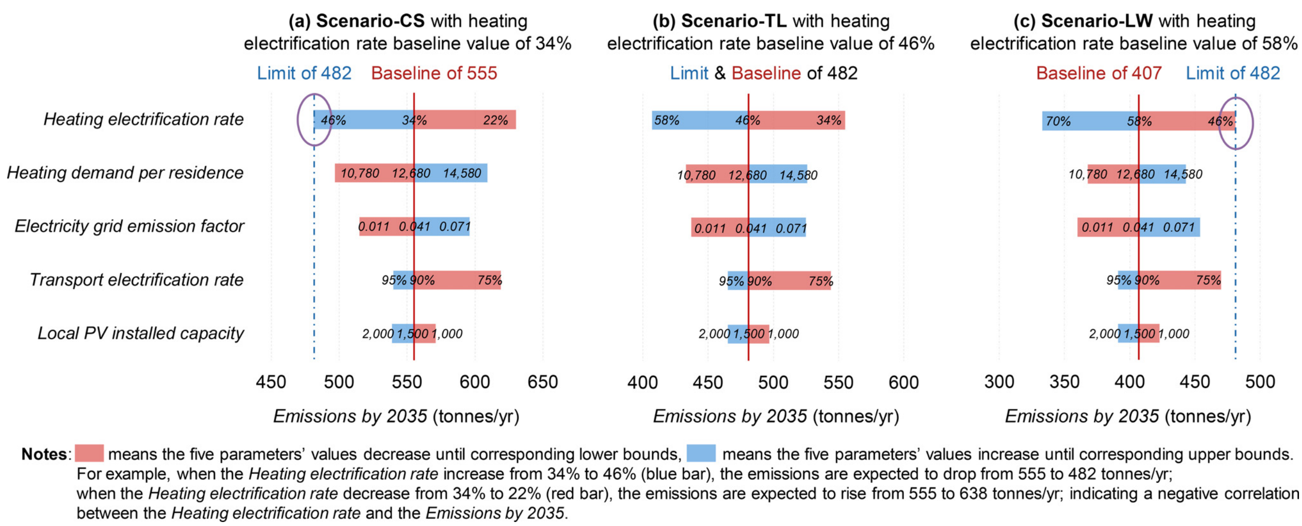


**Fig. 2.** Sensitivity analysis of the five key parameters on hitting the emission limit of 482 tonnes/yr by 2035. Sub-figures (a)~(c) represent Scenario-CS, Scenario-TL, and Scenario-LW respectively; and they share the same y-axis of the five parameters. The input values for the five parameters have been marked on each bar and in line with the values listed in Table 1. The red line denotes the baseline emissions of 555 tonnes/yr when inputting the baseline value from Table 1 into the LEE model. The blue dot line represents the emission limit of 482 tonnes/yr. The blue and red bars denote the *Emissions by 2035* associated with the varying inputs, where the *Heating electrification rate, Transport electrification rate*, and *Local PV installed capacity* show negative correlations with the *Emissions by 2035*, while the *Heating demand per residence* and *Electricity grid emission factor* have positive correlations with the *Emissions by 2035*.

ment rule applies for the electricity grid emission factor (with a baseline value of 0.041 kg $CO_2$/kWh, lower bound of 0.011 kg $CO_2$/kWh and upper bound of 0.071 kg $CO_2$/kWh) and the local PV installed capacity (with a baseline value of 1500 kW, lower bound of 1000 kW and upper bound of 2000 kW). The only exception is the transport electrification rate as the baseline value is already up to 90% based on the discussed estimates. To better explore its sensitivity, we assign 95% as its upper bound, and 70% as its lower bound.

In particular, we then consider 3 heating electrification rate scenarios of Current Scheme (scenario-CS), Touch Limit (scenario-TL), and Lead the Way (scenario-LW), with different baseline heating electrification rates (34%, 46% and 58%) and their associated varying ranges. The logic behind 3 heating electrification scenarios is that when inputting the scenario-CS values into the LEE model and applying sensitivity analysis (see **Method** for the methodology details), we find that the baseline emission of the case district is 555 tonnes/yr by 2035, which exceeds the limit of 482 tonnes/year as illustrated in Fig. 2(a). As long as the heating electrification rate is lower than 46%, the local emissions will always exceed the cap of 482 tonnes/year. Therefore, larger efforts are required on local heating electrification to achieve a higher rate than 46%, in other words, at least 92 of totally 200 local residence need to install heat pumps for heating by 2035. Accordingly, to achieve a 46% heating electrification rate for the UK while in line with the BEIS's commitment for 2020~2028, the UK residential heat pump installation needs a rise from 1000,000 to 1500,000 per year during 2028~2035. In addition, Scenario-LW with a baseline heating electrification rate of 58% has been setup as an arithmetic sequence based on the rate of 34% and 46%.

Sensitivity analysis for the rest 2 heating electrification scenarios as shown in Figs. 2b and 2c further indicates that: (1) The heating electrification rate always has the most considerable impact on hitting the 2035 emission reduction target. (2) As long as the heating electrification rate baseline reaches 46% in Scenario-TL (Fig. 2b), the other 4 parameters would have certain variation margins. When the heating electrification rate baseline value reaches 58% in Scenario-LW (Fig. 2c), the baseline emissions of 407 tonnes/yr can be achieved; no matter how other parameters vary, the emissions would not exceed the limit. (3) With the increase of heating electrification rate, electricity grid emissions factor plays an increasingly important role for decarbonization, the impact of heating demand per residence decreases slightly, the impact of transport electrification rate and the local PV installed capacity remains unchanged.

*Not only energy but also power*

From the energy perspective (measured by kWh), electrification is feasible for the LES to reach the 78% emission reduction target by 2035. While from the power perspective (measured by kW), the daily peak demand would be tripled (up to 950 kW) compared to that of the existing electricity profile (i.e., 300 kW) as shown by a typical winter 24-hour electricity demand profile in Fig. 3(a) in this case, where the additional electricity demand is induced by electrifying heating and

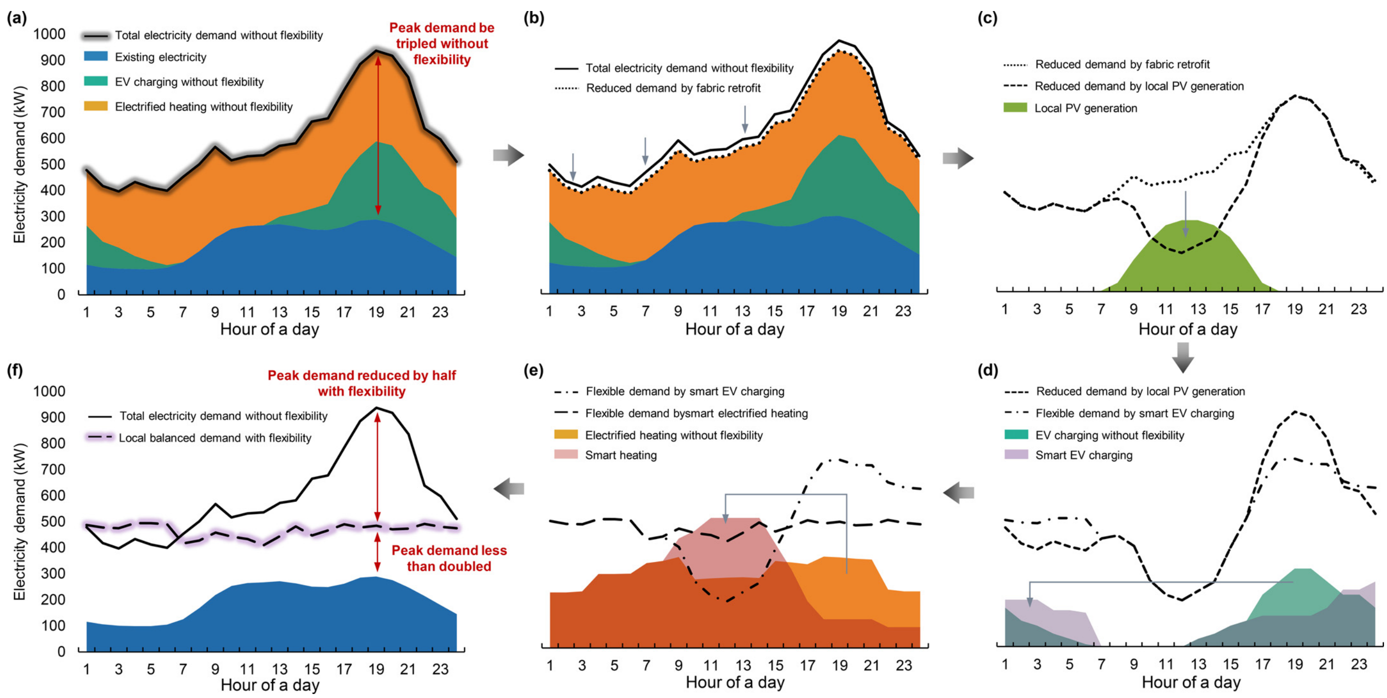


**Fig. 3.** Peak demand difference of the electrified LES with and without flexibility during a typical winter weekday. (a) peak demand would be more than tripled (950 kW) compared to that of existing electricity demand profile (300 kW) if there is no flexibility; (b)~(e) flexibility-induced peak demand drop by fabric retrofit, local PV generation equipped with battery, smart EV charging, and smart heating consequently; (f) the peak demand with flexibility (500 kW) would be half of that without flexibility (950 kW) and less than doubled compared to existing electricity demand profile (300 kW).The way forward.

transport without flexibility. A question mark is hanging on whether the existing electricity grid is sufficient to support electrification; otherwise, heavy investment would be needed to upgrade existing electricity infrastructure. To address the question, a local energy optimization (LEO) model was developed at hourly resolution to investigate the optimal operation strategy of LES. The building fabric retrofit (Fig. 3(b)) could shed the load; and a series of load shifting options, including local renewable generation equipped with battery (Fig. 3(c)), smart EV charging (Fig. 3(d)) and smart heating (Fig. 3(e)), reduce the induced additional demand by shifting the evening peak to solar abundant noon period and low-demand overnight period. By integrating the above-mentioned local flexibility options, the peak demand is reduced to 500 kW as shown in Fig. 3(f), which is significantly lower than 950 kW when without flexibility. Therefore, flexibility helps reduce peak demand significantly in an electrified LES, which is expected to save network investment for accommodating electrification-induced additional demand and improve utilization of network assets. Considering most existing electricity network infrastructure follows the N-1 design philosophy, it would have 600 kW capacity to handle the existing 300 kW peak demand. Therefore, the existing electricity network infrastructure is able to handle the peak demand of 500 kW in 2035 with an increased network utilization rate accordingly. However, the N-1 reliability principle would no longer be always satisfied and the network design and operation philosophy might need to be changed accordingly. An alternative active management regime by implementing local flexibility options and more advanced coordinated control could help tackle the reliability issue and improve the utilization and cost-effectiveness of the network [26,27].

Overall, our analysis reveals local energy-related emissions can be significantly reduced by electrification. However, more efforts are needed to increase the local heating electrification rate from 34% to 46% in order to meet the UK 2035 emission reduction target. By a whole system approach of integrating renewable electricity generation, building fabric retrofit, and a series of flexibility options from heating, transport and storage at the local level, the peak power after electrification can drop from 900 kW (without flexibility) to 500 kW, which implies existing electricity network is able to handle the local energy electrification.

It is noted that local circumstances vary greatly between cases, and the findings in this study do not suggest we only need electrification. Instead, electrification could help local authorities achieve the 2035 near-term emission target and buy more time to develop other promising but not ready yet technologies for other difficult-to-decarbonize sectors towards Net Zero by 2050. For instance, developing carbon capture and storage, hydrogen boilers, and hybrid solutions. In addition, the existing infrastructure needs to be effectively utilized, e.g., retrofitting the district heating network (if exists) and combining it with centralized heat pumps.

Both technology innovation and behavioral change contribute strongly to decarbonization. Shifting to low-carbon transport (e.g., EV, hydrogen vehicle, cycling, and walking), healthier diets (e.g., 35% less meat intake compared to today's level) [28], and uptake of unfamiliar technologies like heat pumps would reduce emissions and also provide co-benefits in some cases (e.g., to health) [29]. The more people are willing to embrace these changes, the faster progress may be possible to reduce emissions. This would be increasingly important, as 96% of the emissions reduction is expected to be achieved (compared to the 1990 level), while the last 4% of emissions reduction would come from the mix of additional engineered removals, further innovation, and behavioral change [28]. The pandemic has led to a record 10.7% emission reduction for the UK and demonstrated how quickly social and behavioral change could occur [30]. Flexible home-working, digital-by-default meetings where appropriate, tracking use-efficiency-living patterns, and introducing low/zero-emission zones for walking and cycling, all these positive visions of public engagement provide significant opportunities to contribute to meeting climate objectives.

## Method

The methodology used in this study includes developing two models and applying a series of simulation and data processing techniques. We first developed a local energy emissions (LEE) model to simulate the annual local energy-related emissions from electricity, heating, transport, and cooking sectors for 1990, 2020, and 2035. Based on the LEE model simulation results, we discussed the feasibility of electrifying LES to meet the UK 2035 target. Then, we applied sensitivity analysis method to quantify each sector's contribution, as well as efforts needed for each sector. Last, a local energy optimization (LEO) model was developed to quantify the impact on peak demand by electrification-induced additional electricity demand and analyze the benefit of flexibility to reduce the peak demand. All the models and methods associated are described in this section.

*Estimate local energy emissions*

The LEE model is a simulation tool that we developed to estimate the emissions of local energy-related activities including electricity, heating, cooking, and transport. LEE model sums up the emissions of these activities at annual basis for a local district as reported in Figs. 1 and 2. For each type of energy-related activity, the emissions are estimated by Eq. (1), which is consistent with methods defined in the international guidance [31].

$$LocalEnergyEmissions = \sum_i Emi_i i \in \{\text{electricity, heating, cooking, transport}\} \quad (1)$$

$$Emi_i = \sum EF_i \times ActData_i \quad (2)$$

where EF is the emission factor, and ActData is the activity data for each type of energy-related activity.

In specific, to estimate emissions from local transport ($Emi_{transp}$), the ActData is the total number of kilometres or miles travelled by that type of vehicle (Dist) and the emission factor (EF) is the amount of $CO_2$ emitted per kilometer or mile. Two types of vehicles are considered, i.e., combustion-engine vehicles (CEV) and EV as shown in Eq. (3).

$$Emi_{transp} = EF_{CEV} \times Dist_{CEV} \times Num_{CEV} + EF_{EV} \times Dist_{EV} \times Num_{EV} \quad (3)$$

As defined in Eq. (4), to estimate $CO_2$ emissions from heating ($Emi_{heat}$), the emission factor (EF) is the amount of $CO_2$ emitted per unit of electricity or natural gas consumed and the activity data is the total amount of electricity or natural gas used for heating each type of building (HeatUse), and NumBuild denotes the total number of buildings heated by either gas or electricity. The amount of electricity or natural gas used for heating is equal to the heating demand (HeatDem) divided by the heating technology's efficiency (Eff) as shown in Eq. (5) and 6. The heating demand for each type of building is obtained from Refs. [32,33]. The efficiency of gas boiler and heat pump for heating is assumed as 0.9 and 3, respectively.

$$Emi_{heat} = EF_{gas} \times HeatUse_{gas} \times NumBuild_{gas} + EF_{ele} \times HeatUse_{ele} \times NumBuild_{ele} \quad (4)$$

$$HeatUse_{gas} = HeatDem_{gas}/Eff_{gas} \quad (5)$$

$$HeatUse_{ele} = HeatDem_{ele}/Eff_{ele} \quad (6)$$

The local area uses natural gas for cooking, and its emissions is assumed proportional to the heating demand [34] as shown in Eq. (7), where $\alpha$ is the proportion with a value of 6% in this case.

$$Emi_{cook} = \alpha \times Emi_{heat} \quad (7)$$

As shown in Eq. (8), the $CO_2$ emissions for fulfilling electricity demand are estimated by the emission factor as the amount of $CO_2$ emitted per unit of electricity multiplied by the total amount of electricity

**Table 2**
Data for estimating the local energy related emissions.

| Category | Item | Value | Unit | Notes & Ref. |
|---|---|---|---|---|
| Municipal | Number of houses | 200 | | Measured from map |
| | Number of offices | 13 | | |
| | Number of schools | 2 | | |
| | Number of stores | 1 | | |
| | Number of Food & Beverage | 2 | | |
| | Number of malls | 1 | | |
| | Number of houses in UK by 2035 | 29,000,000 | | [34] |
| Heating | Gas boiler efficiency | 0.85 | | Industrial average value |
| | Heat pump efficiency | 3 | | |
| | Heat pump installation rate in 2020 | 30,000 | | [24] |
| | Heat pump installation rate in 2020~2028 | 600,000 | | [24] |
| | Heat pump installation rate in 2028~2035 | 1000,000 | | [25] |
| | Residential heating related emissions | 2745 | kg/yr | [20] |
| Emission factor | Emission factor for grid in 1990 | 0.718 | kg/kWh | [36] |
| | Emission factor for grid in 2020 | 0.233 | kg/kWh | |
| | Emission factor for grid in 2035 | 0.041 | kg/kWh | |
| | Emission factor for gas | 0.184 | kg/kWh | |
| | Emission factor for fossil-fueled cars | 0.158 | kg/miles | [37] |
| Renewable | Local PV installed capacity | 500 | kW | from local authority |
| | Annual sun hours | 1000 | hr/yr | |
| | PV panel overall efficiency | 80% | | |
| Cooking | Cooking emissions proportional to heating | 3% | | [34] |
| Transport | Cars per house | 1.2 | | [38] |
| | Predicted number of EV in the UK by 2030 | 18,000,000 | | [19] |
| | Number of EV in the UK in 2020 | 748,000 | | [39] |
| | Annual new car sales on average | 2311,000 | | |
| | Existing cars on road in the UK | 32,697,000 | | |
| | Average car miles per year | 9000 | miles | [40] |
| | Miles per kWh of electricity usage | 3.33 | miles | [41] |
| Electricity | Electricity profile of commercial buildings | 24 h typical day data | | [42] |
| | Electricity profile of houses | 24 h typical day data | | [35] |
| | Existing electricity demand per house on average | 4800 | kWh/yer | Varying 3000~7000 Ref. [43] |

demand (EleUse). The EleUse is estimated from the typical daily electricity profile for each type of building multiplying number of building in that type and the number of days per year as shown by Eq. (9) [35]. Besides, the locally generated energy by PV panels is assumed with no $CO_2$ emissions.

$$Emi_{ele} = EF_{ele} \times EleUse \quad (8)$$

$$EleUse = \sum_j DayEleUse_j \times NumBuild_j \times 365 \; j \in \{\text{residence}, office, \text{shop}, \text{public}\} \quad (9)$$

*Data acquisition*

The input data to LEE model for the case analysis in this study is listed in Table 2.

*Optimization model captures flexibility*

Flexibility flattens the local electricity demand profile with a reduced peak demand, as presented in Fig. 3. This is modelled and captured by the LEO model with an objective function of minimizing investment and operation cost of a LES subjecting to a series of system operational constraints. LEO model follows the bottom-up structure with hourly temporal resolution, 12 typical modeling days (capturing seasonal and weekday/off-week differences), 15-year horizon, and the spatial coverage of the whole local district. It optimizes system investment decisions and operational strategy for the whole system covering local electricity, heating, building and transport sectors. A series of demand-side management options are modeled including the building fabric retrofit as a load shedding measure, and a series of load shifting measures, i.e., local renewables equipped with batteries, smart heating by heat pump with storage, and smart EV charging. It is flexible to set specific constraints in LEO model on purpose, e.g., flatten electricity demand profile or switching on heat pump at a certain time. By inputting the local information into LEO model and running it, the optimal system configuration and 24-hour operational strategy during a typical winter weekday with a flattened electricity demand profile can be obtained as presented in Fig. 3. Since elaborating the optimization model is not the main focus of the present study, detailed model descriptions can be found in **Supplementary** including the (1) parameter and variable definitions, (2) objective function, and (3) model constraints. Eqn (2)

*Handling uncertainty*

The uncertainty exists in obtaining a robust dataset for carbon accounting at local level. This creates difficulties in planning investment, assessing system operation, and developing policies for decarbonizing LES. Those unavailable data at local-level is assumed identical to the average of that at regional level or national level, which is usually more accessible with reliable sources, e.g., the emission factors for electricity grid and natural gas, cars per household, and the number of EV by 2035. Therefore, single-parametric sensitivity analysis is performed to assess the impact of 5 key uncertain parameters on the emissions' variation as presented in Fig. 2.

## Author contributions

R.J., Y.Z., and J.W. designed the study. R.J. collected the data and built the model. R.J., Y.Z., and J.W. analyzed the results. R.J. drafted the paper. Y.Z., and J.W. edited the paper. J.W. provided the fund.

## Data and code availability

The associated data and code are being uploaded on online database.

## Acknowledgment

The authors acknowledge the financial support from the Engineering and Physical Sciences Research Council (EPSRC) funded the EPSRC–NSFC funded 'MC2' project [52061635103 and EP/T021969/1], the EPSRC funded Supergen Energy Networks hub 2018 [EP/S00078X/1], and the Active Building centre Research Programme (ABC RP) [EP/V012053/1].

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