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Distributed local energy: Assessing the determinants of domestic-scale solar photovoltaic uptake at the local level across England and Wales

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ABSTRACT

The withdrawal of the Feed-in Tariff (FiT) by the UK Government at the end of March 2019, which rewarded low carbon electricity generators with subsidy payments, has led to doubts over the future of small-scale generation in the country's energy system. This study contributes to navigating this post-subsidy uncertainty by identifying the factors associated with the uptake of a domestic-scale technology, solar photovoltaics (PV), in England and Wales, and exploring its spatial distribution. It uses FiT installation data from Ofgem, available at a fine-grained spatial resolution for the period April 2010–September 2019, to test the effect of social, housing, political, energy and environmental factors. It is shown that population demographics, housing density, size, type and tenure, and energy consumption practices are important factors influencing the uptake of domestic PV at the local level. The South West and East of England are identified as regions of unexpectedly high uptake, controlling for the other factors. This is, at the time of writing, the first attempt to model PV uptake at a fine-grained spatial level across England and Wales.

1. Introduction

The UK's energy system is in transition, driven by the need to mitigate climate change [1], ensure a secure and affordable energy supply [2,3] and meet social needs [4,5]. Alongside these concerns, opportunities for change are emerging from new and lower cost technologies, and social innovation [6,7]. Multiple trajectories for future transitions have been identified with some including a more influential role for distributed and local energy, for example through local energy markets [8–10]. A key technology in localising and enabling participation in energy generation is solar photovoltaics (PV). PV contributes to decarbonisation targets and increases the diversity of the electricity supply, enhancing system resilience [11]. This technology has seen a dramatic fall in price in recent decades, with the cost of PV modules globally falling 99% between 1975 and 2015 [12]. Driven by this fall and the use of key subsidy mechanisms, the UK has seen rapid PV growth, expanding from 26 MW in 2010 to over 13 GW at the end of 2018 [13], a five-hundred-fold increase. Almost 3 GW of this capacity is in systems sized at 10 kW and below, largely domestic-scale installations.

Feed-in Tariff (FiT) subsidy support was withdrawn at the end of March 2019, having been reduced in value since its inception in April 2010 from 54.17p/kWh to 3.79p/kWh [14].[1] The UK Government has introduced a 'Smart Export Guarantee' [15], placing value on electricity exported to the grid by ensuring larger suppliers offer consumers export tariffs. At the time of writing the guarantee offers limited support, stipulating that prices must be greater than zero pence. Despite global cost reductions, continued domestic investment in PV may require new forms of incentive or innovative business models in order to achieve economic viability. Local energy actors may be positioned to make a more active contribution to enable this. Local authorities are taking greater responsibility for climate action and ambitious local goals are beginning to provide impetus for the diffusion of low carbon pathways [16–18]. This localisation presents an opportunity to re-assess the factors that influence domestic PV uptake, particularly at the local level.

Abbreviations: EPC, Energy Performance Certificate; EV, Electric vehicle; FiT, Feed-in tariff; GW, Gigawatts; ha, Hectares; ICLEI, Local Governments for Sustainability; kW, Kilowatt; kWh, Kilowatt hours; LEP, Local Enterprise Partnership; LSOA, Lower layer super output area; MW, Megawatts; NUTS3, Nomenclature of Territorial Units for Statistics 3 level; OLS, Ordinary least squares regression; PV, Solar photovoltaics; SECAP, Sustainable Energy and Climate Action Plan; VIF, Variance inflation factor.

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[1] Rates shown refer to highest available for small-scale generators.

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There is likely to be significant spatial variation between [19], and within, different localities [20,21] and as such, spatial considerations have become a key theme in understanding the diffusion of PV in studies across Europe and the USA [e.g. 22–30].

This paper offers some background to the role of PV in the UK's low carbon energy transition in section 2, introducing the role of renewables as enablers of change at the local level. Trends in PV costs and UK uptake are considered, coupled with a brief outline of the diminishing subsidy support for small-scale energy generation. Section 3 gives an overview of existing work on the diffusion and uptake of PV. Section 4 contains the study's methodology, providing details of data sources, processing and model specification. Section 5 presents the output of the model and a wider discussion of the implications of the results for encouraging further uptake of small-scale PV post-subsidy. Section 6 offers some concluding remarks and suggestions for further study.

2. Background and overview

In the UK, several pathways to a zero-carbon energy system have been posited by academia [e.g. 31–34], UK Government [35], the energy regulator [36,37], private corporations [e.g. 38], and not for profit organisations [e.g. 39, 40]. These pathways envisage different roles and levels of involvement from government, private sector and civil society, and the use of different technologies. One pathway particularly compatible with local level features is known as 'Thousand Flowers' [32] which envisages a greater role for civil society and citizens in energy generation. In this scenario, the energy system is governed at a more localised level, with highly distributed renewables owned by communities and households. Several studies refer to this as 'civic energy' [41–44], 'local energy' [45,46], 'community energy' [45,47] and 'citizen energy' [48,49] among other identifiers [see also 50, 51], emphasising a wide but disjointed interest in the area. Ofgem [52] suggest the broader move towards devolution, changes in consumer preferences and participation, and declining trust in incumbent energy actors are driving the rise of local energy. Local authorities are becoming increasingly involved in climate and energy governance, declaring 'climate emergencies' [16] and introducing municipally-owned energy companies [53]. Local ownership and governance can contribute to wider societal goals, for example environmental sustainability [54] and the encouragement of learning, engagement and participation [55].

The rise of renewable generation technology has been an important enabler for local actors in the energy sector [56]. One of these technologies, and perhaps the most accessible at the local scale, is PV. The scalability of PV systems means they can be introduced at varying scales, from small-scale rooftop installations to large solar farms. Over the past four decades, the cost of PV has reduced dramatically driven by efficiency gains and mass production [57]. Absolute costs are dependent on module type, country of manufacture and project size, but the trends are consistent across most configurations [58,59]. In the period 1976–2018, Bloomberg New Energy Finance [60] estimate the global average cost of crystalline silicon (c-Si) PV modules fell 28.5% for every doubling of output. This is consistent with Candelise et al. [61] who identify learning rates of 16–47% for different PV technologies globally. The International Renewable Energy Agency [62] observed a 75–80% fall in global PV prices in the period 2010–2015, and a similar fall in the levelized cost of electricity from PV between 2010 and 2017 [59]. Comello et al. [63] agree that there has been a sharper-than-expected fall in PV module prices in recent years, with a ten-fold decrease from 2007 to 2017. Predictions suggest these trends will continue over the next decade, with cost-competitiveness overtaking conventional power plants and continued reductions expected to at least 2050 [59,64]. In the UK and elsewhere, predictions have consistently underestimated price reductions and have been repeatedly revised [61,65]. When limiting UK PV to 10 kW installations or smaller, the price drop trends remain, but cost-competitiveness suffers in comparison with utility scale developments. Despite this, small-scale PV costs are predicted to continue to fall in line with other renewable technologies [65].

By the end of 2018 the UK had more than 980,000 installations of PV with a cumulative capacity of over 13 GW [13]. For comparison at the same time, Germany, Europe's largest PV contributor, had in excess of 1.6 million (subsidised) PV installations with a total capacity of 45.9 GW [66]. PV is an enabling technology for individuals and communities who want more control over their energy choices [67]. At the residential level, installation of PV can redefine the role of individuals from passive consumers of energy, to consumers and producers simultaneously – known as 'prosumers' [68–70]. Others perceive technologies such as energy storage and electric vehicles (EVs) as important for (re)defining how people will participate [71,72]. Emerging digital innovations in smart metering and devices [69] and peer-to-peer energy trading [73] are expected to stimulate new practices and behaviours within the energy system, offering alternatives to established consumer-producer relations [74]. These innovations are being integrated to provide new forms of energy value, provision and use to the consumer.

PV's adaptability also makes it suitable in areas where other solutions may be difficult to implement [75]. With over two-thirds of the world's population expected to live in urban areas by 2050 [76], rooftop PV is likely to become a critical technology in meeting urban energy needs [77,78]. These potentially transformative impacts make residential PV an attractive technology for policymakers. Studying the uptake of domestic PV can give insight into who participates and the local conditions which influence decisions, providing insight into how further diffusion can be encouraged.

Recent UK policy changes have reduced the support available for small-scale PV, removing much of the financial incentive for investing [14,79]. The Feed-in Tariff was introduced in 2010 to incentivise the installation of small-scale (up to 5 MW) low-carbon electricity generation technologies [80]. Generators were paid generation and export tariffs, whilst also benefitting from cost savings resulting from reduced need for grid electricity. Early rates were generous but the unexpected degree by which PV uptake increased, and the fall in price of the technology, prompted cuts in the subsidy [61,81]. The reduction and subsequent removal of policy incentives has caused the payback period for PV to markedly increase despite falling costs, restricting access to this technology for many. However, new domestic installations continue with several new high-profile suppliers entering the UK market [82, 83]. Emerging innovation in EVs and home energy storage could have implications for the affordability of PV systems and could contribute to wider energy cost reductions for all customers [84], although there is a risk of excluding disadvantaged groups from such a transition [85].

3. Previous studies

Earlier studies of PV uptake examined behavioural and attitudinal aspects [86–88], willingness to pay [89], policy incentives [90,91] and other economic factors [86,92]. These studies provided a useful entry point for understanding PV diffusion and in positioning this work in the context of the broader innovation diffusion literature [93,94]. Several related studies highlight a lack of focus on spatial considerations [95–97], although more recent work has acknowledged that the energy system, and any transition it experiences, has important spatial influences and consequences [98–101]. The geography of energy is central to understanding the uptake of PV with a dependency on resources, skills, demographics and other socio-economic and cultural factors at the local level [101,102]. Existing work has identified the importance of the role of local conditions in facilitating and nurturing distributed energy generation technologies [103,104]. Installations of domestic solar PV are highly distributed across the UK, with every local authority containing at least a handful of arrays ($M = 6.28$ MW, $SD = 5.13$ MW) [105].

Understanding what influences uptake beyond financial incentive is an important step in a post-subsidy system. Recent work has identified the spatial nature and social effects of PV uptake [e.g. 22, 23, 25, 106, 107]. Broadly, these have taken one of two approaches: investigating the influence of social effects, or examining the environmental, economic, social and political influences on uptake. Social effects are observed to have an important role in uptake [108,109]. PV has high visibility at the local level, often occupying space on the rooftops of domestic, business, and public buildings, which can lead to observational learning [28]. This can influence decision-making through the development of social and behavioural norms that can inform neighbourhood decision-making [26,106]. Palm [110] concludes that these passive observational effects are of lower importance than interpersonal interactions, although the latter may emerge as a consequence of the former. The influence of more substantive interaction, including frequency and intensity of communication, is supported by Busic-Sontic and Fuerst [111], who find personality traits of openness and conscientiousness associated with stronger peer effects for PV uptake in the UK. Bollinger and Gillingham [108] present evidence of causal peer effects, with higher subsequent adoption rates in zip codes with larger existing installed PV capacity. The strength of this peer effect is commonly found to increase as spatial scale decreases [26,108,109,112], it can enhance the effect of other variables [21], and it is also mediated by financial factors. More affluent neighbourhoods with a larger proportion of detached households show a less pronounced social effect [28], and uptake in these areas may be explained by early adopters [93]. Lower income households are less likely to adopt PV, but peer effects play a greater role in their decisions [108]. The existence of this peer effect has important implications for policymakers, as it shows investors' decisions are not solely financially based [106]. Policy could be targeted at altering social norms or encouraging more direct interactions. Some argue that the most appropriate governance level might be more localised, with a role for local authorities and local intermediaries in inducing further peer effects [106,107].

Spatial influences have also been considered in studies investigating the effects of social, economic, environmental and political drivers. Four key areas are commonly used for predicting uptake of PV: the physical environment; socio-economic and demographic factors; variables relating to housing; and environmental- and energy-related actions or behaviour (summarised in Table 1). Solar irradiation has regularly been used as an explanatory variable in PV diffusion studies [113]. Irradiation varies over space, so those locations receiving a higher amount of solar energy will enable larger amounts of generation for the same sized installation and economic outlay, resulting in improved economic performance. This is consistently found to have a significant positive effect on PV uptake [22,23,27,29,30,76].

Socio-economic and demographic factors used as predictors include levels of education, age, income and population density. Davidson et al. [24] find that being educated to master's level has a strong positive impact on PV uptake, while Dharshing [25] concludes that areas with a high ratio of graduates and lower unemployment were more likely to have larger residential PV capacity. Others agree that higher levels of education or knowledge of energy technology predict higher PV uptake [22,27,114,115].

The effects of age are inconsistent, with some finding different associations across age groups [24,27] and others failing to find a significant relationship [26]. Graziano et al. [21] find middle-age ('around 45″, p.80) to be a predictor of uptake, but only once social effects dissipate. These mixed conclusions are echoed when testing the effect of income. Significant positive [25,29] and negative [21,23,114] relationships have been evidenced, with others finding the relationship not significant [22,28,91]. Some studies suggest accumulated capital or willingness to leverage resources may be a better economic predictor (22, 24, 26]. Social class has been given limited attention in the literature, although Bondio et al. [116: p.647] describe PV as "the technology of the middle class".

Population density, closely tied to aspects of housing and urbanisation [113], is found to have a significant negative effect on PV uptake [22,27,75,117]. Showing similarities with population effects, housing density shows a negative effect on PV uptake [23,26,114], although Schaffer and Brun [29] find a significant positive effect in their study in Germany. As might be expected, a larger proportion of detached houses shows a positive effect [22] while apartment-dominated areas are less conducive for PV [75]. Van Der Kam et al. [114] find house size to be a significant predictor, consistent with the conclusions of Westacott and Candelise [113]. The effect of household size (i.e. number of people within household) is less conclusive, with Bollinger and Gillingham [108] suggesting evidence of a peer effect ("larger households have more eyes per household to see other adoptions of solar" p. 14), but Copiello and Graziano [23] find negative effects. The effect of homeownership is also inconclusive, with some studies showing small positive associations with PV [29,75] and others finding a negative effect [22, 26].

Table 1
Summary of predictors used in existing studies on domestic PV uptake, associated effects and location of study.

Predictor	Effect on domestic PV uptake	Location of studies
Physical environment		
Amount of solar irradiation	Positive	Australia, Germany, Italy, UK, USA
Socio-economic & demographic		
Education level	Positive	Germany, Netherlands, UK, USA
Population density	Negative	Australia, UK, USA
Age	Inconsistent	USA
Income	Inconsistent	Germany, Italy, Japan, UK, USA
Housing		
House size	Positive	Netherlands, UK
Proportion of detached houses	Positive	UK
Proportion of apartments	Negative	Australia
Proportion of rented dwellings	Negative	Australia, USA
Housing density	Negative	Germany, Italy, Netherlands, USA
Household size	Inconsistent	Italy, Malta, USA
Homeownership rate	Inconsistent	Australia, Germany, UK
Environmental- & energy-related		
Electricity consumption	Positive	UK
CO_2 Emissions	Positive	UK
Hybrid vehicle ownership	Positive	USA
Electric vehicle ownership	Not significant	Netherlands
Environmental attitude	Inconsistent	Germany, Italy, Netherlands
Local government commitment	Not significant	USA

The final area from which variables have been derived are environmental- and energy-related actions and behaviours. Dharshing [25] and Schaffer and Brun [29] find inconclusive evidence that green voting (a proxy for environmental attitude) has a significant effect on PV uptake in Germany. Copiello and Grillenzoni [23] also find little association with innovative and responsible behaviour in Italy. More recently, Van Der Kam et al. [114] determined that areas of the Netherlands with more green party voters were positively associated with PV uptake. This kind of predictor has yet to be tested in the UK, nor has the uptake of hybrids or EVs. Davidson et al. [24] find a strong association between hybrid vehicle ownership and PV adoption elsewhere. EVs, as a complementary technology, may show similar associations although geographical disparities are found between EV and PV adoption [114]. Electricity consumption and carbon emissions are also found to have a positive influence on PV uptake [22]. At a broader scale, membership of transnational municipal networks may catalyse change at the local level. Kwan [27] tested local authority membership of ICLEI (Local Governments for Sustainability) but found no significant effect, attributing this to the lack of requirement for action. More recently, membership in other organisations and networks, such as the Covenant of Mayors, has required a commitment to action. It might be expected that areas in which such commitments exist might offer more enabling environments for domestic PV to grow.

4. Methodology

Building on the work of Balta-Ozkan et al. [22] and others, this study provides a renewed analysis using more up-to-date UK PV data at a finer spatial scale and includes previously untested variables that the literature suggests are important. This will have implications for local governance by identifying predictors for the adoption of small-scale domestic PV at the local level. Explanatory variables were derived from existing studies on PV uptake in Western Europe and the United States as summarised in section 3.

4.1. Data

4.1.1. Dependent variable: solar PV capacity

Detailed data on UK renewable energy technology installations exists, compiled and maintained by the energy regulator, Ofgem [105, 118]. New small-scale generation (under 5 MW installed capacity) in the UK was subsidised until April 2019 by the FiT. FiT installation reports [106] are produced quarterly and are publicly available. As of September 2019, over 850,000 installations were registered on the scheme, with photovoltaics comprising the vast majority of these (Table 2). New installations added to the register since its closure were granted a grace period, for example due to issues with grid connections, although pre-registration must have been submitted before the deadline. It is important to note that a small number of renewable electricity installations under 5 MW may not have registered on FiT, and installations larger than 5 MW are serviced by other subsidies such as the Renewables Obligation. The focus of this study is on domestic installations of PV, which can be very strongly linked to the FiT, since they had virtually no presence in the UK until its introduction in 2010 [105]. Within the FiT database there are a number of large installations designated as domestic. Typical residential rooftop PV arrays are 2–4 kW in size, but this study is also interested in those who may invest in modestly larger arrays, up to 10 kW, following Balta-Ozkan et al. [23]. The spatial unit of study is the Lower Layer Super Output Area (LSOA), a census-derived hierarchical geography for England and Wales with populations of between 1000 and 3,000, and household numbers between 400 and 1200 [119]. The use of PV data at a finer spatial scale than previously used, and understanding the predictors of PV uptake at this level enables us to consider localised variations in a system that is becoming increasingly distributed and decentralised. LSOAs are nested within local authority districts, which enables the effects of indicators at this broader district geography to be considered. Further, previous identification of social effects in the uptake of solar PV [108,109] provide evidence that understanding of lower-level dynamics is a worthwhile pursuit and of substantive value for policymakers.

Table 2
Renewable energy installations registered on the UK's Feed in Tariff (up to 5 MW) up to August 31, 2019 [105].

Technology	Number of installations	Total Installed Capacity (MW)
Anaerobic Digestion	419	292.4
Hydro	1169	223.4
Micro CHP	537	0.6
Photovoltaic	853,414	5049.9
Community	*3127*	*271.7*
Domestic	*819,760*	*2886.3*
Non-Domestic (Commercial)	*28,726*	*1600.7*
Non-Domestic (Industrial)	*1, 801*	*291.2*
Wind	7540	749.9
Total	863,079	6316.2

Filtering of the PV data was necessary due to data limitations. Firstly, 57,964 entries from Scotland were omitted as several explanatory variables are not available, with many taken from the 2011 Census [119]. Some entries had missing or incomplete location data; where LSOA data was missing, postcode district data, available in the FiT dataset, could be used. As LSOAs are specified based on population size and socioeconomic status, they do not fit neatly within postcode districts, nor postcode districts within LSOAs. In some cases, however, the postcode district is within the boundaries of a single LSOA. Using lookup tables available from the Office for National Statistics, LSOA information for those installations within postcodes with a single matched LSOA could be derived. Installations that could not be matched to a single LSOA, or without any location data, were removed from the dataset. Finally, installations were limited to 10 kW capacity, as outlined earlier in this section, leaving around 700,000 data points for the study (see appendix A). These remaining values were aggregated at the LSOA level providing accumulated total capacity for each area, against which explanatory variables could be more readily tested. Fig. 1 shows how the accumulated capacity of this small-scale domestic PV is distributed across the UK.

4.1.2. Independent variables

As discussed in section 3, independent variables were identified from existing studies and other relevant organisations (outlined in Table 3; see appendix B for more detail). The authors acknowledge that census data refer to 2011, several years earlier than the PV data, but that these data are the only available source of such indicators. Their use does not assume that socio-demographic indicators are static; as a comprehensive data source across England and Wales, they allow for the development of more policy relevant insights at the national level, and variations between different geographies are likely to be informed, at least partly, by their precedents. Several indicators are defined in percentages to prevent distortion of effects as the LSOA areal units differ in size, while the natural logarithm of income and household density are used to normalise these data. Other variables were excluded due to lack of availability at, or incompatibility with, the LSOA spatial resolution.

4.1.3. A note on omitted variables

Several additional variables were omitted from the study due to insufficient data coverage and multicollinearity (see appendix C). These included proportion of rented dwellings, proportion of flats, unemployment rate, population, fuel poverty rates and constituency green votes. Proportion of rented dwellings and flats were considered in an earlier iteration of the model, but both displayed collinearity with household density, detached houses, homeownership and proportion of retirees and were subsequently removed. Unemployment rate and population displayed collinearity with other variables of greater interest and were also removed. Fuel poverty estimates at the LSOA level are available in England from 2016, but similar data are not available for Wales. The share of votes for the UK Green Party was considered as a predictor following [25,29] who use it as a proxy for environmental attitude. However, some constituencies in England and Wales do not have Green candidates for which the electorate can vote, resulting in a misrepresentation of these LSOAs' environmental attitude. The presence of local community energy initiatives was also considered, given their capacity as trusted sources of information and other forms of social capital, as well as project enablers of projects innovative financing such as crowdfunding. At the time of writing, comprehensive data at a useful spatial scale does not exist. The influence of community energy on residential PV should be of interest to future research if such data becomes available, due to their varied approaches, participatory nature, and their capacity to influence energy system characteristics at the local level. Finally, inclusion of data related to variation in the Feed-in Tariff was not suitable for this study as there was no spatial variation in the tariff rate.

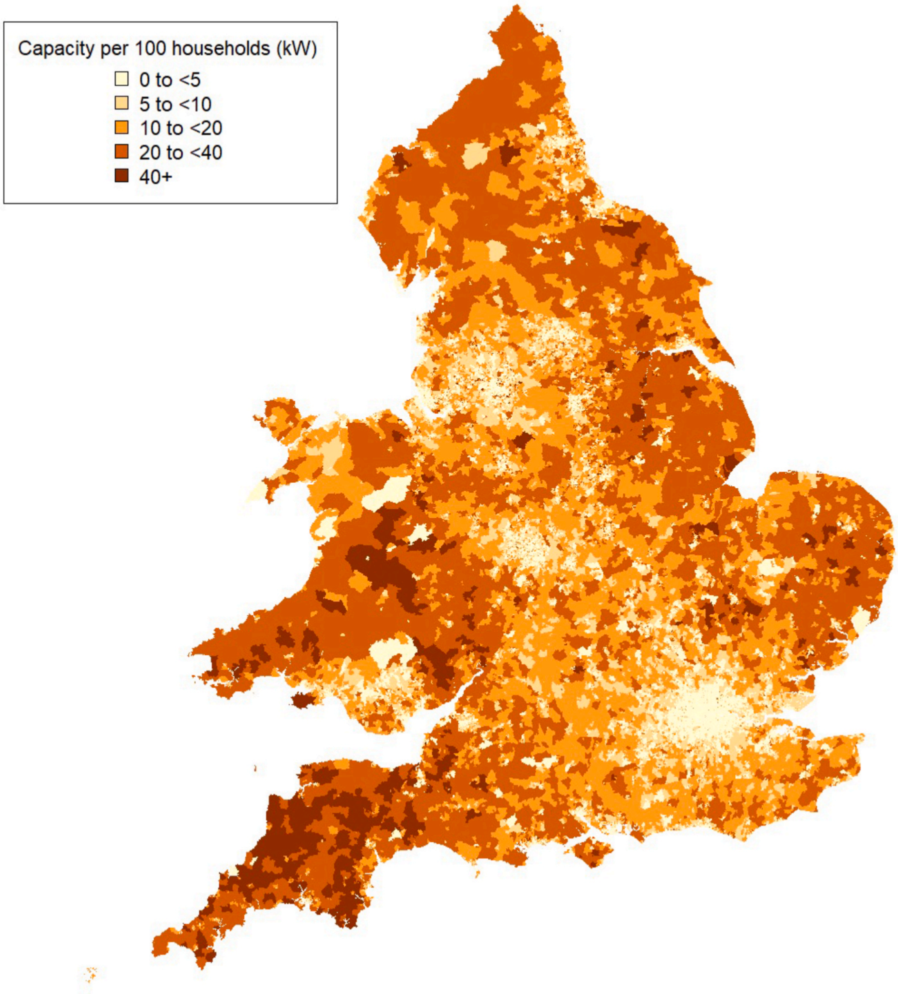

Fig. 1. Distribution of installed small-scale domestic (10 kW and under) solar PV across England and Wales to September 31, 2018.

4.2. *Model specification*

To characterise the conditions under which UK domestic PV uptake takes place and to produce a global model, an ordinary least squares (OLS) regression was performed initially:

$$y = \alpha_{00} + \beta x + \delta z + \eta a + \theta b + \epsilon \qquad (1)$$

where y is the capacity of installed domestic solar PV (kW), α_{00} is a constant, x is a matrix of physical environmental indicators, z is a matrix of socioeconomic and demographic indicators, a is a matrix of housing indicators, b is a matrix of indicators related to environmental- and energy-related actions and behaviours, β, δ, η and θ are the associated regression coefficients, and ϵ is the unobserved error. Early iterations of the model displayed evidence of collinearity between independent variables. The variance inflation factor (VIF) was used to identify variables overly correlated with one another. Theoretical justification for removing variables with high VIF values was evident, for example high collinearity was displayed between unemployment rate within LSOAs and education levels, and between population and household density. Predictors were standardised to allow ease of comparison of their effect sizes prior to producing the final model. Residual plots suggested heteroskedasticity was present in the model. A further consideration was whether spatial effects were influencing the model. As observed by Refs. [22,30], spatial patterning exists within the residential PV data. Testing for correlation between capacity in LSOAs and their immediate neighbours (i.e. those with which they have a shared border) showed evidence of significant positive autocorrelation (r (34,751) = 0.735, p < .001). Using Moran's I, the PV capacity data was tested for spatial autocorrelation using contiguity-based spatial weights. Moran's I statistic for domestic PV capacity is 0.597 (p < .001), suggesting spatial clustering at the LSOA level. Balta-Ozkan et al. [22], who tested for spatial dependency at the NUTS3 level, report a weaker Moran's I statistic of 0.142. This might be expected: LSOAs are much smaller spatial units than NUTS3 areas and thus may display more similar characteristics as one another. The residuals from the OLS were tested for spatial autocorrelation, with spatial effects still evident with a Moran's I of 0.367 (p < .001). As LeSage [120] notes, "spatial data typically violates the assumption that each observation is independent of other observations made by ordinary regression methods." To address this, dummy variables for local authorities were introduced as suggested by Ward and Gleditsch [121], to account for spatial heterogeneity between these areas, such as differences in local policy. This improved the model fit (adjusted $R^2 = 0.56$; OLS adjusted $R^2 = 0.45$ – see Table 4), although spatial autocorrelation remained in the residuals (Moran's I = 0.208, p < .001). A multi-level model was fitted to consider variations in local authority level indicators that were absent in the dummy model.[2] This

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[2] Model notation for multilevel model:$y_{ij} = \alpha_j + \beta_j x_{ij} + \delta_j z_{ij} + \eta_j a_{ij} + \theta_j b_{ij} + \epsilon_{ij} \alpha_j = \alpha_{00} + \mu_{0j} \beta_j = \beta + \mu_{1j} \delta_j = \delta + \mu_{2j} \eta_j = \eta + \mu_{3j} \theta_j = \theta + \mu_{4j}$This notation is as model 1, but now i (LSOAs) and j (Local Authority Districts) represent the levels at which the variables are measured, and the error term has been decomposed into two parts, μ_j and ϵ_{ij}.

Table 3

Outline of variables used in analysis and their data sources.

Variable	Description	Year	Data Source
Physical environment			
Irradiation	Yearly global horizontal irradiation (kWh/m^2)	2014	European Commission
Area	Size of LSOA (ha)	2011	ONS-Census
Socio-economic & demographic			
Education	% people with highest qualification level 3 or above (%)	2011	ONS-Census
25to44	% aged 25–44	2011	ONS-Census
45to64	% aged 45–64	2011	ONS-Census
Retired	% retired	2011	ONS-Census
Logincome	Natural logarithm of median annual household income (£)*	2016	ONS
skilledmanual	% people in C2 social grade	2011	ONS-Census
Housing			
Hh	Number of households	2011	ONS-Census
Loghhden	Natural logarithm of household density (households per ha)	2011	ONS-Census
Hhsize	Mean inhabitants per household	2011	ONS-Census
Detach	% detached houses	2011	ONS-Census
Owned	% houses owned	2011	ONS-Census
epcC	% energy efficiency certificated dwellings with EPC rating C or above	2015	DECC
Sfch	% homes with solid fuel central heating	2011	ONS-Census
Environment- & energy-related			
EV	Number of electric vehicles	2018	DfT
Hybrid	Number of hybrid vehicles	2018	DfT
perCO2	Carbon dioxide emissions per capita (t) **	2016	BEIS
Medcons	Median consumption of electricity (kWh)	2017	BEIS
Secap	Local authority membership of Covenant of Mayors **	2019	Covenant of Mayors

* only available at MSOA level; ** only available at Local Authority level.

model accounts for a larger proportion of the variance in domestic PV capacity, but does not address the spatial patterning in the residuals (Moran's $I = 0.209$, $p < .001$). Our results from this fixed effects model suggest that 26% of residual variance remains at the local authority level. Using lagrange multiplier diagnostic tests, it was found that a spatial error model might better account for spatial autocorrelation in the PV data. Earlier models provide evidence for spatial heterogeneity with influences at the local authority level, but inclusion of local authority dummy variables was computationally prohibitive. Despite this, Akaike's Information Criterion provides evidence of a better model fit, however a smaller proportion of the variance in domestic PV capacity is accounted for.[3]

5. Results and discussion

Table 4

Results of four models characterising PV uptake across England and Wales at the LSOA level. Dummy variables are not presented due to the number of local authorities included (n = 348).

		OLS	OLS w/ dummy	Multi-level Model	Spatial error model
Variable	sd	Estimate	Estimate	Estimate	Estimate
(Intercept)		62.11***	59.02***	63.82***	64.23***
		(0.000)	(0.000)	(0.000)	(0.000)
Irradiation	75.97	2.66***	1.63	1.60	1.50
		(0.000)	(0.022)	(0.013)	(0.007)
Area	1472.65	4.02***	6.06***	5.97***	6.48***
		(0.000)	(0.000)	(0.000)	(0.000)
Education	13.40	4.96***	−0.63	−0.23	−1.52
		(0.000)	(0.277)	(0.692)	(0.019)
25to44	7.53	−3.65***	−2.85***	−2.94***	−3.88***
		(0.000)	(0.000)	(0.000)	(0.000)
45to64	5.58	6.64***	6.90***	6.86***	5.46***
		(0.000)	(0.000)	(0.000)	(0.000)
Retired	6.03	8.56***	9.45***	9.50***	8.53***
		(0.000)	(0.000)	(0.000)	(0.000)
Logincome	0.24	−5.99***	0.43	−0.21	−3.82***
		(0.000)	(0.427)	(0.691)	(0.000)
skilledmanual	6.43	10.31***	7.95***	8.13***	6.76***
		(0.000	(0.000)	(0.000)	(0.000)
Hh	131.39	12.11***	11.42***	11.51***	11.45***
		(0.000)	(0.000)	(0.000)	(0.000)
Loghhden	1.54	−9.86***	−6.81***	−7.02***	−5.48***
		(0.000)	(0.000)	(0.000)	(0.000)
Hhsize	0.30	7.53***	8.44***	8.42***	7.12***
		(0.000)	(0.000)	(0.000)	(0.000)
Detach	21.86	18.94***	13.24***	13.58***	14.45***
		(0.000)	(0.000)	(0.000)	(0.000)
Owned	20.56	−5.47***	−4.65***	−4.63***	−2.71**
		(0.000)	(0.000)	(0.000)	(0.000)
epcC	17.19	8.12***	5.99***	6.08***	5.63***
		(0.000)	(0.000)	(0.000)	(0.000)
Sfch	1.69	7.11***	4.77***	4.94***	4.42***
		(0.000)	(0.000)	(0.000)	(0.000)
EV	0.53	0.57	0.54	0.54	0.49
		(0.050)	(0.040)	(0.042)	(0.041)
Hybrid	3.67	−4.01***	−1.06	−1.29**	−0.85
		(0.000)	(0.003)	(0.000)	(0.010)
perCO2	4.27	2.29***	[b]	1.19	2.37***
		(0.000)		(0.190)	(0.000)
Medcons	610.85	1.37*	3.61***	3.46***	3.01***
		(0.001)	(0.000)	(0.000)	(0.000)
Secap	0.46	2.78***	[b]	−3.93	−1.05
		(0.000)		(0.295)	(0.408)
Observations		34,753	348	34,753	34,753
Adjusted R^2		0.45	0.56	0.63	0.57[c]
AIC		369113.9	361227.3	362079.8	360003.4

Signif. Codes: <0.05'*' [a], < 0.01'**' [a], <0.001'***' [a].

[a] Adjustment for multiple comparisons: Bonferroni.

[b] Excluded due to scale of variable (only available at LAD level).

[c] Method for SEM pseudo-R^2: Nagelkerke.

Table 4 shows the model estimations for UK domestic PV adoption, with a Bonferroni correction applied to account for the effect of multiple comparisons on significance. The results suggest that domestic PV adopters live in detached, less densely distributed housing. This is in line with previous studies [22,24,109], given the accessibility advantages of detached houses for installation and maintenance [22]. LSOAs with greater area and more households show higher PV uptake, as would be expected. Conversely, areas of high household density have lower rates of PV adoption, likely impacted by a higher proportion of flats, which is of particular relevance in urban areas [75] (these urban 'cold spots' can be seen in Fig. 1, a map of small-scale PV (under 10 kW) in England and Wales). Depending on the lease agreement, the right to use roof space may not belong to occupants, or may be shared, limiting the viability of installing rooftop PV [113]. Shared ownership or 'collective prosumerism' [122] may be an interesting path to explore for further research.

The data suggest a higher share of retirees is a strong predictor of higher PV adoption. Increased time availability and higher overall and daytime electricity consumption may influence this group's decision to invest. A distinction is also present between older and younger workers, with 45- to 64-year-olds showing a greater propensity to install and 25- to 44-year-olds displaying a negative relationship. There are likely to be several factors involved here, such as disparities in accumulated wealth and limitations imposed by different stages of family life.

Skilled manual workers from the C2 social grade also invest in PV, suggesting technical knowledge and skills for installation and maintenance may be of importance. This challenges the findings of Bondio et al.

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[3] Model notation for spatial error model:$y = \beta x + \delta z + \eta a + \theta b + \nu \nu = pW\nu + \varepsilon$Again, this follows model 1, with the inclusion of p as an autoregressive coefficient, W as a matrix of spatially lagged errors using contiguity and ϵ as the unobserved error.

[116] that PV is a 'middle-class technology', although a more detailed study of social grade might be pertinent given the lack of attention received thus far. This relationship may be caused by cultural norms or place attachment [123], for example. The OLS suggests a positive effect for education level, but inclusion of spatial considerations alters this, showing a negative and no longer significant effect. As many of the other predictors show stability with the inclusion of spatial considerations, the influence of education here is difficult to discern. Households with larger numbers of occupants are more likely to have PV installed, providing further evidence that uptake of PV is influenced by social interaction. This may also be influenced by higher bills or the potential for greater daytime consumption. This is contrary to Balta-Ozkan et al. [22] who find a significant negative effect of household size, which they explain by identifying post-family households as the primary adopters of PV, a finding that correlates with the positive association of retirees. The effect found here may be explained by the limited capacity for those in younger age brackets to participate in residential PV, who may also inhabit smaller households. Individuals, groups of individuals such as young professionals, students, or flat-sharers, as well as younger couples all have barriers to installing PV. These range from rental tenancies, a lack of financial means, and other priorities (e.g young families, life events such as marriages, leisure preferences, etc). As summarised in section 3.0, mixed and varied conclusions have been found in previous analyses, and this is perhaps indicative of the broad range of groups engaging in PV.

Interestingly, house ownership has a negative association with PV uptake, and this is consistent with some previous studies [22,26]. This may seem counter-intuitive; as a long-term capital investment, PV seems to fit better with the longer-term occupancy patterns of homeowners and those who have the financial means to invest. However, the costs of mortgage repayments associated with a large proportion of homeownership may restrict disposable income [22,26], whilst higher incomes do not indicate higher available capital *per se*. Alternatively, it may indicate that those with higher incomes are less concerned about high electricity costs or may be an indicator of their environmental standpoint, although income is not found to be a significant predictor. Some measure of accumulated and available capital, including savings [124], may be an interesting alternative predictor. The effect of homeownership on PV uptake is certainly worth exploring in further depth, given the need for mobilising decarbonisation of owner-occupied homes, the largest tenure in the country. Further work could consider stratifying homeowners to understand if PV uptake differs across groups. For example, it seems reasonable that younger homeowners with substantial mortgages, lower incomes, and young families might have other financial priorities.

Alternative environmental- and energy-related behaviours including the use of solid fuel central heating and hybrid vehicles, show positive associations with PV uptake. LSOAs with higher proportions of solid fuel central heating, which can be a more accessible option for those without a gas grid connection and can be more affordable, have higher amounts of small-scale PV. PV is also an enabler of off-grid generation so may be attractive to those without these connections. There may also be an association between PV and newer forms of solid renewable fuels such as biomass for use in heating systems in low carbon dwellings, as these are often used in combination, particularly by early adopters [125]. Similarly, energy efficiency may be associated with self-generation in low carbon dwellings. Domestic energy efficiency ratings are found to have a positive effect on PV uptake, although this is expected as the FiT required dwellings to have an EPC rating of D or above [see [126] for some exclusions].

Alternative fuel car ownership is found to have mixed effects on PV adoption; contrary to Van Der Kam et al. [114], EV ownership is found to have a positive impact, although this result was not significant, whereas hybrid vehicles show a negative relationship (significant in OLS and multi-level model). EVs are a complementary technology to PV: they can enable greater self-consumption of electricity generated, reduce costs of personal transport, and have the potential to deliver future value propositions such as flexible storage and vehicle-to-grid for storage and demand response [87,127]. Uncertainty over the future direction of the UK's energy system and other socio-technical barriers [128, 129] may have stymied EV investment. Kufeoğlu and Pollitt [84] find that most EVs in Great Britain are charged at home, which could influence the economics of PV favourably, and suggest wider rollout of EVs could lead to cost reductions for all households. These innovations could be catalysts for one another in a broader system-shift, if the support is available.

Positive effects on PV uptake are also found in households with higher electricity consumption and high carbon dioxide emissions. Offsetting electricity use with self-generation is likely to offer an economic incentive, particularly to those with high demand [22]. The incentive is less clear in a post-FiT environment, although innovations in energy storage and supply tariffs may provide opportunities. High energy consumption is also linked to higher levels of domestic carbon dioxide emissions, and findings from the OLS suggest this may be linked to high PV adoption. Domestic PV capacity is also higher in those areas where local authorities have implemented SECAPs and are thus members of the Covenant of Mayors transnational municipal network. The existence of greater local authority action in climate and energy governance could be due to more enabling and supportive local policy, driven by demands of local people. This is a potentially important finding given widespread declaration of a 'climate emergency' at local, regional and national scales [16].

Reflecting on the model specification and fit, bias still exists in the model with heteroskedasticity present in the model residuals. Unmeasured or excluded factors may account for unexplained variance. For example, spatial influences at scales not considered may enable PV installation across regions. Mapping the multi-level model higher level residuals, representing the local authority districts, highlights several clusters (Fig. 2). Prominent clusters exist in the South West and East of England (Table 5). Observing local authority residuals is relevant in the context of local energy approaches, with heightened interest in council governance of energy and the increase in local activism. There could also be broader-scale spatial processes at work in these regions, such as the contribution of Local Enterprise Partnerships (LEPs) or energy-related partnerships. It may also be pertinent to consider cultural influences. These regional clusters could provide interesting case studies for more nuanced or detailed studies of local PV uptake.

6. Conclusion

Civic and local energy approaches, including individual ownership, offer an alternative to the centralised, top-down model of the current UK energy system, dominated by a few large energy companies. More locally appropriate and locally owned energy could lead to greater local value retention contributing to needs of local people. Development of local energy is particularly pertinent in a global energy market increasingly influenced by geopolitical forces beyond local and national boundaries. The subsequent increase in market uncertainty requires enhanced energy security to be a principal focus of future energy policy and localised approaches have a role in enhancing participation and increasing autonomy. PV is an accessible enabling technology for civic and local energy, allowing a wider set of actors to participate in energy generation. This study has tested the determinants of domestic PV using data related to the physical environment, socio-economic and demographic measures, indicators of housing, and environmental actions and behaviours. It provides further evidence that the uptake of small-scale PV has a strong spatial component, as found by several previous studies [22,28,108,109].

This study used a more fine-grained spatial scale than has been used before in the UK and many of the predictors used at broader spatial levels show similar effects at the local level. Predictors found to influence domestic PV uptake in previous studies in Europe and the USA, but not tested before in the UK context have been shown to have significant effects, including local authority involvement in climate and energy

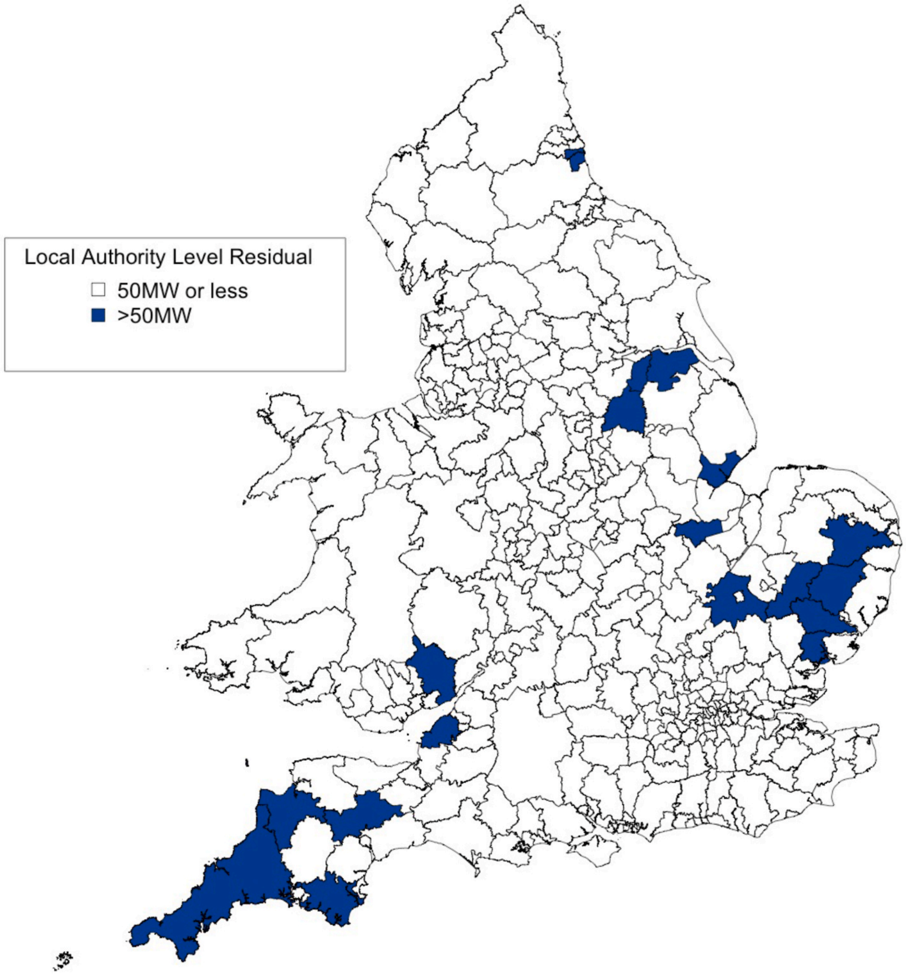

Fig. 2. Distribution of local authorities with largest domestic solar PV capacity after controlling for other explanatory factors (SD = 25.28).

Table 5
UK local authorities with residuals >50 MW (two standard deviations) at the Local Authority Level from OLS with local authority dummies and multilevel model. Scores are ranked based on multilevel model.

Local Authority	Region	Residuals at Local Authority Level (MW)			
		OLS w/dummy variables		Multilevel model	
		Residual	Rank	Residual	Rank
Peterborough	East of England	155.06	1	146.68	1
Mid Devon	South West	138.77	2	124.38	2
South Hams	South West	122.92	3	110.60	3
South Cambridgeshire	East of England	104.08	4	96.06	4
North Lincolnshire	Yorkshire & the Humber	103.74	5	84.63	5
Colchester	East of England	90.85	8	84.17	6
Torridge	South West	96.37	6	84.00	7
Boston	East Midlands	93.29	7	81.28	8
Bassetlaw	East Midlands	83.04	9	73.96	9
St Edmundsbury	East of England	73.61	10	64.96	10
Babergh	East of England	66.83	11	58.66	11
South Norfolk	East of England	64.95	13	57.38	12
Monmouthshire	Wales	65.95	12	56.81	13
Mid Suffolk	East of England	62.06	14	53.88	14
Cornwall	South West	55.42	16	53.09	15
Sunderland	North East	55.01	17	53.06	16
North Somerset	South West	58.95	15	52.71	17

governance, and associations with complementary technologies. Findings suggest that domestic PV installation at the LSOA level is positively associated with areas with lower housing density and detached houses, and areas with more retirees and skilled manual workers, suggesting time and skills as important factors. Average household size also has a significant positive effect, as described by Bollinger and Gillingham [108], as do the presence of solid fuel central heating, electric vehicle ownership, electricity consumption and carbon dioxide emissions. Homeownership shows a negative relationship with PV uptake, as [22,26] concluded. This could be explained by the need for accumulated and available capital to invest in PV, which is likely to be restricted by mortgage payments and other financial commitments, or by lower concern about costs of electricity by those with higher incomes.

Following the closure of the Feed-in Tariff on March 31, 2019, new PV owners are unable to access the financial incentives it provided. There is a need for a clearer outlook for the UK's domestic PV sector at all levels of governance, and a broader definition of priorities in the wider energy sector. It is hoped studies such as this one will provide some useful insight for future initiatives, ones that are more sensitive to geographical considerations of energy. For example, developing schemes that encourage uptake in the short-term might be best positioned in areas more open to adoption, allowing for a greater return on promotion in terms of installation rates. These might be where existing skills can be used, or by developing more systemic approaches that work in places that are more receptive to technological innovation. Further work might also be interested in refining the modelling procedure, better accounting for spatial effects, or including additional explanatory variables such as those related to planning.

Credit author statement

Samuel Collier: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft preparation, Writing – review & editing, Visualization, Project administration. Jo House.: Conceptualization, Supervision. Writing - Reviewing & Editing. Peter Connor: Conceptualization, Supervision. Writing - Reviewing & Editing. Richard Harris: Conceptualization, Methodology, Supervision. Writing - Reviewing & Editing.

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

Filtering process of FiT dataset

	Number of Installations	Accumulated Capacity (MW)
Stage 1: Domestic PV	819,760	2886.3
Stage 2: Domestic PV with LSOA or Postcode equivalent data in England and Wales	735,904	2621.4
Stage 3: Domestic PV with LSOA or Postcode equivalent data (10 kW and under)	726,322	2327.6

Appendix B

Included variables have been grouped into broad areas identified in section 3.2: i) physical environment; ii) socio-economic and demographic; iii) housing; and iv) environmental behaviour. Variable names are included in italics and brackets.

Physical Environment

Solar Irradiation (irradiation) is a measure of the sun's radiant energy reaching the Earth's surface. Yearly global horizontal irradiation (kWh/m^2) estimates were obtained from the European Commission's Joint Research Centre in raster format. Values for each LSOA were estimated as the mean of raster cells intersecting with the LSOA's polygon. Data are taken from 2014.

LSOA area (area) is used in the regression to counter the effects of disparities in LSOA size. As LSOAs are based on population and socio-demographic indicators, areas with lower population densities are likely to be defined by much larger LSOAs and are thus more likely to have more available space. LSOA areas are available from the 2011 England and Wales census in hectares.

Socio-economic and demographic indicators

Education (qual3) is measured as a proportion of population aged 16 and over with highest level of qualifications at level 3 or above (equivalent to A level, IB diploma and level 3 NVQ). These data are available from the 2011 census. Previous studies have identified degree-level education and higher as a predictor of PV uptake, however this variable displayed substantial collinearity with other variables, such as social grade and income. This study follows Balta-Ozkan et al. (2015) in its use of level 3 and higher.

Age is included in the model using three separate groups. 25to44 is the proportion of people aged between 25 and 44 years of age (inclusive), and 45to64 represents the proportion of those aged between 45 and 64 (inclusive). Proportion of retirees in the LSOA (retired) is used as a proxy for age and will be based on the proportion of population who are designated as retired, available from the 2011 England and Wales Census. This is used in place of an older age band (e.g. 65+) as retirement has been identified as an instigator of interest in solar PV (Reeves et al., 2017) and includes those who have retired earlier than the statutory age.

Income (logincome) data in England and Wales is available from the Office for National Statistics but lacks the fine-grained spatial resolution at the level of the study. As it has been identified as a predictor of interest for PV adoption, this study uses available MSOA estimates of median annual household income (£) for the financial year ending 2016 and applies them to all LSOAs within each MSOA. The natural logarithm of these data is used.

Social grade (c2) is also tested despite limited inclusion in existing literature. A common theme in local energy discussions is the requirement for local capacities including skills and knowledge (de Vries et al., 2016). The C2 social grade in the UK refers to skilled manual workers, individuals who may have technical skills and knowledge potentially applicable to PV. This will be tested using approximated number of C2 social grade persons as a proportion of 16- to 64-year olds. These data are also available through the 2011 census. Other social grades were excluded due to collinearity with other variables such as income and housing characteristics.

Housing

Number of households (hh) is used as existing studies have found a significant peer effect in the uptake of domestic solar PV. Larger numbers of households per LSOA might be expected to host greater capacity of PV. Household numbers are available from the 2011 census. Household density (loghhden) is a measure of number of households per hectare and is calculated by dividing the number of households in an LSOA by its area. The natural logarithm of these data is used. Household size (hhsize) represents the mean number of inhabitants per household within each LSOA and is calculated by dividing population data from the 2011 census by the number of households.

Detached houses (detach) refers to the proportion of detached houses in each LSOA. Owned houses (owned) refers to the proportion of houses within each LSOA that are owned outright or with a mortgage or loan. Again, these data are extracted from the 2011 Census.

Domestic energy efficiency (epcC) relates to the number of dwellings in each Energy Performance Certificate (EPC) band per LSOA. The variable epcC is the proportion of certificated dwellings per LSOA with a rating of C or above. This data was collated by the Department of Energy and Climate Change (DECC, 2015). The original data was produced to be representative at the regional level, not the LSOA level. Caution will be exercised when interpreting the effect of domestic energy efficiency due to potential bias associated with data collection and weighting for the LSOA level.

Solid fuel central heating (sfch) refers to the proportion of homes within each LSOA with solid fuel central heating, for example in houses not connected to the central gas grid. Central heating data is available through the 2011 Census at the LSOA level.

Environmental and energy actions and behaviours

EV ownership (EV) and hybrid electric vehicle ownership (hybrid) are counts of the number of electric vehicles and the number of hybrid electric vehicles owned within each LSOA. Data were accessed through the Department for Transport and includes all vehicle registrations up to the end of September 2018.

Carbon dioxide emissions per capita (perCO2) is a measure of annual domestic carbon dioxide emissions at the local authority level, measured in tonnes per capita. Methods for measuring emissions at a more localised level are limited, so data is not available for individual LSOAs. These data are available through BEIS (2018c) and shows estimates for emissions in 2016.

Domestic electricity consumption (medcons) is represented by median consumption of electricity by LSOA in kilowatt hours (kWh). This is calculated by dividing the total domestic electricity consumption by the number of domestic electricity meters in each LSOA. These data are from 2017 and are available from BEIS (2018d).

A final political variable (secap) will be used to signify whether the local authority has developed a Sustainable Energy and Climate Action Plan (SECAP) as a requirement of membership to the Covenant of Mayors. Membership of a similar organisation was tested by Kwan (2012), though without conclusive results. This variable is binary, with a value of 1 assigned to LSOAs in local authorities with SECAPs, and a value of 0 to those in local authorities without SECAPs.

Appendix C. List of variables removed from study

Population.
Population density.
Unemployment rate.
Share of constituency green votes.
Urban/Rural designation.
Flats.
Mean Age.
Single.
Married.
House Price.
Fuel poverty – only England.
IMD.

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