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The energy flexibility divide: An analysis of whether energy flexibility could help reduce deprivation in Great Britain

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ABSTRACT

The provision of energy flexibility services (such as shifting consumption) to electricity systems is becoming increasingly valuable, and can offer additional income for households. Here, we show how the locational distribution of flexibility impacts its value, and whether this could help reduce deprivation in Great Britain. Geospatial analysis shows that nearly 90 % of people (1.3 million) living in the most deprived areas of Greater London can offer high-value flexibility. This could help improve their economic condition, provided that the adoption of appropriate appliances (such as demand response devices) is incentivised, e.g. through government's spatially targeted incentive schemes. The results show that the provision of flexibility could help reduce deprivation in several regions, including Scotland, Greater London, and Yorkshire. By contrast, other areas such as North and North-East England tend to offer lower-value flexibility, and therefore the benefit would be smaller. A flexibility-adjusted deprivation index is proposed to highlight regions where providing flexibility may most help reduce deprivation.

1. Introduction

Flexibility services, such as increasing generation or shifting consumption, are becoming increasingly important in energy systems, as they are effective tools operators can use to help manage network congestion and the intermittency of renewable energy resources [1]. The International Energy Agency estimates that the amount of energy flexibility needs to quadruple to support the large-scale deployment of renewables required to meet net-zero carbon emissions by 2050 [2]. At the global level, one billion households and 11 billion appliances are expected to provide flexibility services by 2040 [3].

In the next few years, the provision of energy flexibility services may give families an additional income source, which could improve their economic conditions and reduce their energy bills. This could also help reduce fuel poverty, which affects around 13 % of households in England, 25 % in Scotland, and 12 % in Wales [4]. However, the value of flexibility depends on the location where these services are provided, and may vary significantly across a country. This means that some people will be more advantaged than others, which can increase inequality among the population.

In Great Britain (GB), the concept of *deprivation* has been adopted by the government to extend inequality metrics (usually based on income) to capture a broader range of factors, including employment, education, health, crime, and living environment. This gives a more accurate representation of areas that are deprived, and that would require more urgent government intervention. For this reason, the analyses presented in this work are based on the GB deprivation index, instead of other indicators. The GB deprivation index is officially termed Index of Multiple Deprivation (IMD) [5–7], and is depicted in Fig. 1.

The aim of this work is to assess whether the provision of energy flexibility services could help reduce deprivation in GB, or not. We also investigate if high-value flexibility will most benefit deprived or non-deprived areas. Finally, we propose a flexibility-adjusted deprivation index, to highlight regions where energy flexibility provision could contribute to increasing or decreasing deprivation. The value of flexibility is estimated by simulating the functioning of the Balancing Mechanism (BM), which is the market used by the electricity system operator in GB to balance national electricity supply and demand, and resolve network congestion. This allows us to estimate how the locational distribution of flexibility impacts its value. Then, geospatial analyses are performed to assess the relationship between deprived areas and the value of flexibility. To summarize, the main contributions of this work are:

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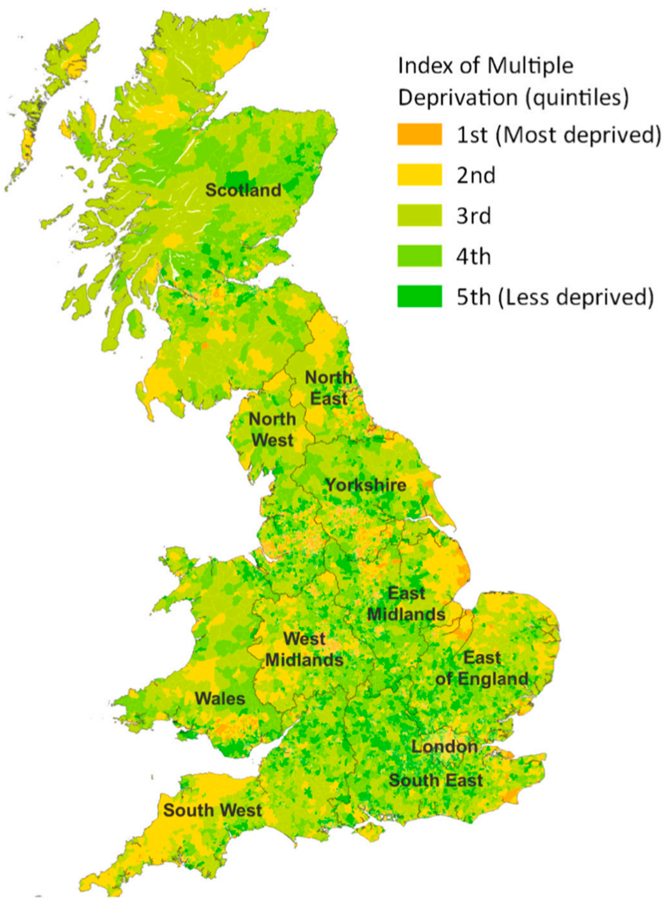

Fig. 1. Index of Multiple Deprivation (IMD) in GB. The first quintile shows the most deprived areas, while the 5th quintile the less deprived ones.

- Estimating how location affects the value of flexibility services in GB.
- Performing geospatial analyses to investigate the relationship between deprivation and flexibility value, highlighting areas where flexibility provision may help reduce deprivation.
- Assessing if deprived or non-deprived people will obtain the most benefit from the provision of high-value flexibility.
- Proposing an indicator of flexibility-adjusted deprivation to highlight regions where flexibility provision may contribute most to reducing inequalities between people.

Key findings show that almost 1.3 million people living in the most deprived areas of Greater London could offer high-value flexibility, which could help improve their economic conditions, potentially counteracting deprivation. Similarly, the provision of high-value flexibility services may help reduce deprivation in several other regions, including Scotland and Yorkshire. By contrast, deprived areas in e.g. North and North-East England would not significantly benefit.

The remaining sections are structured as follows. Section 2 reviews the literature on spatial justice and flexibility provision, discussing benefits and barriers. Section 3 describes the mathematical model developed to assess the locational value of flexibility. Section 4 reports the obtained results, showing whether flexibility may help reduce deprivation in GB. Finally, Section 5 concludes and discusses some policy implications.

2. Literature review

This work fits in the context of the emerging literature on spatial energy justice [8], which applies spatial lens to conceptualize and analyse forms of energy injustice [9]. Recently, Garvey et al. [10] discuss the concept of spatial justice in reaching net-zero targets, and provide a comprehensive review that examines equity and fairness in the geographic distribution of benefits and burdens in decarbonisation pathways, which may create “winners and losers” [11]. They also list barriers in making the low-carbon transition more spatially just, which include administrative fragmentation and the lack of coordination across spatial scales, and suggest that a significant benefit could be obtained by designing spatially targeted policy interventions. Perez-Sindin et al. [12] discuss how a geographical uneven distribution of electricity generation can lead to inequality, as areas importing electricity do not necessarily bear all costs of generation (such as environmental costs). They propose three metrics to measure this effect, and report case studies based on Spain, Denmark, and South Korea, which show a common rural-urban divide. Powells and Fell [13] argue that in constrained systems (such as energy networks), the benefits enjoyed by some people may hinder those for others, with the risk that this negative effect could be locked into energy systems, becoming long-lasting.

Many low-income households are renters that may lack control over the type of appliances installed in their residences, which instead are owned by their landlords, who may not be motivated to invest in smart appliances [14]. However, technologies such as demand response devices are easier to install and significantly more affordable (compared to e.g. rooftop solar), and can offer greater accessibility to low-income households [15]. Smart electric storage heating can also provide flexibility for long periods [16]. Moreover, governments can directly support the deployment of more costly appliances (such as heat-pump and home batteries), for example in public rental housing, as described in [17], improving the conditions of low-income families. Judson and Zirakbash [18] show that small-scale solar energy in community social housing can offer vulnerable groups (such as low-income sole parent) access to lower-priced electricity reducing energy poverty.

To benefit consumers and foster the transition to a more flexible energy system, the UK government is actively supporting the rollout of smart meters [19]. However, despite this intervention, the extent to which residential users can actually provide flexibility depends on additional aspects, including their time availability, social practice [20], technical factors [21], and the role of women in carrying out domestic labour [22]. For example, lighting, cooking, eating and leisure cannot be easily shifted in time, whereas domestic activities such as laundering are relatively flexible [23]. Moreover, some barriers need to be overcome to fully unlock the potential value of flexibility [24], including the perceived risk of giving control of home devices to a third party [25], and bounded rationality, as users have access to limited knowledge, time and resources that may defer or induce sub-optimal choices [26].

Nevertheless, [27] shows that low-income households exhibit a significant willingness to participate in demand-side management activities, aiming at reducing their energy bills, even though the non-negligible initial capital investment might be a barrier to adoption [28]. This suggests that deprived people might be willing to engage in flexibility service provision as long as appropriate incentives to offset up-front costs are available. However, by analysing demand-side response trials in California, [29] determined that low-income customers were less willing to shift consumption from peak to off-peak periods compared to high-income people. This suggests that the electricity demand of low-income households might be more inelastic compared to affluent persons, implying that the share of energy that could be actually used to provide flexibility services might be relatively small. However, a recent nationwide survey focusing specifically on the UK [30] found out that demand-side responsiveness is actually a function of both income and the specific activity, with lower-income households being more responsive to shifting e.g. heating, while high-income families are more willing to shift e.g. dishwashing and laundry. This suggests that policy interventions to support the deployment of specific flexible devices, like heat pumps, could be more effective in supporting deprived people rather than incentivising smart home appliances generically.

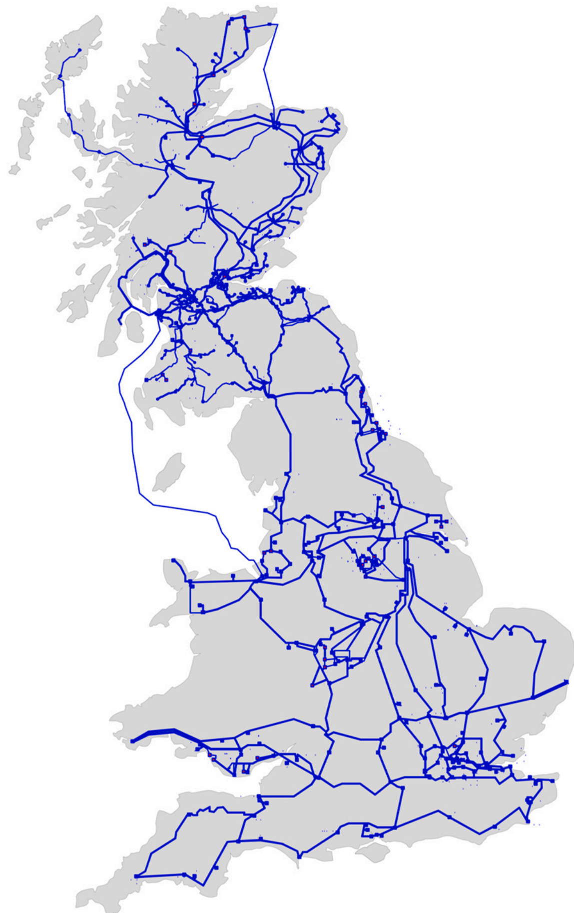

Fig. 2. The transmission network in GB.

3. The balancing mechanism in GB

The GB electricity market architecture is based on a self-dispatch mechanism [31], where generators and retailers' suppliers trade the bulk of electricity directly among them through long-term over-the-counter bilateral contracts, and only a small portion, around 15 % [32], is exchanged in centralized marketplaces (e.g. the Nord Pool day-ahead market). However, regardless of how these trades are performed, a key characteristic of this self-dispatch design is that network constraints are ignored during electricity trading. This means that the whole GB electrical network, sketched in Fig. 2, is considered as a single point (copper-plate assumption [33,34]). One hour before delivery (gate closure), generators and suppliers must submit to the transmission system operator (TSO) in GB (currently National Grid ESO) their net positions, formally termed final physical notification [35], which are used to verify whether the resulting net power injections violate any network constraints. If a constraint is violated, the TSO utilizes the Balancing Mechanism (BM) to increase or decrease power at the required network nodes until all constraints are satisfied [36]. Users can provide flexibility to the BM by submitting proposals to increase their power injection (by raising generation or reducing demand), or to decrease it (by curtailing generation or increasing demand), in return for a monetary compensation. Formally, proposals to increase (upward flexibility) or decrease power injection (downward flexibility) in the BM can be represented by the pairs $P_{t,k}^{up}, C_{t,k}^{up}$ and $P_{t,k}^{down}, C_{t,k}^{down}$, respectively, where $P_{t,k}^{up}$ and $P_{t,k}^{down}$ are the maximum upward/downward power flexibility offered, and $C_{t,k}^{up}$ and $C_{t,k}^{down}$ are the associated prices. Given the set of users providing upward flexibility K_t^{up}, and those providing downward flexibility K_t^{down}, the TSO will accept proposals in the BM to rebalance the grid and offset energy imbalances, at the least cost, by minimising the following objective function:

$$min \sum_t \left(\sum_{k \in K^{up}} p_{t,k}^{up} C_{t,k}^{up} - \sum_{k \in K^{down}} p_{t,k}^{down} C_{t,k}^{down} \right) \Delta_t \quad (1)$$

where $p_{t,k}^{up} \geq 0$ and $p_{t,k}^{down} \geq 0$ are decision variables representing the accepted power increase and decrease, respectively, of participants k at time t, with $p_{t,k}^{up} \leq P_{t,k}^{up}$ and $p_{t,k}^{down} \leq P_{t,k}^{down}$. The term Δ_t is the BM settlement timespan, currently 0.5 h. Power balance constraints can be represented as follows:

$$\sum_{k \in K_n} \left(P_{t,k}^{FPN} + p_{t,k}^{up} - p_{t,k}^{down} + P_{t,k}^{IMB} \right) = \sum_{l \in L_n} f_{t,l}$$
$$\left[\lambda_{t,n} \in \mathrm{R} \right] \forall t \in T, \forall n \in N \quad (2)$$

where N is the set of network nodes, K_n is the set of users located at node $n \in N$, $P_{t,k}^{FPN}$ are the final physical notifications declared at the gate closure, $P_{t,k}^{IMB}$ are the forecasted power imbalances, and the variables $f_{t,l} \in H$ are power flows over the lines $l \in L_n$ connected to node n, where the set H represents network constraints. The terms $\lambda_{t,n} \in \mathbb{R}$ reported in squared brackets are the dual variables associated with the power balance constraints.

For each node $n \in N$ and settlement period $t \in T$, the marginal value of flexibility can be computed as the ratio between the dual variables $\lambda_{t,n}$ and the scaling parameter Δ_t in the objective function [37]. Positive values identify areas with excess demand, where providing upward flexibility would be beneficial, by contrast negative values highlight areas where it would be desirable to provide downward flexibility. In this work, we focus on estimating the overall value of flexibility, regardless of whether it is upward or downward. Therefore, we define the *locational marginal value of flexibility* (LMVF) for providing services to the BM, as:

$$\mathrm{LMVF}_{t,n} = \frac{|\lambda_{t,n}|}{\Delta_t} \quad (3)$$

where the symbol "| |" is the absolute value.

4. Results and discussion

This section reports the geospatial analysis performed to highlight whether the provision of flexibility services in the BM could help reduce deprivation in GB. In detail, Section 4.2 estimates the average LMVF in different areas of GB, Section 4.3 shows the geospatial relationship between the value of flexibility and deprivation, and finally Section 4.4 highlights who could gain and lose from this, for each region in GB.

4.1. Data and settings

The Index of Multiple Deprivation for England refers to 2019 and has been collected from the Ministry of Housing, Communities and Local Government [5]. It reports the level of deprivation experienced by people living in each of the 32,844 lower layer super output areas (LSOA) in England. The Scottish Index of Multiple Deprivation refers to 2020 [6], and shows the level of deprivation in the 6976 small areas (termed Data Zones) that divide Scotland. The Welsh Index of Multiple Deprivation refers to 2019 and it is computed for the 1909 LSOAs in Wales [7]. Each small area (LSOAs and Data Zones) contains around 1500 people, on average. In the following, for ease of reading the term LSOA will be used to refer to both LSOAs and Data Zones. The data about population refers to mid-2020 [38,39]. Regional boundaries for GB (NUTS level 1) have been obtained from the Office for National Statistics

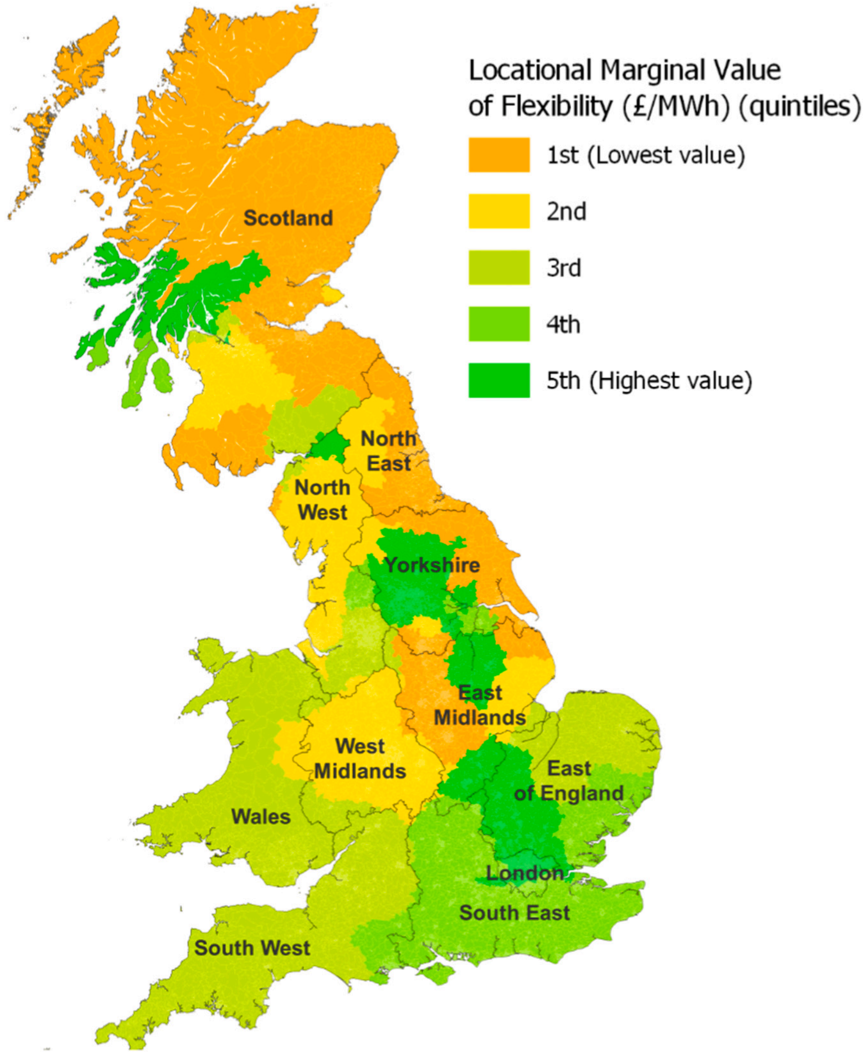

Fig. 3. The figure reports the average locational marginal value of flexibility (LMVF) for each LSOA in GB.

[40]. The data related to the BM has been collected from the provider EnAppSys [41], and refers to January 2021 and August 2020. The GB transmission network depicted in Fig. 2 has been adapted from the National Grid's Electricity Ten-Year Statement [42]. It comprises nearly two thousand nodes and three thousand transmission lines, and it is available open-source at [43]. The mathematical program used to estimate the marginal value of flexibility, described in Section 3, has been implemented in Python 3.9 using Pyomo [44], and solved with CPLEX 20.1 [45]. Each settlement period includes 847 BM proposals, on average. The geospatial analysis has been performed with QGIS 3.20 [46].

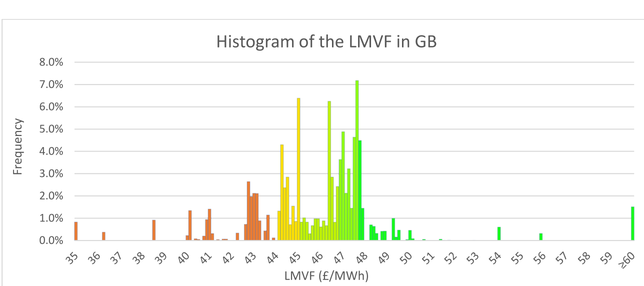

Fig. 4. Histogram of the locational marginal value of flexibility (LMVF) in GB. Quintiles are highlighted using the same colours as in Fig. 3.

4.2. The locational marginal value of flexibility in GB

This section reports the average LMVF during the months of January 2021 and August 2020 for each LSOA in GB, showing how the locational distribution of flexibility impacts its value. To compute the LMVF for a LSOA, first we have estimated the LMVF in each grid supply point (GSP) (i.e. the nodes that connect transmission and distribution networks) by using Eq. (3) and the data described in Section 4.1. If a LSOA has only one GSP within its borders, then the LMVF of this node has been used as a reference for the area. If a LSOA has more than one GSP, then the average of the LMVF for those GSPs has been used. If an area does not have any GSP, then the LMVF of the closest one has been used. The obtained results are shown in Fig. 3 (see also Appendix A), and are clustered in quintiles, i.e., each group represents 20 % of the LSOAs. The 1st quintile depicts the areas where the provision of flexibility services offers the lowest value, with a minimum of 34 £/MWh. By contrast, the 5th quintile highlights the areas where it would be substantially more profitable to provide flexibility, with a maximum value of 76 £/MWh. The figure shows that the average LMVF across GB differs significantly between the northern and southern regions, and between the eastern and western areas. This is due to several factors, including network congestions and proximity to large demand centres, such as London. Areas with some of the highest average LMVF (>70 £/MWh) include New Cross in London, and the Harker substation, which is part of the backbone that transmits power between Scotland and the southern

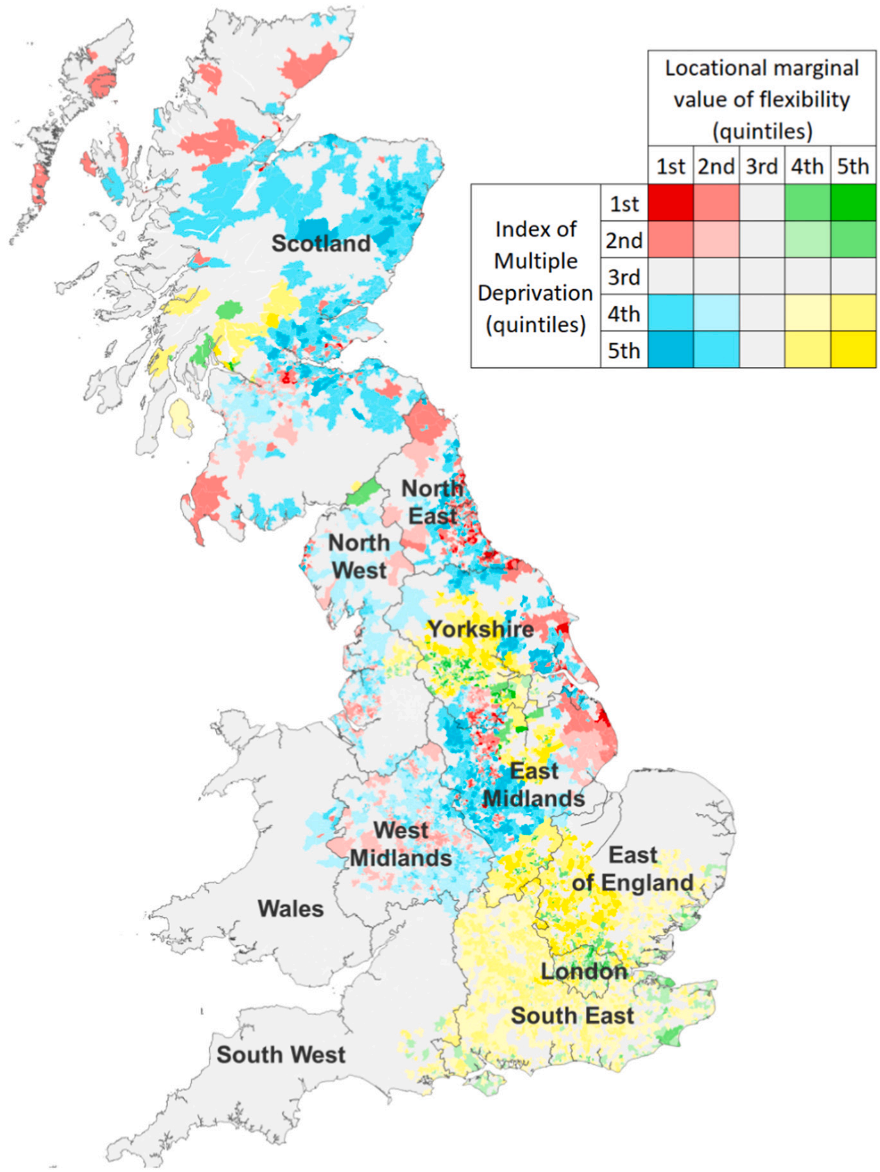

Fig. 5. The figure shows the relation between the index of multiple deprivation and the value of flexibility provision for each LSOA in GB.

regions of GB. By contrast, areas with the lowest flexibility values (<35 £/MWh) are mostly clustered in the North East of GB. Nevertheless, the LMVF is never zero, which means that regardless of the amount, the provision of flexibility services can always offer some benefit to the electricity system as a whole. The key aspect however is that the value of flexibility is not homogeneously distributed, but depends significantly on the location where the flexibility service is offered, signalling a flexibility value divide. The histogram in Fig. 4 reports the detailed distribution of the LMVF in GB, where the quintiles are highlighted using the same colours as in Fig. 3.

In the UK, the average electricity consumption per household is around 4.16 MWh/year [47], while the average retail electricity price in the period analysed (2020–2021) was 205 £/MWh [48]. This translates into an average household electricity bill of around £853 per year. Therefore, providing high-value flexibility (which is paid up to 76 £/MWh) could contribute to reducing households' electricity bills by up to £316 (37 % of the total bill). It is also worth noting that the TSO in GB is currently running a series of demonstration tests for emergency services [49], termed Demand Flexibility Services, which are paid 3000 £/MWh, suggesting that the value of flexibility provided at the local level might generate even higher revenues in the future.

Moreover, additional revenues might be obtained by offering ancillary services [50], such as frequency response and power reserve, in addition to BM services. Furthermore, specific DNO flexibility schemes to engage households and small businesses in the provision of flexibility services at the local level could be implemented, which may yield even greater revenues. However, these schemes could also contribute to increasing inequality if implemented in some regions but not others. Similarly, the development of new structures, such as local energy markets, may bring benefits to households (e.g. by decreasing electricity prices [51,52]), but may also end up increasing inequality if these local markets develop primarily (or at a higher rate) in affluent areas, for example, due to better availability of resources, information, or education.

4.3. The geospatial relation between deprived areas and the value of flexibility provision

This section analyses the geospatial relationship between deprived areas and the value of flexibility in GB. It provides insights on whether the provision of flexibility services can help reduce deprivation, or not. Indeed, the provision of high-value flexibility may represent an

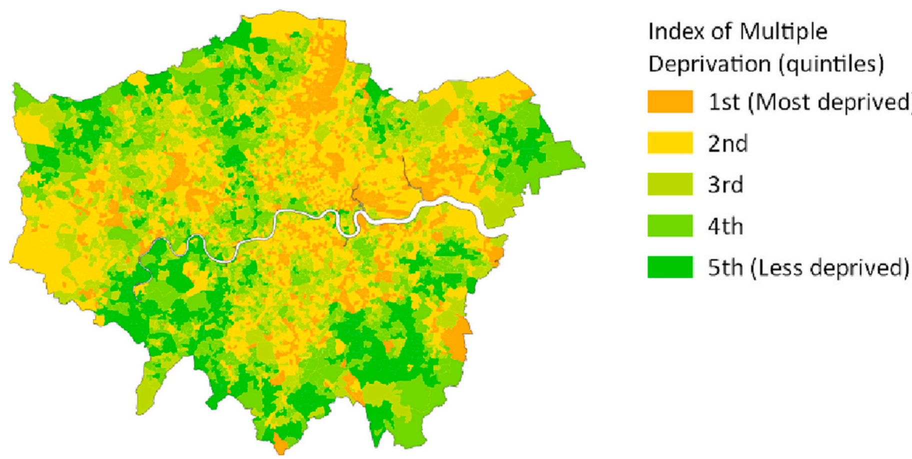

Fig. 6. *Index of multiple deprivation, Greater London* [5].

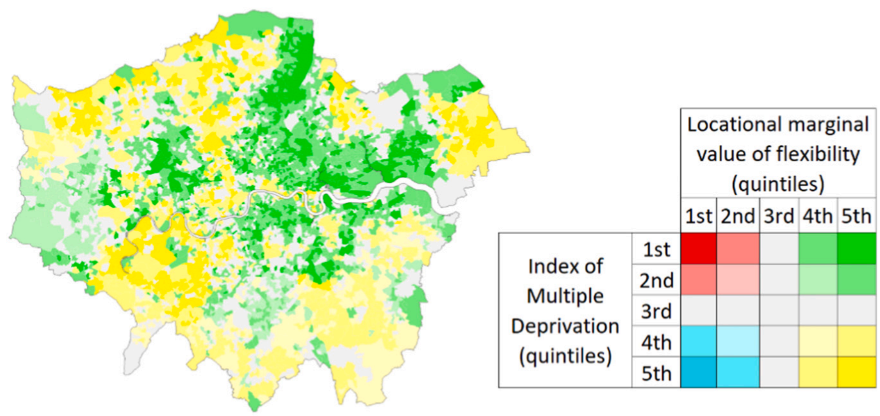

Fig. 7. Relation between the index of multiple deprivation and the value of flexibility in Greater London.

additional stream of revenues for households, which may contribute to improving their conditions. To highlight this relationship, we focus on four possible combinations, which have been graphically represented in different colours in Fig. 5. The red colour highlights deprived areas with low-value flexibility. These are areas that are deprived and that will obtain the lowest benefit from providing flexibility services. By contrast, green areas are deprived areas with high-value flexibility, where the provision of flexibility services may yield a significantly larger stream of revenue. The areas coloured in yellow are non-deprived areas, with high-value flexibility. These may be regarded as wealthy areas that can become even better off thanks to the additional revenues from flexibility services. Finally, the areas in blue are non-deprived, where the value of flexibility is low. These can be regarded as wealthy areas where providing flexibility may have a lower overall impact. Red areas are clustered in the centre-east of GB, particularly in North East England. By contrast, the region where deprived people can achieve the most benefit from flexibility provision is Greater London, which is detailed in Figs. 6 and 7.

Fig. 6 reports the level of deprivation in Greater London. It shows that a significant number of deprived areas (1st quintile IMD, depicted in orange) are present, particularly in the north-east.

The relationship between the IMD and the LMVF is depicted in Fig. 7. We recall from Section 4.2 that Greater London is one of the regions where the provision of flexibility has the greatest value. Fig. 7 shows that there are a significant number of green areas, representing zones where deprived people could offer high-value flexibility, which may contribute to improving their conditions, for example by helping to reduce their energy bills. More importantly, there is no red area, implying that all deprived people may potentially benefit from the provision of flexibility services.

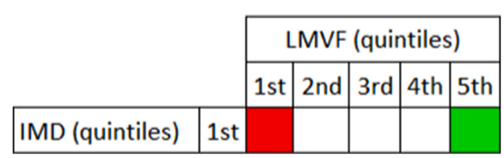

Fig. 8. The red colour represents the areas that are at the same time the most deprived and with the lowest value of flexibility. By contrast, the green ones have the greatest LMVF among the most deprived areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.4. *Who gains and who loses? a regional analysis of deprivation, flexibility and inequality*

This section aims to answer three fundamental questions. First, could the provision of flexibility services help improve the conditions of people living in the most deprived areas? Second, who will benefit the most from high-value flexibility, people living in deprived or non-deprived areas? Third, which region could make the most of flexibility provision to help reduce deprivation?

To address the first question, i.e., assessing whether flexibility provision can help support people in the most deprived areas, we focus our analysis on the 1st quintile of the IMD. Given the population living in

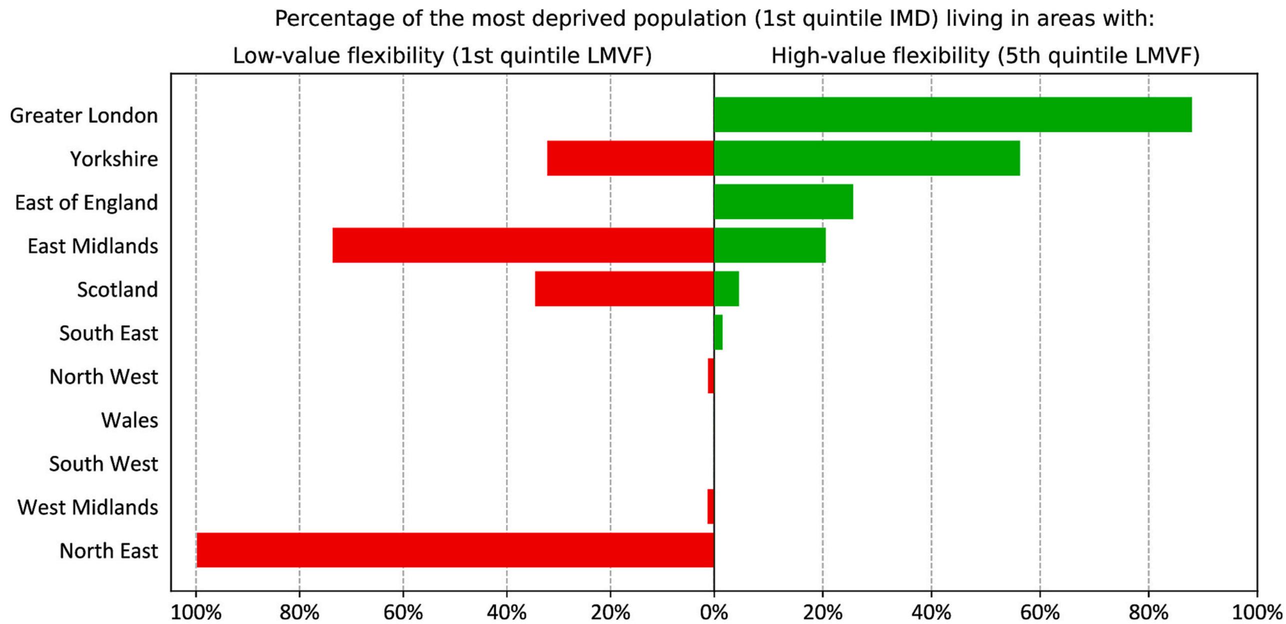

Fig. 9. For each region in GB, the figure shows the percentage of the most deprived people, i.e. 1st quintile of the Index of Multiple Deprivation (IMD), with low (1st quintile) and high (5th quintile) average locational marginal value of flexibility (LMVF).

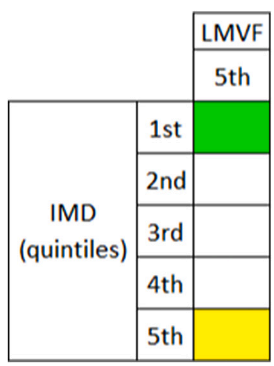

Fig. 10. In green (yellow) the high-value flexibility areas that are the most (less) deprived. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

these deprived areas, we computed the percentage of those with low-value flexibility (1st quintile LMFV) and high-value flexibility (5th quintile LMVF). Using the classification introduced in Fig. 5, this can be graphically represented as the population living in the red and green areas (see Fig. 8), respectively, w.r.t. the total population in the 1st quintile of the IMD. Fig. 9 reports the results obtained for each region in GB. The region where the most deprived people could obtain the most benefit from offering flexibility services is Greater London, where almost 90 % of the population (1.3 million) living in the most deprived areas (1st quintile IMD) could offer high-value flexibility (5th quintile LMVF). This could potentially help those people to improve their conditions, provided that appropriate incentive schemes are introduced to install smart devices, e.g. through specific government interventions targeting these areas. By contrast, the regions where deprived people will not significantly benefit from the provision of flexibility services are clustered in the north-east of GB, particularly the East Midlands and North East England.

To investigate who will most benefit from high-value flexibility, we focus our analysis on the population living in areas that can offer the highest value of flexibility (5th quintile LMVF). For these areas, we have computed the percentage of people who are in the most deprived (1st quintile IMD) and in the less deprived areas (5th quintile IMD). Using the classification in Fig. 5, this can be graphically represented as the population living in the green and yellow areas (see Fig. 10), respectively, w.r.t. the overall population with the highest LMVF (5th quintile). Fig. 11 reports the results for each region in GB. The region where the provision of high-value flexibility could most benefit deprived rather than non-deprived people is Yorkshire, followed by the North West of England and Greater London. By contrast, the East and South-East England are the regions where the percentage of population with high-value flexibility is both the lowest for deprived people and the highest for non-deprived people, which could potentially increase inequality among the population.

Finally, to highlight regions that could make the most of flexibility provision to help reduce deprivation, we propose the following flexibility-adjusted deprivation index δ_k, defined as:

$$\delta_k = \frac{(R_k + Y_k) - (G_k + B_k)}{N_k} \tag{4}$$

where N_k is the total population in the region k, whereas (using the classification in Fig. 5) the terms R_k, Y_k, G_k, and B_k represent the population in the red, yellow, green and blue areas, respectively (see Fig. 12). The term R_k represents the number of people that are deprived and will not significantly benefit from flexibility provision, while the term Y_k represents the non-deprived people that could potentially gain a non-negligible income source. Therefore, the amount $(R_k + Y_k)$ highlights the population whose economic conditions, ceteris paribus, may diverge as a result of flexibility service provision, potentially increasing inequality. By contrast, the term G_k represents the number of people that are deprived, but that could offer high-value flexibility services, which could contribute to improving their economic conditions. Finally, the term B_k are those who are not deprived, and that will not significantly benefit from flexibility. Therefore, the amount $(G_k + B_k)$ can be interpreted as a sign of convergence, where deprived people can benefit from additional revenues, and the non-deprived ones may get less benefits. As a result, if the amount $(R_k + Y_k)$ is greater than $(G_k + B_k)$, then the index proposed in Eq. (4) will be positive, signalling a potential exacerbation of inequality among people. By contrast, a negative value highlights that the provision of flexibility services could contribute to reducing inequality. Table 1 reports the results for each region in GB. The three

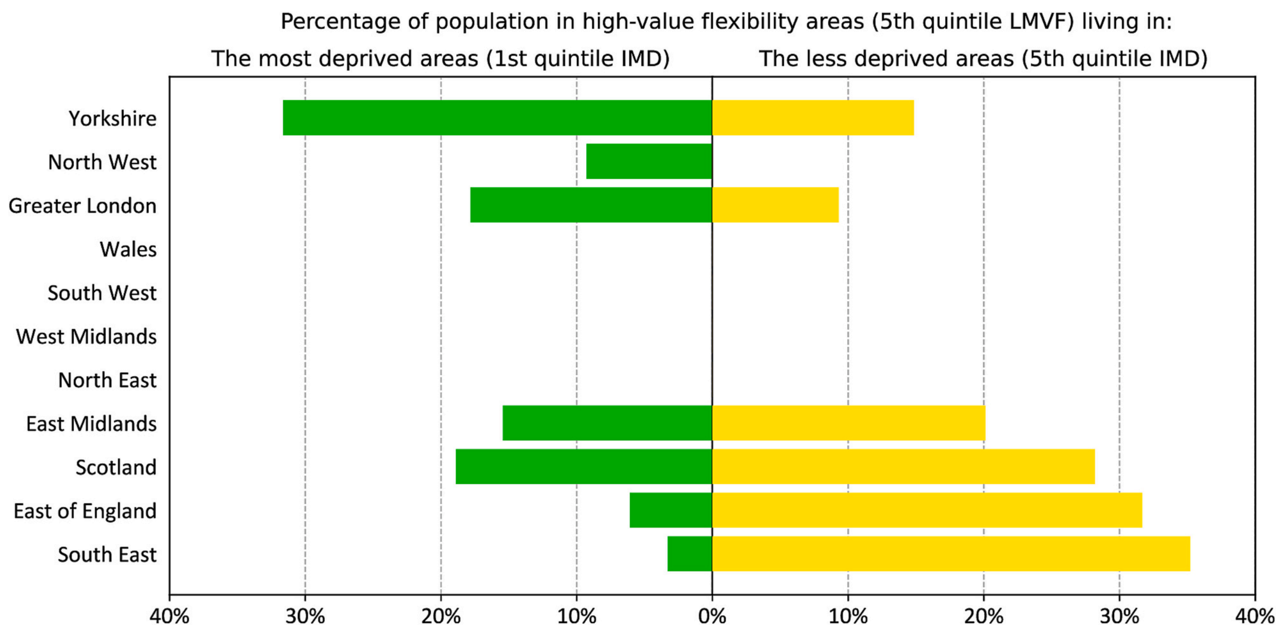

Fig. 11. For each region in GB, the figure shows the percentage of people in high-value flexibility areas (5th quintile LMVF), that are in the most deprived (1st quintile IMD) and the less deprived (5th quintile IMD) areas.

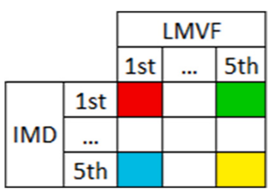

Fig. 12. The four quintiles involved in the computation of the flexibility-adjusted depri-vation index.

regions where providing flexibility services could help reduce deprivation are Greater London, Scotland, and Yorkshire. By contrast, regions where deprivation could increase are East and North-East England. In particular, North-East England is the region with the greatest value of R_k (last row, second column in Table 1), with more than nine hundred thousand people living in the most deprived areas, with low-value flexibility.

5. Conclusion and policy implications

The provision of flexibility services is essential for the functioning of the energy system. However, the value of these services is significantly affected by their location, signalling a flexibility value divide, and depends on factors such as proximity to large demand centres and constraints in the power network. For these reasons, regions such as Greater London can offer high-value flexibility, while areas in North England tend to offer low-value flexibility. This difference is important as high-value flexibility could provide households with an additional source of income, helping to improve their material conditions. Geospatial analysis shows that nearly 90 % of the population (1.3 million) living in the most deprived areas (measured through the Index of Multiple Deprivation) in Greater London could offer high-value flexibility (reaching >70 £/MWh). This could help reduce deprivation, provided that smart meters and appropriate appliances (e.g., demand response devices) are installed. The results also show that flexibility provision could help reduce deprivation in several other regions, including Scotland and Yorkshire. By contrast, areas such as North and North-East England tend to offer low-value flexibility.

These findings suggest that regulators could propose both spatially and income targeted incentive schemes to support the deployment of flexibility devices in areas and among segments of the population where they could help reduce deprivation more effectively. These incentives are critical, as low-income users may be unable to install costly flexibility devices, such as home batteries, electric vehicles, and smart appliances, without financial support. In conclusion, regulators could effectively incentivise flexibility while simultaneously reducing deprivation. To achieve this, a flexibility scheme could be designed (e.g. to

Table 1
Flexibility-adjusted deprivation index for each region in GB (last column). The columns from two to five report the population in the red, green, blue, and yellow areas, as defined in Fig. 12. The total population in each region in reported in column six.

Region	R_k	G_k	B_k	Y_k	N_k	δ_k
Greater London	–	1,284,952	–	669,715	9,002,488	−6.83 %
Scotland	365,185	47,979	711,175	71,570	5,466,000	−5.90 %
Yorkshire	548,582	959,447	346,447	450,446	5,526,350	−5.55 %
East Midlands	635,147	177,064	695,997	230,722	4,865,583	−0.15 %
West Midlands	22,793	–	26,337	–	5,961,929	−0.06 %
South West	–	–	–	–	5,659,143	0.00 %
Wales	–	–	–	–	3,169,586	0.00 %
North West	30,287	1345	10,103	–	7,367,456	0.26 %
South East	–	11,595	–	124,305	9,217,265	1.22 %
East of England	–	162,084	–	844,491	6,269,161	10.89 %
North East	902,746	–	366,032	–	2,680,763	20.02 %

help buy heat pumps) targeting those in energy poverty who live in regions where flexibility offers high value. By contrast, deprived people who live in low-value flexibility areas would require additional supporting mechanisms, as revenues from flexibility would be small. Finally, affluent people should only marginally benefit from these incentives, to avoid them to reap excessive advantages that would increase inequality instead.

Future work will aim at (i) extending our analysis to include energy poverty indicators, (ii) introducing a detailed representation of distribution networks to account for a broader set of energy services, and (iii) proposing an incentive scheme to support the deployment of devices (e.g. batteries) accounting for the effect that they may have on reducing deprivation. Finally, notice that the developed methodology can be applied to any country with a liberalised electricity market, provided that access to granular power system, energy market and economic deprivation data is available.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Detailed distribution of the locational marginal value of flexibility in GB

The following figure is based on the same data of Fig. 3, but shows the numerical values instead of the quintiles.

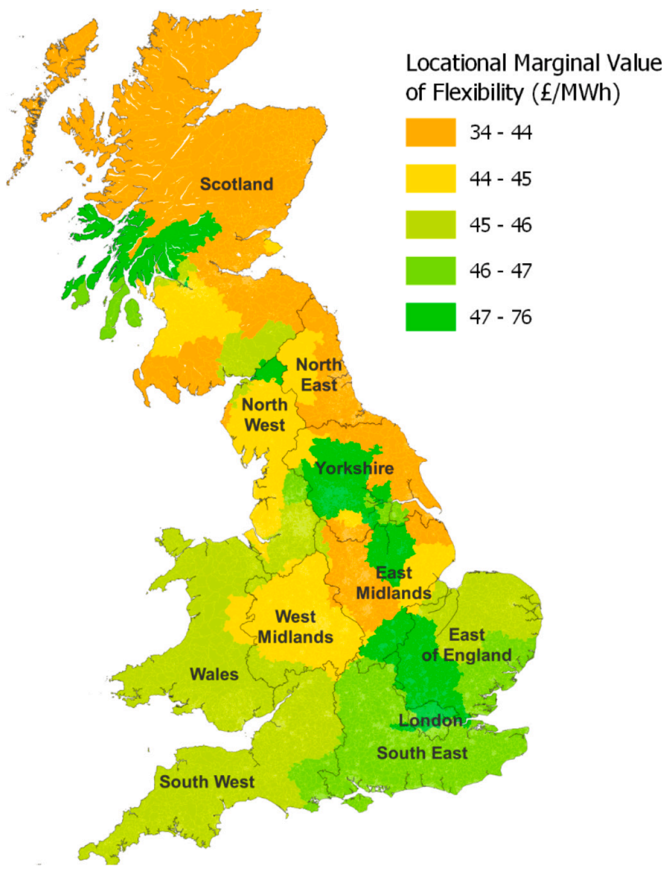

Fig. 13. The figure reports the detailed distribution of the average locational marginal value of flexibility for each LSOA in GB (£/MWh).

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