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Patterns of Sustainable Energy Use in the UK's Northern Powergrid

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Abstract **–** The United Kingdom (UK) aims to achieve net zero greenhouse gas (GHG) emissions by 2050. Hence, the government is promoting use of heat pumps in residences, use of domestic solar photovoltaic (PV) panels, and adoption of electric vehicles (EVs). However, critics cite barriers to adopting these strategies, and current adoption patterns and domestic energy consumption (DC) are unclear. This project uses open data on primary substations (PS) in the Northern Powergrid, which serves the UK's North East. The UK provides a good case study, given its readily available data and the key fact it is undergoing a net-zero transition. This paper aims to answer the research questions: 1) In the 2022 data, what were patterns of DC in the Northern Powergrid, and 2) How are DC patterns associated with heat pump, solar PV, and EV use? Using data from 541 PSs, DC patterns were mapped, and correlation and regression analysis was used to characterise the relationship between number of heat pumps, solar PV use, number of EVs and DC for the areas served by the PSs. Areas of high DC had higher population and were more affluent. Increasing number of heat pumps and EVs were statistically significantly associated with higher DC in both correlation (heat pumps $r = 0.8579$, EVs $r = 0.3246$, $p < 0.0001$) and regression analysis, and higher solar PV use was statistically significantly positively correlated with higher DC ($r = 0.6937$, $p < 0.0001$). Residences in more densely-populated and affluent areas are newer and therefore more likely to be suitable for heat pumps, and EV infrastructure is more likely to be established in these areas. These results support criticisms that the UK's net zero strategy goals may be unattainable, and that adopting sustainable strategies may inadvertently exacerbate underlying inequities.

Keywords**:** Electric vehicles, greenhouse gasses, domestic energy consumption, United Kingdom, heat pumps, solar photovoltaic, renewable energy consumption, primary substations.

1. Introduction

The United Kingdom (UK) government is promoting several sustainability initiatives to achieve a goal of a future net zero strategy [1], [2]. These initiatives include promoting residential heat pump, residential solar photovoltaic (PV), and electric vehicle (EV) adoption [1]. However, there are current practical challenges to adopting these sustainability practices, and how current use of these practices impacts current domestic energy consumption (DC) remains unknown.

First, UK policy to improve sustainable energy usage will be described, including how heat pump, solar PV, and EV usage is being promoted and adopted. Next, a project that forecasts future energy usage in the Northern Powergrid, which serves northeastern England, will be presented, which is the source of the data used in this analysis.

1.1 UK Policy to Improve Sustainable Energy Usage

In 2019, the UK became the first Group of Seven (G7) country to enshrine a new commitment into law to reach net zero greenhouse gas (GHG) emissions by 2050 [2]. In 2021, the UK government announced its net zero strategy pursuant to Section 14 of the Climate Change Act 2008 [1]. It set a target to reduce carbon dioxide emissions by 68% from 1990 levels by 2030, and to achieve net zero for carbon emissions by 2030 [1], [3], [4]. However, the goals are not on track to be met, partly because the UK government continues to modify policies aimed at sustainability, such as delaying the ban of new diesel and petrol cars, and adjusting the promotion of heat pumps [3], [5]. Meeting these goals is greatly dependent upon how the UK government promotes these policies [5].

As residents change from less to more sustainable energy usage approaches, energy demand will be impacted [4]. EVs are cheaper to use and maintain than traditional petrol and diesel vehicles, and energy efficiency measures in residential homes will substantially lower people's heating costs [1], [2]. Heat pumps may be more economical in the long run than gas boilers, depending on a range of factors [2]. Many groups therefore develop models and algorithms to forecast future demand [6], [7], [8].

However, in order to understand how well policies to promote sustainability are working now, analyses of current data are needed. DC should theoretically be impacted by the widespread adoption of sustainable energy approaches currently promoted through UK policy, such as installing heat pumps for residential housing energy use reduction [9], using domestic PV (solar) panels to generate energy [10], and using EVs to reduce fossil fuel consumption [1]. Significant challenges would exist in implementing an "all electric" pathway in the UK, where the power system's capacity and operations from renewable energy sources are needed to decarbonise the current electrical demands [11]. An all electric pathway would also potentially add large-scale energy demands due to electrification of heat and transport [11]. As the UK is transitioning to net zero, how these efforts are impacting patterns of current DC in the UK is unclear.

1.1.1 Heat Pump Adoption

The goal set by the Climate Change Committee (CCC) as part of striving toward net zero was to have 10% of homes heated with heat pumps by 2030 [3]. However, currently, the level of residential heat pump adoption in the UK is only 1% [3]. In a survey in Hope Valley, only 16% expressed interest in installing heat pumps [4]. To meet ambitious climate goals by 2050, quick and effective heat decarbonisation is essential, and one strategy is the usage of heat pumps where possible [11].

There are many barriers to installing heat pumps in current residential housing in the UK, as heat pumps only improve energy consumption in electric heating systems [1]. Nearly 24 million residents in the UK live in homes that use gas boilers, which are responsible for 37% of the country's carbon emissions [11]. Only 55,000 heat pumps were installed in UK residences in 2021, which is a lower deployment of heat pumps per capita than made in large European nations like France, Italy and Germany [2]. Since a majority of existing housing in the UK uses older fossil fuel technology, these residences would have to be updated to electric heat in order to take advantage of heat pumps [1], [9]. While new residences may be built with electric heat so as to be able to utilise heat pumps, in order to do this, the expertise for installing such heat pumps would need to be available [1], [9]. Currently, patterns of actual heat pump installation and usage in the UK, and how this impacts DC is not clear.

1.1.2 Domestic Photovoltaic (Solar Panel) Adoption

Solar PV panels on the roofs of buildings allow electricity to be generated without taking the land for other uses [4]. A typical 4 kilowatt (kW) system produces about 3,400 kilowatt hours (KWh) annually, which would meet the electricity demand of a three-bedroom domestic household [4]. Implementation of residential and industrial solar PV is part of the UK's net zero strategy [1]. Domestic solar PV options are popular in the UK, in that results from a survey in Hope Valley showed that 90% of respondents were in favour of solar generation on houses and non-domestic roofs, with 18% having already installed solar panels and 20% considering them [4].

To that end, the UK has implemented a Public Sector Decarbonisation Scheme which provided over £1 billion in grants over 2020 through 2022 that could be used for adding solar PV [1]. However, a clear roadmap for solar deployment is lacking, even though solar capacity is expected to grow fivefold by 2030 [2]. There is currently no target to make rooftop solar a standard for buildings across the UK [2]. A mixed-methods study of adoption of solar PV residentially in the UK was completed, and this effort actually exacerbated existing inequities [10]. Wealthy homeowners were more likely to have solar PV installed than those who were council tenants, even though many council tenants participated in solar granting programs [10]. Even so, the fact that certain residences are more suitable for solar PV than others was also a source of inequity, and authors recommended that the UK address this with policy [10]. Given this pattern of adoption of solar PV in the UK, its current impact on patterns of DC is not known.

1.1.3 Electric Vehicle Adoption

Global carbon emissions in 2019 totalled 37 gigatonnes (Gt), with road transport contributing 16% [12]. Passenger cars are the largest source of road transport emissions, making them a key target for reducing global GHG emissions [12]. Although EVs are being promoted as a sustainable alternative through the net zero policies put forth by the UK government, operation and maintenance of an EV requires a significant amount of energy [1], [6]. Wider adoption of EVs is expected to add stress to the power grid, although there are challenges to adoption in some areas, including drivers experiencing range anxiety in response to a lack of necessary infrastructure [6], [10].

The UK government acknowledges that a charging infrastructure is needed to support EV adoption which must focus on supporting local on-street residential charging [1]. In a survey from Hope Valley, 11% of respondents reported having an EV, with 39% saying they are considering buying one in the next four to five years [4]. In 2021, it was estimated that over one million EVs had been registered in the UK, and more than one in five new cars sold were EVs [1], [2]. For the first time in the UK, in 2022, sales of EVs eclipsed those of diesel vehicles, making up nearly 17% of the market [13]. However, it is unknown how the current use of EVs in the UK impacts patterns of DC.

1.2 Domestic Future Energy Scenario (DFES) Data

In the UK, to forecast future energy demand, the Northern Powergrid has implemented the Distribution Future Energy Scenarios (DFES) project [5]. The Northern Powergrid refers to the collection of primary energy stations and substations serving eight million residents across almost four million homes and businesses located in the UK's North East, Yorkshire and northern Lincolnshire regions [14]. Primary substations (PSs) directly feed from high voltage networks, and typically step down the voltage from 33 to 11 kilovolts (kV) [15]. PSs are a crucial part of the UK energy distribution network, enabling homes and businesses to use electrical devices [15].

Much data have been collected in the DFES project to support the development of future forecasts, and these data have been posted for reuse to an open data portal [16]. The intention of this analysis was not to forecast future energy use, but to characterise patterns of current heat pump, solar PV, and EV use, and how these patterns are associated with current DC. The most recent original data collected by DFES available for this analysis was from 2022, and included information about regions served by each PS, DC by these regions, and heat pump, solar PV, and EV ownership by these regions. These data were used for the current project.

1.3 Research Aims

Using the DFES data estimated from PSs in 2022, this paper aims to answer the following research questions about the Northern Powergrid: 1) What are the patterns of DC? and 2) How are these DC patterns related to the use of energy conserving practices promoted through the UK governments net zero strategy, which include heat pumps, domestic solar PVs, and EVs?

2. Methods

The following variables from the DFES data for areas served by PSs from 2022 were analysed: Number of registered plug-in EVs (pure and hybrid), number of heat pumps per residential household and commercial properties, domestic PV installed capacity for installations less than 4kW, and DC in megawatt hours (MWh) excluding EV and heat pump consumption [16]. After descriptive and geographic analyses to assess patterns of DC were conducted, separate Pearson correlations were developed with number of EVs, heat pumps, and domestic PV as independent variables, and DC as the dependent variable. To better understand relative contributions of the independent variables to DC, a linear regression analysis was done with DC as the dependent variable and the others as independent variables; covariates were retained in the model if their slopes were statistically significant ($\alpha = 0.05$).

3. Results

The original DFES dataset contained data for 545 primary substations; four were removed due to missing data, and the other 541 were used in analysis. Table 1 summarises the descriptive results.

Table 1: Summary Statistics

				Domestic Consumption*	
Category	**Levels**	**Median (IQR)**	**All n, %**	**Above Median n, %**	**Below Median n, %**
All	All	N/A	541, 100%	270, 50%	271, 50%
Number of electronic vehicles	0 to 49	112 (58-185)	110, 20%	2, 1%	108, 40%
	50 to 99		124, 23%	38, 14%	86, 32%
	100 to 149		109, 20%	75, 28%	34, 13%
	150 to 199		79, 15%	61, 23%	18, 7%
	200 and more		119, 22%	94, 35%	25, 9%
Number of heat pumps	0 to 99	71 (34-129)	352, 65%	104, 39%	248, 92%
	100 to 199		146, 27%	124, 46%	22, 8%
	200 or more		43, 8%	42, 16%	1, 0%
Domestic photovoltaic installed capacity (kW)	0 to <1 kW	0.75 (0.35-1.22)	341, 63%	102, 38%	239, 88%
	1 kW to < 2 kW		157, 29%	126, 47%	31, 11%
	2 kW and higher		43, 8%	42, 16%	1, 0%
Domestic underlying energy consumption*	0 to <20,000 MWh	18,053.00 (9,169.60-28,006.60)	302, 56%	31, 11%	271, 100%
	20,000 MWh to < 40,000 MWh		212, 39%	212, 79%	0, 0%
	40,000 MWh and higher		27, 5%	27, 10%	0, 0%

* Excludes electric vehicle and heat pump consumption. IQR = Interquartile range. N/A = not applicable.

2.1. Geographic Patterns of Domestic Energy Consumption

Figure 1 shows geographic patterns of DC by areas served by PSs.

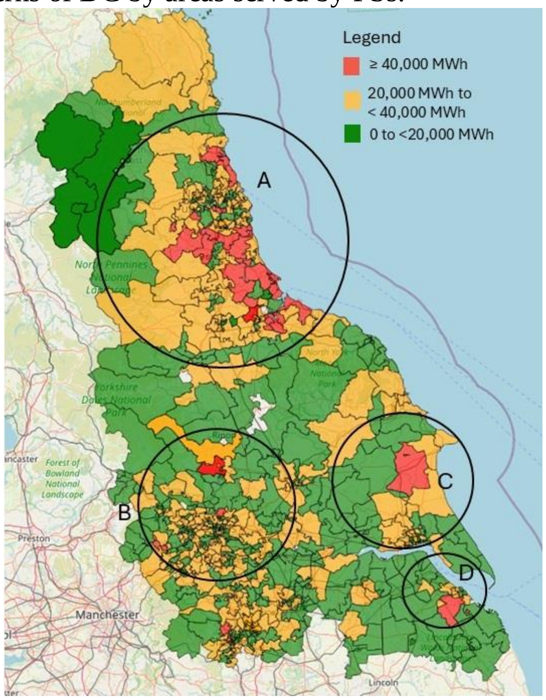

Fig. 1: Rate of Domestic Energy Consumption by Areas Served by Primary Substations, 2022.
Mwh = Megawatt hours of consumption excluding electric vehicle and head pump, A = Newcastle upon Tyne area, B = Leeds and Bradford area, C = Feeds Hull area (south), D = Feeds Grimsby area (north)

As shown in Figure 1, DC was highest in more populated areas, especially more affluent areas, such as Newcastle upon Tyne and Leeds and Bradford (A and B on Figure 1).

2.2. Patterns in Use of Heat Pumps, Solar Photovoltaic, Electric Vehicles and Domestic Energy Consumption

There were statistically significant positive correlations between number of heat pumps and DC ($r = 0.7533$), solar PV and DC ($r = 0.6937$), and EVs and DC ($r = 0.3246$, $p < 0.0001$ for all). Because EVs had a skewed distribution (see Table 1), Figure 2 was developed to help interpret the association of both EV and heat pumps with DC simultaneously.

Fig. 2: Association Between use of Electric Vehicle and Heat Pumps and Domestic Energy Consumption, 2022.
MWh = megawatt hours, EV = Electric vehicles.

In Figure 2, number of heat pumps is on the x axis, and DC is on the y-axis. Each dot in the scatter plot represents a PS; grey dots represent PS areas where EV count is below the median and pink dots represent areas where EV count is above the median (least square lines are included for each group). The figure suggests a general trend of where DC is low, both heat pumps and EVs are unpopular, and where DC is high, both heat pumps and EVs are more plentiful.

For linear regression, the slope for solar PV was not statistically significant, so was not retained in the model. The final model equation was:

$$\hat{y} = x_1 116.38 + x_2 12.25 + 6{,}804.63$$

where $\hat{y}$ is estimated DC, x_1 is number of heat pumps, and x_2 is number of EVs ($F = 415.2$ on 2 and 538 df, $p < 0.0001$, adjusted $r^2 = 0.6054$).

4. Conclusion

In this analysis of 2022 data covering areas around PSs in the Northern Powergrid, DC was highest in more densely-populated and affluent regions. Use of heat pumps and EVs were strongly directly associated with DC. The association between number of heat pumps and DC was likely due to the fact that heat pumps can only be installed in residences with electric heat, and those are more likely to be in more affluent areas and areas with higher population levels which include newer residences. The association between number of EVs and DC was likely a reflection of the underlying EV infrastructure, which is much more developed in affluent areas and areas with higher population levels.

This analysis has both strengths and limitations. A strength is that it leverages real-world open data from DFES to understand progress toward the implementation of sustainable energy strategies in the UK. While the results provide a picture of current progress, the project was limited to the variables from DFES that were available for analysis. There are likely many other influences on DC that were not accounted for in the analysis, and this is another limitation.

The findings from this analysis suggest that in less-populated areas of the Northern Powergrid where DC is low, heat pumps and EVs will face barriers to adoption. These areas contain older residences that will require an upgrade of their heating systems before being suitable for heat pumps. Further, EV infrastructure such as charging stations must be developed in these low DC areas before residents there will be willing to give up cars using fossil fuel and adopt EVs. These findings underscore the challenges behind the UK's net zero strategy, and are consistent with the finding that implementation of such strategies may exacerbate rather than alleviate inequities [1], [10].

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