Supporting Solar: The Causal Impact of Subsidies on Domestic Photovoltaic Installations

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Abstract

This study investigates the causal effects of the 2017 Home Energy Scotland Loan (HESL) scheme on domestic solar photovoltaic (PV) installations in Scotland, using a matching with difference-in-differences strategy and exploiting the decentralized nature of the renewables support policy between Scotland and England. Leveraging administrative data encompassing all domestic solar photovoltaic installations in the UK, we find that the HESL mitigated the decline in PV installations post-UK-wide renewable support cuts. However, the policy led to a reduction in the average size of PV installations in Scotland. Distributional analysis suggests increased installations in areas with the lowest and highest property values, indicating potential success in promoting equitable access to renewable energy. Overall, our study highlights the intricate balancing act and the need for comprehensive assessments on the impacts of decarbonization policy instruments on multiple socioeconomic outcomes.

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1 Introduction

Microgeneration technologies such as solar photovoltaic panels are expected to play a key role in tackling climate change and ensuring energy security across the globe. They are also seen as a way for firms and households to lower their electricity bills and CO_2 emissions, while also easing the burden on the distribution grids. Projections show that by maintaining current installations rates, the number of households relying on rooftop solar PV will grow from 25 million in 2021 to more than 100 million by 2030 (IEA, 2021). Public support schemes are generally found to increase distributed PV deployment (e.g. Hughes and Podolefsky (2015); Borenstein (2017); Ros and Sai (2023) in the US, Best et al. (2021) in Australia and Feger et al. (2022); Sendstad et al. (2022) in Europe), at the same time, studies also highlight that policies tend to benefit higher income households (e.g. Borenstein, 2017; Best et al., 2021). This is important because perceived fairness is an important determinant of public support for such policies (Huber et al., 2020; Bergquist et al., 2022), without which policies may be short lived.

Indeed, the recent literature documents a growing acknowledgment that assessing the impact of decarbonization policies requires navigating complex trade-offs among diverse socioeconomic and technical outcomes (Peñasco et al., 2021; Deng et al., 2017). In the case of renewables support policies, for example, key measures of success may include environmental benefit in the form of CO_2 reductions, as well as cost effectiveness, innovation outcomes, distributional outcomes and competition outcomes. There is increasing interest in understanding how trade-offs between these outcomes can be reduced or managed through the design of specific policies and the overall policy mix (Hoppe et al., 2023). Few studies to date, however, have been able to provide a comprehensive causal analysis of environmental programs to shed light on multiple outcomes and the trade-offs between them.

This paper contributes to the literature by empirically examining the impact of the Home Energy Scotland Loan Scheme (HESL). At a time when UK-wide government support for green projects was declining, this Scottish policy was introduced in 2017 to provide interest-free loans to homeowners to install domestic microgeneration and energy efficiency upgrades, including solar PV. We assess the effect of the policy on multiple dimensions including PV installation and system characteristics, and ask which households primarily benefited from the policy. By simultaneously obtaining robust estimates on multiple outcomes, we explore the evidence on the link between policy design and trade-offs or co-benefits.

To identify causal effects of the HESL, we exploit the devolved nature of renewable energy support policy in the UK, which enables us to compare outcomes in Scotland with those in England, where no policy similar to the HESL exists. We use two quasi-experimental research designs. First, our main empirical strategy combines difference-in-differences with cardinality matching (Visconti and Zubizarreta, 2018) to compare outcomes between similar Scottish and English locales. Second, we test the robustness of this approach with a regression discontinuity (RD) design that exploits the discontinuity in policy eligibility at the border between Scotland and England. The two methods complement each other by addressing different types of potential selection biases, and by providing different types of treatment estimates. In both approaches, we exploit the variation caused by the eligibility being restricted to Scottish households.

We use detailed administrative data from the Microgeneration Certification Scheme (MCS)'s Installation Database, covering 1.52 million domestic renewable installations in the UK from 2008, 83.5% of which are solar PV systems. The latter represents the universe of UK domestic solar PV installations. This rich dataset includes information on installed capacity, estimated annual generation, product reference and manufacturer, installation cost, as well as the postcode of each installation. We combine the MCS database with data on several important drivers of solar PV adoption, including local solar energy potential from the World Bank Global Solar Atlas, and the share of Green Party votes in the European Parliamentary Election in 2014 at the local authority level, which we use as an indicator for households' green preferences. To enable our analysis of the distributional impacts of the policy, we use house price data from HM Land Registry and Registries of Scotland to construct a localised indicator of property value; we show that this indicator is a good proxy for localized household income, which is not available at disaggregated level for England.

Our empirical analysis delivers a rich set of results. First, on the first order effects of the policy on PV installation, we document a statistically significant increase in domestic solar photovoltaic installations in Scotland by around 1 installation per 1000 inhabitants following the implementation of HESL. This finding suggests that the HESL played a pivotal role in averting the decline in PV installations following substantial cuts in UK-wide support for renewable generation. Second, we uncover the novel finding that the scheme affected the installed system size. When we repeat the difference-in-difference analysis on a split sample that separates large and small installations, we find that the entirety of the policy impact has been concentrated on very small installations with estimated annual generation below 1,700 kWh. Relatedly, the distribution of installation costs in Scotland diverged significantly from England after the introduction of the HESL, with a notable shift towards relatively low cost installations in Scotland.

Next, we ask which households benefited from the scheme. Resonating with the solar adoption inequality literature (e.g. Darghouth et al., 2022), descriptive analysis suggests that solar PV installations are regressively distributed across Lower Layer Super Output Areas (LSOAs) in Scotland

and England, and became more so during our sample period. However, this increase in inequality was stronger in England than in Scotland. We employ our cardinality matching with difference-in-differences strategy to assess whether the HESL scheme played a causal role in these distributional changes. We find that installations increased in Scotland across all deciles of the LSOA property value distribution due to the policy, but that these impacts were strongest at the lower and upper deciles of the distribution. The point estimates suggest that the poorest and wealthiest Scottish LSOAs saw between 2 and 3 additional installations compared to similar LSOAs in the same decile in England, while Scottish LSOAs in the middle of the wealth distribution saw between 1 and 2 additional installations compared their matched counterparts in England. These distributional effects of the Scottish policy appears to be more nuanced than findings from analyses of other solar PV policies.

This paper contributes to several related literatures. Studies evaluating policies that incentivize solar PV adoption, generally found that these policies are quite effective in increasing adoption. For example, ex-post evaluations of financial incentives for residential solar adoption in California (Hughes and Podolefsky, 2015; Borenstein, 2017), Connecticut (Gillingham and Tsvetanov, 2019), the US (Ros and Sai, 2023), Belgium (De Groote and Verboven, 2019), and Germany (Germeshausen, 2018) suggest that households respond strongly to these policies. Nevertheless, numerous studies find that solar PV adoption is highest amongst high-income households (Barbose et al., 2020; Best and Chareunsy, 2022; Bollinger and Gillingham, 2012; Borenstein, 2017; De Groote et al., 2016; Hansen et al., 2022; Jacksohn et al., 2019; Lukanov and Krieger, 2019; O'Shaughnessy et al., 2021). In the UK specifically, Grover and Daniels (2017) find that benefits of the Feed-in-Tariff (FiT) scheme were unequally distributed across households and that high socio-economic status households benefited most from the policy. This paper is amongst the first to evaluate the impact of Home Energy Scotland's Loan & Grant Scheme on solar PV adoptions, contributing evidence on the impact of upfront subsidies on solar PV adoption as well as how the benefits of this policy are distributed across the wealth distribution.

This paper also relates to the literature that compares different policy designs for incentivizing residential solar PV uptake. A common comparison in this literature is upfront subsidies paid when the household installs solar PV versus subsidies paid as the household's PV system generates electricity. For example, Taveli (2022) and De Groote and Verboven (2019) use data from the UK and Belgium respectively and find that policies that pay households upfront rather than delayed payments would be more cost effective. Burr (2016) finds that in California delayed payments based on production would be more efficient but upfront subsidies encourage more adoption. Feger et al. (2022) use data from Switzerland and a model that includes electricity consumption; they find that marginal prices for electricity are more efficient and progressive than upfront subsidies for solar PV installation. This paper evaluates ex-post the impact of the addition of an upfront subsidy in a context in which a subsidy for generation (the FiT scheme) was already present, providing insight into the role of upfront subsidies amongst a broader package of policies supporting solar PV adoption.

2 Policy context

In April 2022, the UK government published the British Energy Security Strategy, which set a goal to increase solar energy capacity in the UK from 14 GW to 70 GW by 2035.[1] The March 2023 Energy Security Plan reiterated this goal and highlighted the important role of small-scale rooftop solar in meeting this target.[2] Various policies to support household adoption of solar PV exist at the levels of both the UK and the devolved governments. The main UK-wide policy during our sample period is the Feed-in-Tariff (FiT) scheme, which ran from April 2010 to March 2019. Under the FiT scheme, installations of solar PV systems (and other renewable technology systems such as wind turbines) of up to 5 MW capacity could receive a subsidy on every kWh generated for a period of 20-25 years.[3] On top of this subsidy for generation, participants receive an additional subsidy for every excess kWh exported back to the National Grid. In addition to these subsidies paid as household solar PV systems generate electricity, a few policy schemes aim to help households with the upfront costs of installing a solar PV system. Most of these schemes, such as the Energy Company Obligation (ECO) launched in 2013 in England, Scotland, and Wales, and the Warmer Homes Scotland (WHS) scheme launched in 2015, target low-income, energy poor households and are therefore not accessible to all households.[4]

In 2017, this policy landscape changed when the Scottish government introduced the Home Energy Scotland Loan (HESL) scheme.[5] This scheme is available to all homeowners and private landlords, and does not specifically target low-income and or fuel-poor households, thereby greatly expanding eligibility for support for solar PV adoption beyond WHS and other existing schemes. Under this scheme, households can receive interest free loans for energy efficiency improvements and renewable technology installations such as solar PV. Initially, the maximum loan amount that participants could receive for solar PV systems was £2,500, but this cap increased to £5,000 in May 2018 and then £6,000 in December 2022. In December 2022 grant funding was also added to this scheme: if solar PV was installed as part of a package of measures, £1,250 of the £6,000 maximum loan was available as a grant. In June 2023, the scheme changed again and now solar PV is only eligible for the funding if it is installed as part of a package of measures that includes a heating and

[1] The April 2022 British Energy Security Strategy is available here.
[2] The March 2023 Energy Security Plan is available here.
[3] Initially FiT contract lengths were 25 years; in 2012 the government reduced the contract length to 20 years.
[4] These schemes also focus much more on energy efficiency and heating rather than solar PV. See the appendix for more details on these means-tested schemes.
[5] For more information on the HESL scheme, see the Home Energy Scotland webpage here.

energy storage system. Our study focuses on the period from 2017 to 2021, during which solar PV was eligible for funding on its own.

An important contextual aspect the HESL scheme in Scotland is that it was introduced against the backdrop of declining UK-wide support for household solar PV under the FiT scheme.[6] Besides an annual inflation adjustment in line with the Retail Price Index, the tariff rates that FiT scheme participants receive remain fixed for the duration of their contract. However, the tariff rates offered to new installations were subject to change each quarter. In particular, the generation tariff decreased substantially over the course of the scheme, from 41.3 pence per kWh in April 2010 to 3.79 pence per kWh in January 2019.[7] Panel A of Figure 1 illustrates this decrease in the generation tariff rate over time, as well as a relatively modest increase in the export tariff during this period. The adjacent Panel B shows that this decrease roughly tracks with a decrease in installation costs over this period (as observed in the MCS data). Accordingly, despite the decrease in expected annual net revenue from the scheme (shown in Panel C), solar PV remained a profitable investment by the end of the FiT scheme. Panel D illustrates the expected number of years until the initial investment costs of a 4 kWh system is paid back by FiT scheme revenue and electricity cost savings. This payback time increased over time, meaning that profitability decreased as policy support waned, despite the decline in installation costs. However, in 2018 the expected payback time remained less than the 20 year FiT contract length both in Highland and Eastbourne, which have the least and most solar potential amongst all Local Authorities in the UK.

The FiT scheme closed in March 2019, and after a brief period of no UK-wide subsidy scheme to support small-scale solar PV generation, the UK government introduced the Smart Export Guarantee (SEG) in January 2020.[8] The SEG provides a subsidy for each kWh exported back to the grid, but unlike the FiT scheme it does not include a subsidy on generation. Another key difference from the FiT scheme is that SEG tariff rates and contract lengths are set by energy suppliers rather than the UK government. Under the SEG scheme, large electricity suppliers[9] in the UK are required to offer at least one tariff rate. Households are not eligible for SEG payments if they already receive payments under a FiT scheme contract. As of November 2023, SEG tariff rates offered by UK energy suppliers range from 1.0 to 16.5 pence per kWh.[10]. More recently, in April 2022 the UK government introduced a zero-rate of VAT for solar panels, which runs until 2027. Overall, while some UK-wide

[6]For more information on the FiT scheme, see Ofgem FiT Guidance here and Ofgem FiT FAQ here

[7]In 2016, the UK government introduced deployment caps, which limited the total capacity of new installations that could receive a given tariff rate in a given quarterly period. If the deployment cap was reached within the period, then tariff rates were reduced by 10% in the subsequent period. For historic data on the FiT scheme tariff rates see this webpage

[8]For more information on the SEG see the Ofgem webpage here

[9]Those with at least 150,000 domestic electricity customers

[10]Current SEG tariff rates are summarised by Solar Energy UK on this webpage

support for household solar PV adoption remains, this support has definitely declined since the early years of the FiT scheme, and with the addition of the HESL scheme households in Scotland have access to more public funding for solar PV systems than households in England.

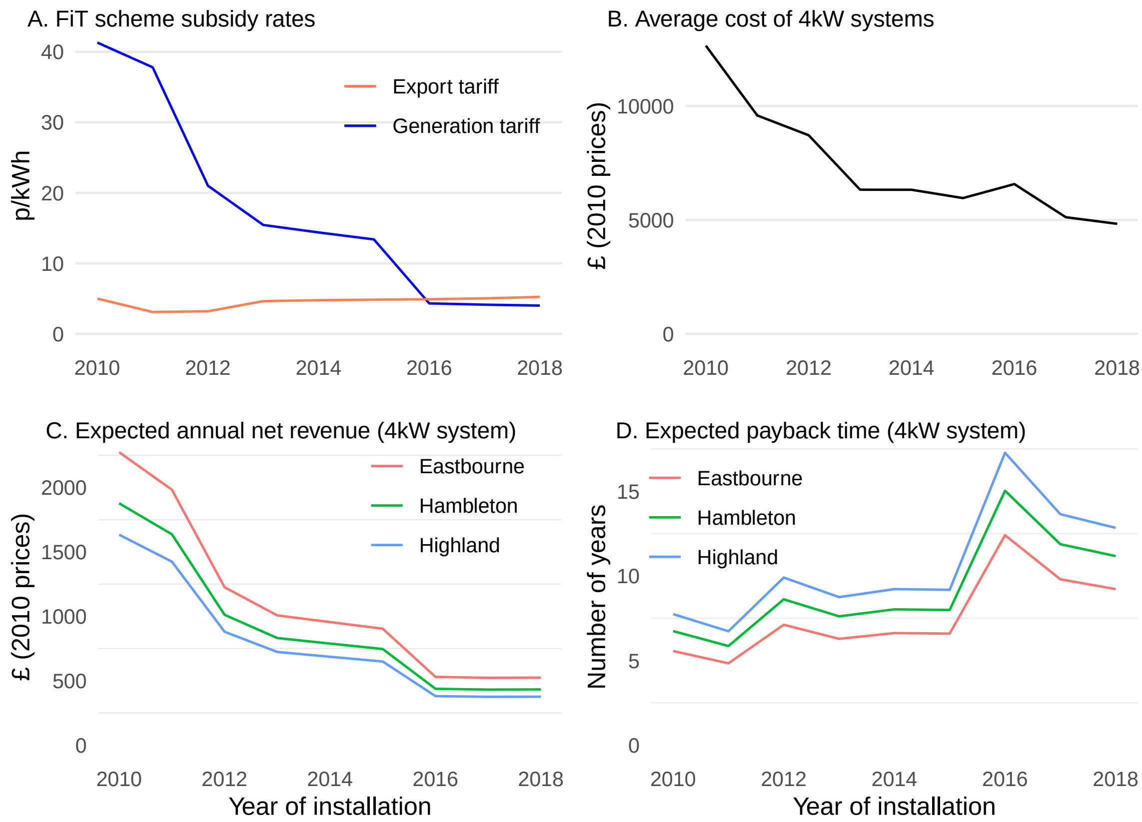
Although the UK policy landscape for domestic solar PV is somewhat complex, a salient feature that we exploit in our analysis is that while the FiT and SEG schemes operate in both England and Scotland, no scheme similar to Scotland's HESL exists in England. Our empirical strategy exploits this devolved nature of policy support for solar PV in the UK. The bolstering of policy support for domestic solar PV under the HESL scheme in Scotland occurred against the backdrop of declining policy support under the UK-wide FiT scheme and decreasing costs of solar PV systems. By comparing outcomes in England versus Scotland before and after the HESL scheme launched, we uncover the impact of continued versus declining policy support as the market for domestic solar PV matured. As noted, some low-income, energy-poor households in England may have had access to policy support via the ECO scheme (although funding for solar PV under this scheme seems to have been limited), so strictly-speaking our quasi-experimental setting identifies the impact of the HESL scheme on middle- and high-income households in Scotland versus England.

3 Data and Descriptive Facts

The Microgeneration Certification Scheme (MCS) creates and maintains standards for the certification of products, installers and installations in the UK domestic renewable energy sector. Obtaining MCS certification is necessary for households to be eligible for government support, including both the UK-wide FiT scheme subsidies (Ofgem, 2023) and Scotland's HESL scheme (Home Energy Scotland, 2022). The certification process occurs at the installer and product levels; each installer must be certified to be able to install certified products, the combination of which yields a certified installation. The MCS Installations Database is a centralized and comprehensive database of all such products, installers and installations across the UK, which we analyse in the present paper.

The MCS Installation Database covers 1.52 million domestic renewable installations from 2008 onwards, 83.5% of which are solar photovoltaic (PV) systems. Given the certification requirements to benefit from renewable subsidies, we believe these observations to encompass the universe of domestic solar PV installations. This rich dataset includes detailed information about each installation including the total capacity, estimated annual generation, product reference and manufacturer information, as well as near-comprehensive coverage of the postcode of each installation. Furthermore, the total cost of installation is reported for 48% of all installations on average across the sample period, with coverage increasing to almost 100% by the end of the sample period.

Figure 1: Expected profitability of a 4kW solar PV system under the FiT scheme

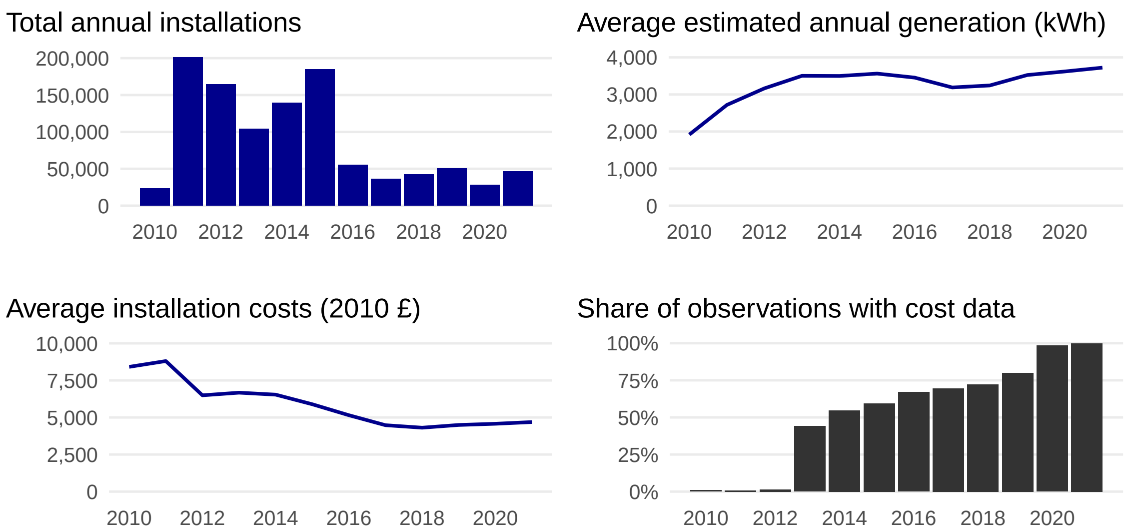


Notes: Panel A illustrates the FiT scheme tariff rates offered to installations with an eligibility date in Q1 of the financial year. These values are in contemporaneous prices. Panel B is shows the average cost of 4kW installations from the MCS installations database (deflated to 2010 prices using the UK retail price index (RPI)). Panels C and D illustrate the range of profitability of a 4kW PV system under the FiT scheme for 3 representative LADs. Highland in Scotland and has the lowest solar potential in the UK; Hambleton in the North East of England is in the matched sample and has a low- to mid-range solar potential relative to the rest of the UK; Eastbourne in the South East has the highest solar potential in the UK but is not in our matched sample. The expected annual net revenue comes from FiT scheme payments, electricity savings (calculated using data on electricity prices from BEIS) and assumed annual operating costs of £70. We assume that the household exports 50% of generation back to the grid. Annual net revenue is deflated to 2010 prices using the RPI.

Figure 2 illustrates the evolution of installation numbers, sizes, and costs of domestic solar PV installations in the UK from 2010 to 2021. While the average size of installations has remained relatively steady at around 3.5 kW estimated annual generation since 2012, the number of installations dropped significantly from around 185,000 in 2015 to around 55,000 in 2016. This drop in installations corresponds to a sharp decrease in the FiT rate between 2015 and 2016 (as shown in panel A of Figure 1). Meanwhile, the average overall costs of installations decreased over the sample period, particularly between 2011 and 2016.

We also obtain historical data on MCS-certified installers, which covers 16,722 unique domestic renewable installation companies that have MCS-certification for at least one year during the period from 2010 to 2023 Q3. This database includes the name of each company and their MCS certificate number, the start and end date of their MCS certification, and the postcode at which the company is registered. Using the company name, we can link this database to specific installations in the MCS installations database. 42% of MCS-certified installers never perform a single installation in the MCS Installations Database, and of the 9,752 installers that have ever been active, in 2023 (up to Q3) only 3,500 are active in the installations database, which suggests a high degree of turnover in the domestic renewables market. 7,502 firms perform at least one solar PV installation. To understand the degree of competition in local markets for domestic solar PV installations, we compute the Herfindahl-Hirschman Index (HHI) across installations at the Local Authority District (LAD) level. Figure B.5 illustrates the distribution of HHI across LADs, which suggests that a high degree of competition exists in these markets.

Figure 2: Evolution of UK domestic solar PV installations, 2010-2021



Notes: These plots illustrate summary statistics for solar PV installations in the MCS Installations Database from 2010 to 2021. Installation costs are considered missing if they are recorded as zero or if they are an outlier (above the 0.1% percentile of observations). Costs are deflated to 2010 prices using the Retail Price Index (RPI).

Our empirical strategy to estimate the impact of Scotland's HESL scheme compares installations in Scotland versus England. Accordingly, Table 1 summarises the average cost and size of installations for the full sample as well as individually for England and Scotland. Unsurprisingly given the vastly different population sizes of the two nations, the number of solar PV installations in Scotland is much smaller than the number of installations in England. Nevertheless, installations per capita are slightly higher in Scotland (17 installations per 1000 people) compared to England (15 per 1000 people). Moreover, installations in Scotland are slightly smaller and cheaper on average

Table 1: Summary statistics for UK domestic solar PV installations, 2010-2021

	Full sample	England	Scotland
Number of installations	1,076,072	865,540	94,854
Installations per 1000 people	16	15	17
Installation Costs (2010 £)			
Mean	5,512	5,725	3,952
Std. Dev.	5696.9	5790.1	4953.1
Share missing	0.59	0.62	0.42
Estimated Annual Generation (kWh)			
Mean	3,270	3,295	2,777
Std. Dev.	4551.7	4592.6	4117.6
Share missing	0	0	0

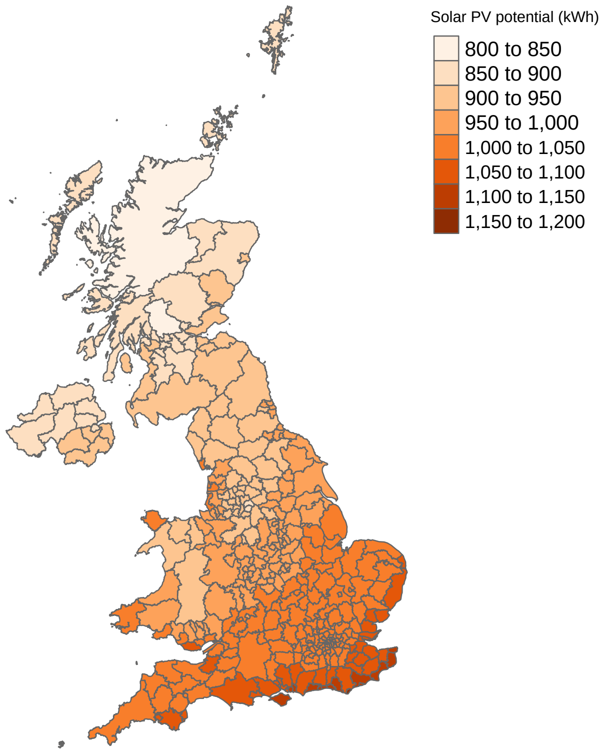
Notes: Installations per 1000 people are calculated based on 2021 populations. Installation costs are considered missing if they are recorded as zero or if they are an outlier (above the 0.1% percentile of observations). Costs are deflated to 2010 prices using the Retail Price Index (RPI).

than installations in England. The average estimated annual generation is 3.3 MWh for installations in England and 2.8 MWh for those in Scotland.

As discussed further below, we employ a matching strategy across localities in Scotland and England to ensure that we compare localities in which households have a similar propensity to install solar PV. To enable this matching, we collect data at the Local Authority District (LAD) level for several variables that are likely to be associated with solar PV adoption. First, we use data from the World Bank Global Solar Atlas to compute the average solar energy potential in each LAD, illustrated in Figure 3. Next, we collect LAD-level data on population, population density, gross household disposable income per capita, and home ownership rates from the Office for National Statistics (ONS). Finally, to proxy for green preferences we use the Green Party share of votes within each local authority council in the 2014 European Parliamentary Election; these data are from the UK Electoral Commission.

Finally, for our distributional analysis of the impacts of Scotland's HESL scheme we collect real estate transaction data. Granular income data is not readily available for the UK; while it is possible to obtain income estimates for Scotland at the Lower Layer Super Output Area (LSOA) level, which groups approximately 650 households on average, for England these estimates are only available at the Middle Layer Super Output Area (MSOA) level, which encompasses an average of 3,000 households. Instead, we collect real estate transaction data from the HM Land Registry in England and the Registries of Scotland, providing more than six million transactions from 1996 to 2016. A benefit of this approach is that property values provide a measure of household wealth, which is a good instrument for households' permanent income. Using these real estate transactions data, we construct an index of property sale prices in each LSOA across both England and Scotland, including transactions completed in the five years prior to the HESL enactment (2012 to 2016). Figure D.1 verifies that this index correlates very well with household income in Scotland, which is available at the LSOA level.

Figure 3: Solar energy potential by UK Local Authority District (LAD)



Notes: Data from the World Bank Global Solar Atlas

4 Identification and Methodology

4.1 Empirical design

We aim to identify the causal impact of complementary policies supporting domestic solar PV installations in the United Kingdom. While the Feed-in-Tariff was applied uniformly across the UK over our period of interest, the design and implementation of complementary support policies for solar PV was devolved to the national governments within the UK. For example, our policy of interest, the Home Energy Scotland Loan, was only available to Scottish residents and did not have contemporary equivalent in England, Wales, or Northern Ireland. Our empirical strategy exploits this policy variation across nations composing the UK.

More specifically, we employ a difference-in-difference (DiD) framework that compares outcomes in Scotland versus England before versus after the HES Loan was introduced. The validity of this setup to identify the impact of the HES Loan on solar PV adoptions rests heavily on whether the parallel trends assumption is satisfied: in other words, whether English localities are a good counterfactual for Scottish localities in terms of the propensity of households to install solar PV. However, for key variables associated with solar PV adoption, such as solar potential and household income, we expect that the typical English locality is quite different than the typical Scottish locality. Indeed, Figure 4 illustrates that the distribution across Local Authority Districts (LADs) of variables such as household income, population density, and solar PV potential differ notably in England versus Scotland. A naive DiD setup that pools together and compares all Scottish versus all English LADs therefore likely violates the parallel trends assumption.

To tackle this difficulty, we combine our DiD framework with a matching strategy to obtain a subsample of English and Scottish localities for which parallel trends is a plausible assumption. We match at the LAD level using 2019 borders, which encompass 383 local authority districts across the UK, including 32 council areas in Scotland. We match on variables known to influence domestic solar PV adoption: solar PV production potential; household income; population density; and green preferences. We discuss the details of implementing this matching strategy further below, but first we highlight several stylised facts on household solar PV adoption that underscore the need to identify comparable units from within Scottish and English LADs and justify our choice of matching variables.

First, solar PV installations predominantly occur in rural local authority districts with low population density in both England and Scotland (see Figure B.1). This finding is expected given the higher prevalence in rural areas of detached houses which make solar PV installation relatively easy. Second, contrary to previous findings reported in California, in particular (Borenstein, 2017), we find that installations do not concentrate among top income deciles but rather in the middle of the income distribution (see Figure B.2). Third, as expected household solar PV installations are more frequent in areas with greater solar potential. Finally, domestic solar PV installation decisions are known to be influenced by households' pre-existing green preferences (Graziano and Gillingham, 2015). To measure these preferences, we obtain the share of votes for the Green Party in the 2014 European Parliamentary Election within each local authority council (see Figure B.4). This approach provides a more continuous measure of environmental preferences compared to alternatives such as the prevalence of Green Party members in local authority councils, which yields a great number of zeros.

Figure 4: Overlap in the distribution of key covariates between England and Scotland (2010-2016)

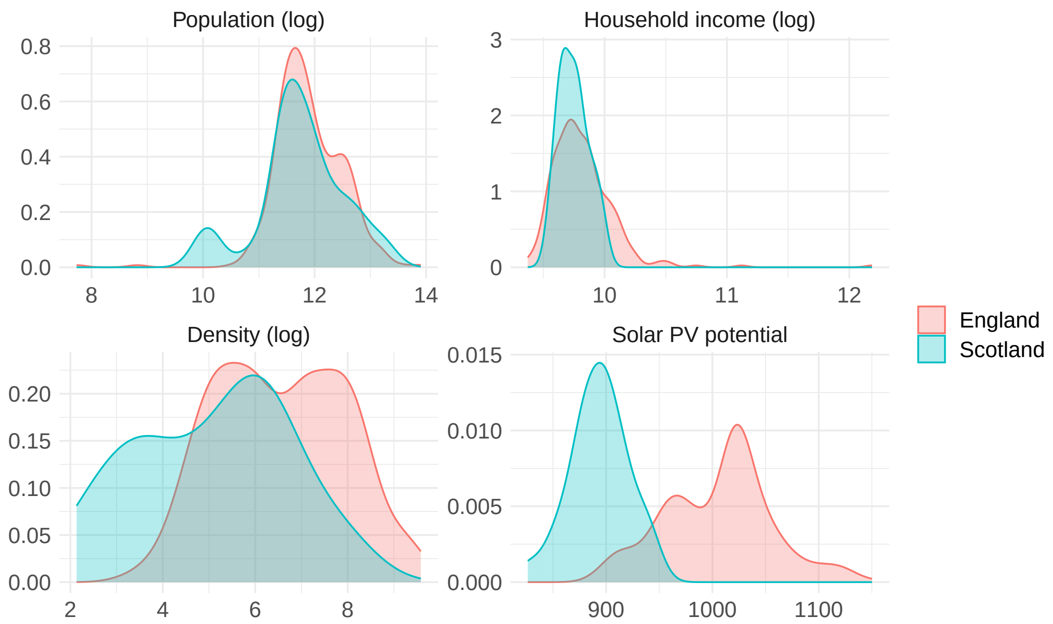


Figure 4 presents the respective English and Scottish distributions for the main covariates used to implement our matching strategy. Crucially, despite some notable differences between the Scottish and English distributions, we consistently observe a significant degree of overlap, which ensures the feasiblity of obtaining a subsample of Scottish and English LADs that are similar in terms of these covariates. However, this overlap is most limited in the case of solar PV potential. In the following subsection we address the challenge of overcoming this constraint.

4.2 Cardinality matching

The limited degree of overlap between the English and Scottish distributions in solar potential raises a significant challenge in implementing a matching strategy within our context. Unsurprisingly, the level of sunshine experienced across local authority districts in England and Scotland can vary considerably: southern England and northern Scotland, in particular, exhibit stark differences, with an average solar PV potential of 1,150 kWh per square metre in the sunniest areas of southern England compared to a mere 850 in the northern-most reaches of Scotland.

As a consequence, overlap in solar PV potential between Scottish and English LADs is predominantly observed for LADs located within a limited distance to the border. Traditional matching approaches, such as propensity score matching – including coarsened versions – prove insufficient to address this issue. As illustrated in the Appendix, these methods fail to achieve a satisfactory level of balance among covariates between English and Scottish LADs, particularly with regard to solar

PV potential.

To tackle this problem, we employ cardinality matching (Visconti and Zubizarreta, 2018). This method seeks to identify the largest subset of treatment and control units that satisfy a specified level of tolerance concerning covariate balance. In our case, we strive to find the most substantial subset of local authority districts in Scotland and England that achieve a certain degree of matching, signified by the absolute mean standardised difference between the English and Scottish subsets across all covariates. Considering the set of Scottish (treated) LADs $\mathcal{T}$, the set English (control) LADs $\mathcal{C}$ and a threshold ε the matching problem can be formulated as follows:

$$
\begin{aligned}
\max_{\mathcal{T},\mathcal{C}} & \sum_{t\in\mathcal{T}} \mathbf{1}_t + \sum_{c\in\mathcal{C}} \mathbf{1}_c \\
\text{s.t.} & \sum_{t\in\mathcal{T}} \mathbf{1}_t = \sum_{c\in\mathcal{C}} \mathbf{1}_c, \\
& \left| \frac{\sum_{t\in\mathcal{T}} \mathbf{1}_t x_{tp}}{\sum_{t\in\mathcal{T}}} - \frac{\sum_{c\in\mathcal{C}} \mathbf{1}_c x_{cp}}{\sum_{c\in\mathcal{C}}} \right| < \varepsilon
\end{aligned}
$$

In this particular specification, we aim to obtain the largest subset of English and Scottish LADs that minimize their absolute mean difference for each covariate x_p. In our implementation, we impose of $\varepsilon = 0.2$ to ensure standardised absolute mean differences are less than 0.2.

Figure 5: Covariate balance across matched LADs

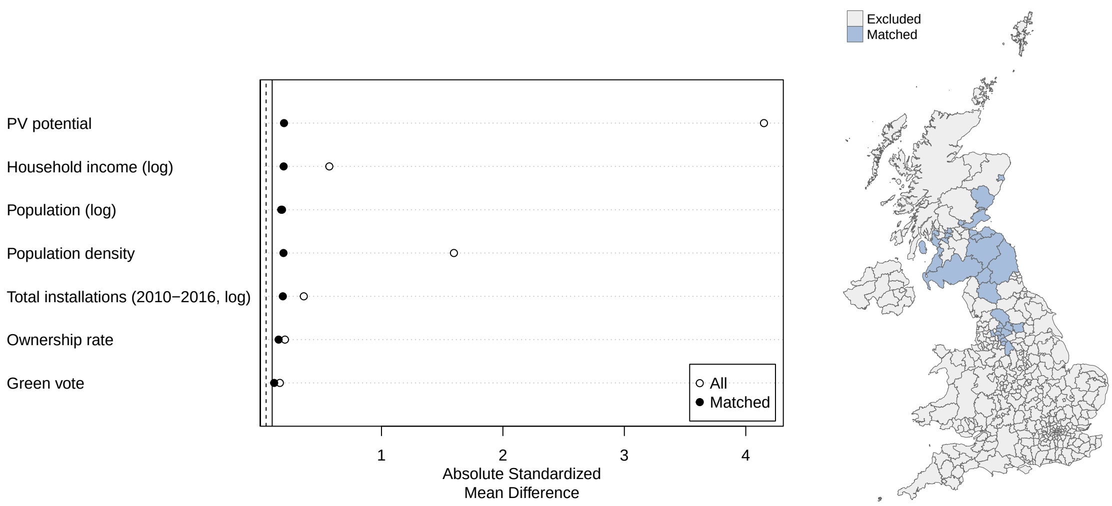


Figure 5 presents the results of this matching procedure. As discussed above, we match on solar potential, household income, total population, and share of vote for the Green Party in the 2014 European Parliamentary Election. We further include population density to account for the higher prevalence of domestic solar PV installations in rural areas (Balta-Ozkan et al., 2015). We also match on total solar PV installations completed over 2010-2016 to account for potential peer effects (Bollinger and Gillingham, 2012; Graziano and Gillingham, 2015; Carattini et al., 2022; Balta-Ozkan et al., 2021; Rode and Müller, 2021) and installer market structure – a lower number of installations prior to the implementation of the policy might indicate a dearth of installers. Finally, we also include home ownership rate, since the Home Energy Scotland Loan is only accessible to homeowners. Table 3 compares covariate balance in our full versus matched sample of LADs, further illustrating that the matching procedure notably reduces the average differences between English versus Scottish LADs. Within our matched sample, the standardised absolute mean differences between Scottish versus English LADs across covariates range between 0.03 and 0.20, with a mean of 0.09, well within the threshold recommended by Rosenbaum and Rubin (1985). Our matched subsample comprises of 32 LADs, 16 each in Scotland and England.

We then estimate the following specification on our sample of matched LADs:

$$Y_{it} = \alpha + \beta \mathbb{1}_i^{\text{HESL}} t + \gamma X_{it} + \epsilon_{it} \tag{1}$$

where Y_i represents the outcome variable for LAD i at time t; $\mathbb{1}^{\text{HESL}}$ is a binary indicator variable equalling 1 if the LAD is located Scotland after May 2017 (and therefore exposed to the HES Loan) and 0 otherwise; X_i denotes the additional control variables; and ϵ_{it} is the error term, clustered at the LAD level. Our primary coefficient of interest, β, captures the causal impact of the HES Loan under the condition that the parallel trends assumption holds within our matched sample. Since our analysis discards some UK LADs and focuses on a subsample to ensure a strong match quality, this estimate represents the average treatment effect on the matched sample (ATM) rather than the average treatment effect (ATE) on the population of interest (UK LADs). However, given the likely issues discussed above with a naive comparison of all English LADs with all Scottish LADs, this compromise between the ATM versus the ATE is necessary to ensure a robust causal estimate.

5 Results

5.1 Main results

We find that the Home Energy Scotland Loan has had a positive and statistically significant impact on the number of domestic solar PV installations in Scotland. Table 2 presents the results from estimating our difference-in-difference specification (Equation 1) on our matched sample of local authority districts. Each column adds an additional control variable to the specification. The estimated effect of the HES Loan is robust to the inclusion of these covariates, ranging between 0.9

and 1.0 additional installation per 1000 inhabitants. Notably, the coefficient estimates for covariates across specifications are not statistically different, emphasising the quality of the covariate balance achieved through the cardinality matching procedure. In our preferred specification (column 5), no covariate is significant at the 5% level, further highlighting the balance quality within our matched sample.

Table 2: Main results

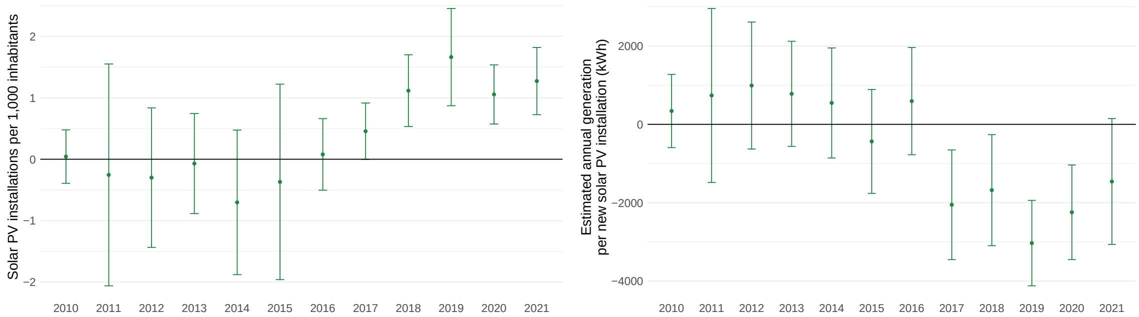
	(1)	(2)	(3)	(4)	(5)
Scotland HEL	**0.900*** **	**0.917*** **	**0.974*** **	**0.974*** **	**0.997*** **
	(0.184)	(0.191)	(0.187)	(0.185)	(0.178)
Solar PV potential	-0.492	4.673	9.544	10.736	12.970*
	(5.106)	(7.792)	(7.710)	(8.221)	(7.553)
Household income (log)		-0.325	-0.925**	-1.097*	-0.946
		(0.286)	(0.372)	(0.553)	(0.621)
Population (log)			-0.354**	-0.401**	-0.349
			(0.134)	(0.194)	(0.209)
Green Party vote				2.584	2.595
				(4.662)	(4.506)
Ownership rate					1.528
					(1.593)
N	401	401	401	401	401
R^2	0.4	0.41	0.43	0.43	0.44
AIC	1,269	1,268	1,253	1,254	1,252

* p < 0.1, ** p < 0.05, *** p < 0.001

Notes: Table 2 presents the results of a difference-in-difference estimation on the matched sample obtained in the previous section. The dependent variable is the number of solar PV installations per 1,000 inhabitants in each LAD. Treated observations are the Scottish LADs post-2017. Standard errors are clustered at the LAD level.

Examining the dynamics of this effect through an event study design on our matched sample, we observe an increase in the number of installations over time (Figure 6, left panel). Once more, we remark that the matching procedure ensures the absence of pre-trends: there is no significant difference between Scottish and English local authority districts with regards to solar PV installations before May 2017 when the policy was first implemented. The impact then progressively built up over 2017-2019 and then remained stable at around one extra installation per 1,000 inhabitants.

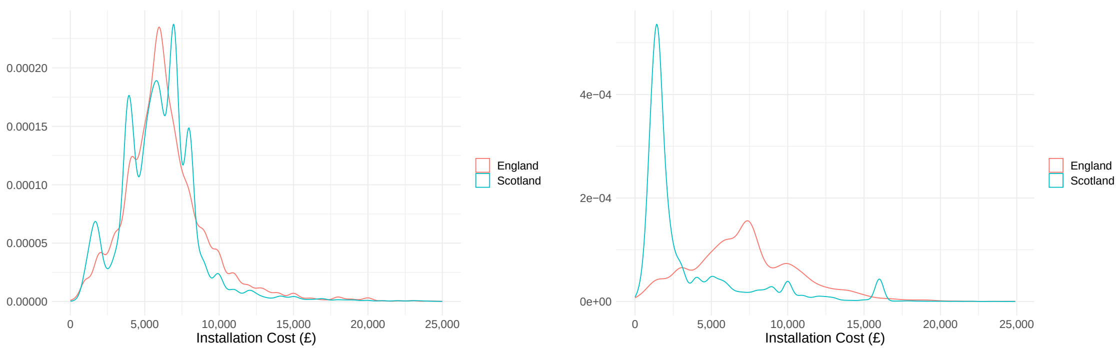
Figure 6: HESL impact on the number and size of solar PV installations over time (2010-2020)



Notes: The point estimates are obtained using the specification of column (5) in Table 2. The dependent variable is the number of installations per 1,000 inhabitants in each LAD in the left panel, and the size of the installation as measured by the estimated annual generation capacity in the right panel. Standard errors are clustered at the LAD level.

However, when assessing the average size of installations as measured by potential annual output in kilowatt-hours, we find that installation sizes have decreased following policy implementation (Figure 6, right panel). To delve deeper into this result, we turn to installation costs. Cost data are available in the MCS dataset for approximately two-thirds of our observations across the entire sample, with coverage approaching 100% in recent years. Comparing the distribution of installation costs before policy implementation (2013-2016) in England and Scotland reveals no statistically significant differences (Figure 7, left panel). Yet after the HESL became available to Scottish residents (2018-2021), the two distributions diverge strikingly (Figure 7, right panel). While England's total installation costs distribution remains unchanged (Figure C.1), Scotland's distribution exhibits significant bunching below £2,500 after the introduction of the HES Loan. This finding is reinforced when we repeat our analysis on a split sample that separates small and larger installations (Figure C.2). We find that the entirety of the policy impact has been concentrated on very small installations below 1,700 kWh per year.

Figure 7: Distribution of total installation costs in England and Scotland, before and after the HESL



While this result does not challenge the finding that the HESL has increased total installed capacity for solar PV in Scotland, it does impact the cost effectiveness of the policy. While not as salient as in utility-scale solar (Srivastav, 2023), economies of scale remain important in the context of domestic solar PV installations. Figure C.3 illustrates that very small installations below 1.5 kW are almost twice as expensive on a levelized cost of electricity (LCOE) basis as larger installations, particularly the more common 4 kW installation. In recent years, LCOE in the 1 kW range is 12 pence per kWh compared to only 6 pence per kWh at the 4 kW mark.

5.2 Robustness: Border Regression Discontinuity Design

To assess the robustness of our results under our primary estimation strategy of DiD with cardinality matching, we estimate the impact of the HES Loan under the alternative empirical strategy of a regression discontinuity (RD) design. Given that the HES Loan was exclusively enacted in Scotland, the England-Scotland border provides a quasi-experimental setup, under the assumption that households' propensity to adopt domestic solar PV is comparable on either side of the border save for the implementation of that subsidy.

We do not use the RD design as our main specification for two reasons. First, this design limits statistical power due to the relatively low population density along the Scottish border, which results in few observations of solar PV installations located near the border discontinuity. This reduced sample size caused by focusing our analysis near the England-Scotland border severely limits the potential to extend our analysis to assess heterogeneity in the effect of the HES Loan in terms of installation size, cost, estimated annual generation capacity as well as its distributional impacts (see section 6).

Second, we believe that DiD with cardinality matching provides a more robust basis for causal inference compared to the RD design. The England-Scotland border is not a randomly assigned threshold that determines eligibility for the HES Loan and therefore does not meet gold standard criteria for an RD design. Indeed, this border has existed for hundreds of years and therefore is potentially correlated with identities and preferences such as environmental concerns that may influence solar PV adoption. We prefer to explicitly deal with these potential confounding variables using a matching strategy rather than rely on the assumption that they vary smoothly on either side of the border. Given that the main constraint in achieving covariate balance in our matched subsample is solar PV potential, which we know does vary smoothly across the England-Scotland border, the RD design can be seen as a simplified version of our main design in which we match solely on solar potential and ignore socioeconomic variables such as average household income and green vote share. Our main design is a more sophisticated version of the RD design because it accounts for these additional covariates.

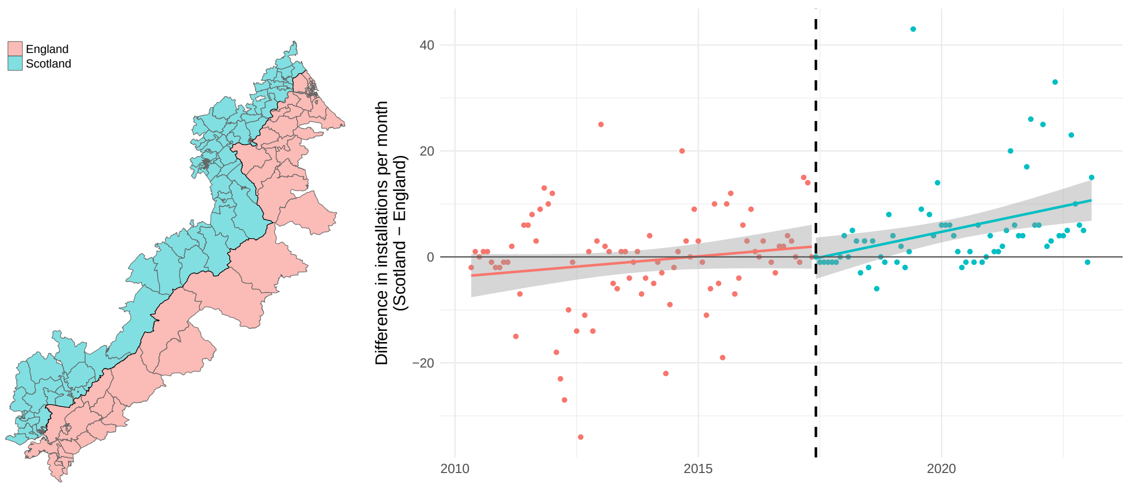
Although it is not our preferred specification, the RD design serves as an important source of validation for our main results. The geographical unit of observation for this alternative design is postcode districts, which number 2,979 across the UK. In our main estimation, we employ a bandwidth of 10km around the border (Figure 8, left panel).

The RD design employs the following econometric specification:

$$Y_{ip} = \alpha + \beta \mathbb{1}_p^{\text{Scotland}} + \gamma X_{ip} + \epsilon_{ip} \tag{2}$$

where Y_{ip} represents the outcome variable for postcode district i in proximity p to the border. Once again, our outcome of interest is the number of domestic solar PV installations per 1,000 inhabitants; $\mathbb{1}_p^{\text{Scotland}}$ is a binary indicator variable equalling 1 if the postcode area is in Scotland and 0 otherwise; X_{ip} denotes the additional control variables used in specification (5) in Table 2; and ϵ_{ip} is the error term, clustered at the postcode district level. Our primary coefficient of interest, β, captures the causal impact of the policy under the assumption of covariate balance across the border.

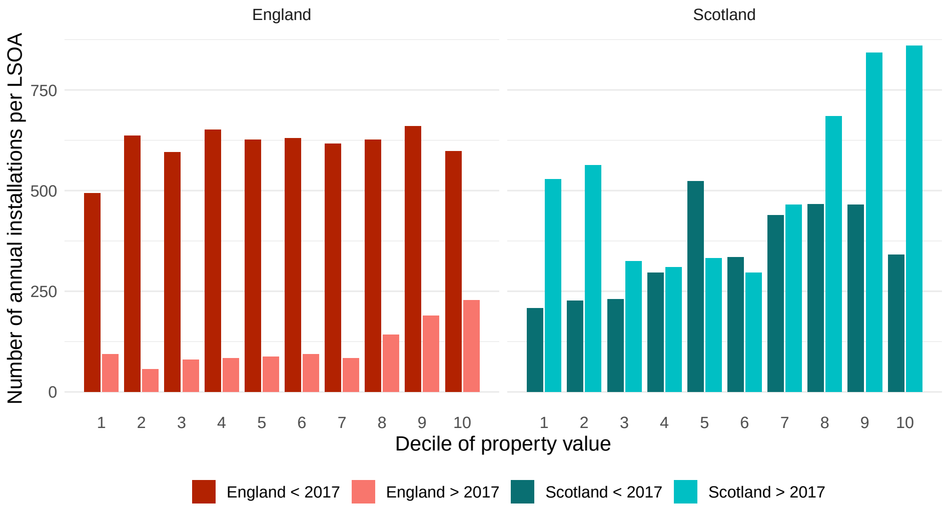
Figure 8: Border Regression Discontinuity design and results



To help verify the causal nature of our identification, we undertake pre-treatment covariate balance checks, ensuring the postcodes on either side of the border do not significantly differ on observable characteristics, mitigating the risk of confounding. Furthermore, we employ falsification tests wherein the policy variable is shifted temporally and spatially to confirm that the estimated effects are not driven by spurious pre-existing trends or regional heterogeneity.

Figure 8 (right panel) illustrates the sample of postcode districts within the 10km bandwidth and presents the estimation results. Despite the significantly reduced sample size, the border discon-

Figure 9: Unconditional distributions of installations per LSOA



tinuity design corroborates our main findings in terms of direction, statistical significance and effect magnitude. We confirm that the HESL has led to an increase of approximately one installation per thousand inhabitants upon implementation on the Scottish side of the border.

6 Who Benefited? Distributional analysis

The HESL distinguishes itself from other complementary renewable support policies by its non-conditional nature with respect to household resources. Homeownership is the only strong requirement to qualify for the scheme. Consequently, a distributional analysis is essential to identify where the beneficiaries of this subsidy fall along the income and wealth distribution.

As discussed above, we face limitations in the availability of granular income data in the UK, and so to proxy for household income and wealth we use an index of property value at the Lower Layer Super Output Area (LSOA) level over 2012-2016. See Section 3 above for further information on how we collect and construct the property value measure. Figure D.2 shows the unconditional joint cumulative distributions of LSOA-level property value and installations in Scotland and England before and after the introduction of the HESL in 2017. First, in both England and Scotland the joint distribution is below the 45 degree line, which indicates that installations are unequally distributed and skewed towards wealthier LSOAs. Before 2017, the Suits index index was -0.01 in England and -0.11 in Scotland, indicating that this regressivity was stronger in Scotland.

After 2017, a stark divergence occurs in the distributions of solar PV installations in England versus Scotland. In England, solar PV installations became more unevenly distributed compared to the earlier period, and the Suits Index increased to -0.21. Figure D.3 highlights that this period saw a large drop in installations in England across the wealth distribution, but this decline was smaller in wealthier LSOAs. By contrast, the Suits Index only marginally increased to -0.13 in Scotland after 2017, which implies that the distribution of solar PV installations became slightly more regressive. More specifically, solar PV installations shifted more towards both the lower and upper ends of the wealth distribution compared to the earlier period. Despite the decline in FiT scheme support during this period, solar PV installations in Scotland seem to have suffered a much smaller decline than in England, and in many LSOAs installations even increased relative to the pre-2017 period. Figure D.3 shows that similar patterns in the change in the distributions of solar PV installations in Scotland and England after 2017 also occur when measuring based on estimated annual generation. However, despite the relative stability of the number of new installations in Scotland after 2017, the additional generation capacity declined in Scotland as well as England compared to the pre-2017 period.

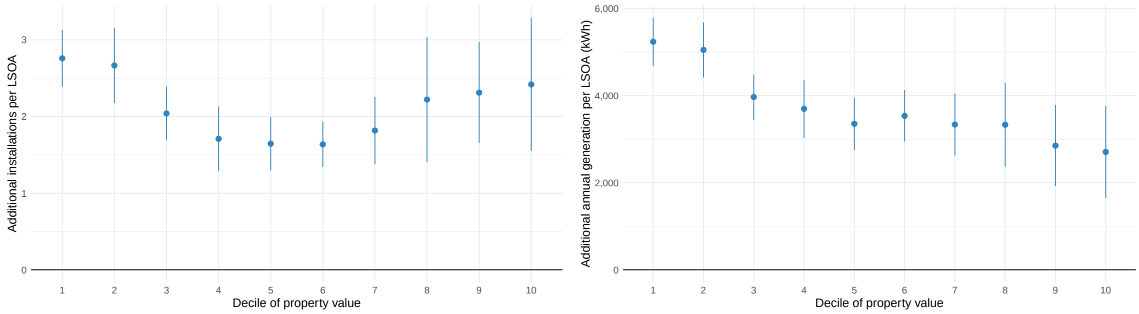
To test whether these distributional shifts in solar PV installations after the HESL was introduced are causal impacts of the policy, we once again employ a matching with difference-in-differences strategy. Specifically, we keep the LSOAs within our matched sample of the 32 LADs used in the main results above, and then we compare installations in Scottish LSOAs with those in English LSOAs before versus after 2017. We estimate the following specification using OLS:

$$y_{jdt} = \sum_{d=1}^{10} \beta_d^{HELS} \delta_{jd} \times \mathbb{1}_{jt}^{HELS} + \gamma X_{jt} + \epsilon_{jdt} \tag{3}$$

where y_{jdt} is the outcome variable (e.g. installations) in LSOA j and year t, and the LSOA is in decile d of the property value distribution. $\mathbb{1}_{jt}^{HELS}$ indicates exposure the HESL scheme, meaning that the LSOA is located in Scotland and the year is 2017 or later; to test whether impacts of the scheme vary across the wealth distribution, we interact this treatment dummy with δ_{jd}, which indicates whether LSOA j falls in property value decile d. X_{jt} denotes additional control variables, which include solar PV potential, property value at the LSOA level, year fixed effects, and property decile fixed effects; $_{jdt}$ is the error term, which is clustered at the LSOA level.

Figure 10 illustrates the results of this causal analysis of the distributional impacts of the HESL scheme on number of installations and estimated annual generation. The results indicate that LSOAs at all deciles of the wealth distribution benefited from the this policy: compared to English LSOAs in the same decile, solar PV installations and annual generation were higher in Scottish LSOAs after 2017. However, as suggested by the unconditional distributions, the magnitude of these impacts differed across the wealth distribution. For the number of installations, the impacts are strongest

Figure 10: Causal impact of the HESL policy in Scotland versus England by LSOA property value decile



Notes: These figures plot the estimation results for the specification given by Equation (3). In the left panel the dependent variable is the number of new installations per 1000 people in an LSOA, and in the right panel the dependent variable is the additional annual generation in an LSOA.

in the poorest and wealthiest LSOAs. The point estimates suggest that the poorest and wealthiest Scottish LSOAs saw between 2 and 3 additional installations compared to similar LSOAs in the same decile in England, while Scottish LSOAs in the middle of the wealth distribution saw between 1 and 2 additional installations compared to similar LSOAs in England. For annual generation, the impacts are highest in the poorest LSOAs. The point estimates imply that additional solar PV generation due to the policy is roughly twice as high in the poorest LSOAs compared to the wealthiest LSOAs. Together, these distributional impacts suggest that the HESL policy was somewhat progressive, particularly with respect to solar PV generation capacity.

Previous findings on the impact of policy support for domestic solar PV in California (Borenstein, 2017; Lukanov and Krieger, 2019; Barbose et al., 2020), Switzerland (Feger et al., 2022), and the UK FiT scheme (Grover and Daniels, 2017) suggest that these policies can be regressive, with the benefits accruing mostly to high income households. Our analysis of Scotland's HESL scheme suggest that the distributional impacts of the policy did not follow this trend. While solar PV installations are relatively skewed towards wealthier areas across both England and Scotland, this inequality is less strong in Scotland after the introduction of the HESL scheme. Moreover, without the compensatory support provided to Scottish households by the HESL, installations of solar PV amongst English households decreased and became more regressive as support under the FiT scheme declined.

7 Conclusion

This paper evaluates the impact of the HES Loan scheme on solar PV adoption in Scotland. We use rich microdata on household solar PV installations in the UK and an empirical strategy that combines cardinality matching with difference-in-differences to causally identify the impact of HES

Loan scheme on solar PV adoptions in Scotland versus England. Our analysis yields three main results. First, the HES Loan successfully boosted household adoption of solar PV, leading to 1 additional solar PV installations per 1000 inhabitants. Second, the impact of the policy was concentrated amongst small solar PV systems, and so the average size of new solar PV installations decreased in Scotland after the HES Loan was introduced. Third, the increase in installations due to the HES Loan was strongest in localities at the lowest and highest ends of the wealth distribution (as measured by average property values).

These results provide insight into the role of complementary policies to support household adoption of solar PV. While the main policy to support household solar PV during our sample period was the UK-wide FiT scheme, our results suggest that the addition of the HES Loan in Scotland was effective in spurring additional adoptions relative to the adoption rate in England. Moreover, as the UK government decreased FiT rates in response to the increasing financial viability of solar PV as a private investment, installation rates were higher in Scotland than in England after the HES Loan was introduced, which suggests that despite the decline in costs of solar PV, policy may still have a role to play in increasing uptake of solar PV amongst UK households.

Our results also illustrate the potential co-benefits of HES Loan scheme beyond beyond CO_2 abatement. In particular, the policy seems to have had a progressive redistribution effect on solar PV installations across the distribution of average LSOA property values. In other words, our results provide insight into the potential co-benefits of the policy in enabling equitable access to renewable energy.

These co-benefits are important in light of the high cost of the policy if we evaluate it only in terms of CO_2 abatement. We make a very simple back-of-the-envelope calculation to get a rough idea of the value for money in terms of only the CO_2 abatement associated with the additional renewable energy capacity due to the HES Loan. Estimates from our matching with difference-in-difference strategy suggest that over 2017-2021 additional household solar PV installations due to the HES Loan scheme amounted to 2,435 MWh per year of additional electricity generation. The abatement associated with this additional capacity depends on the extent to which the UK electricity grid decarbonizes over the lifetime of the panels.[11] Assuming no further abatement (the carbon intensity of the UK electricity grid remains at 2022 levels), the lifetime CO_2 avoided is 11,112 tCO_2; on the other hand, if the UK electricity grid decarbonizes in line with the Climate Change Committee's balanced pathway scenario, abatement due to the HES Loan is 3,439 tCO_2. Freedom of Information requests suggest that the Scottish government spent roughly £12 million annually on the scheme,

[11] For this calculation, we assume a 25 year lifetime for solar PV panels.

so we assume the policy cost £60 million over 2017-2021. Together with the abatement estimates, these costs imply that abatement was quite costly under the HES Loan scheme, in the range of 5,400 to 17,447 £/tCO_2 depending on the extent to which the UK electricity sector decarbonizes in the coming years. For comparison, using a similar approach and Srivastav (2023)'s estimates for the effect of the FiT scheme, utility-scale solar capacity additions cost 569 to 1040 £/tCO_2 abated under the FiT scheme, again depending on the extent to which the UK electricity sector continues to decarbonizes.

These estimates of the cost of abatement under the HES Loan scheme may reflect the limited solar PV potential in Scotland, the dis-economies of scale in the small PV systems that the HESL scheme drove adoption of, as well as the fact that the carbon intensity of the UK electricity sector is already fairly low. More importantly, these back-of-the-envelope calculations are very simple and not a full cost benefit analysis. Increased household adoption of solar PV may have many additional benefits beyond CO_2 abatement that we are not accounted for in this straightforward calculation, such as increased learning-by-doing in the innovation process for solar PV, decreased congestion in the electricity grid, and lack of distribution costs relative to utility-scale solar. Moreover, our results suggest that the HES Loan scheme seems has been successful in redistributing solar PV installations away from relatively wealthy areas. Future work will aim to incorporate these additional benefits of the policy in our assessment of its cost effectiveness.

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A Additional details on the policy context

As mentioned, several policy schemes exist in the UK that target support for low-income, energy-poor households to make energy efficiency upgrades and install renewable energy systems. For example, the Energy Company Obligation (ECO) scheme launched in 2013 and requires large energy suppliers in England, Scotland, and Wales to give grants to low-income, fuel-poor households for energy efficiency and boiler replacement. Solar PV has not been a focus of this scheme, though a small number of installations have been made under the scheme. A similar scheme exists in Northern Ireland, under the Northern Ireland Sustainable Energy Programme (NISEP).

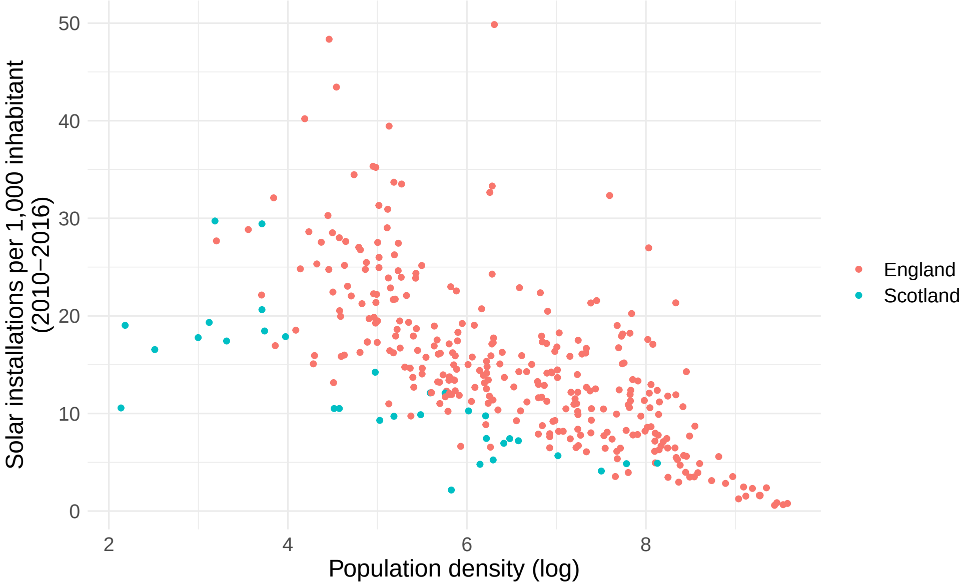
In addition to the ECO scheme, the devolved governments of Scotland and Wales provide further sources of funding for vulnerable households to make energy efficiency improvements. These schemes mainly focus on insulation and heating systems, but solar PV is also within the remit of the policies. In Wales, the Nest scheme launched in 2011 and offers free energy efficiency upgrades to households that live in an energy inefficient home and either receive a means-tested benefit, have a health condition, or are low-income.[12] Similarly, the Scottish government provides funding for energy efficiency upgrades for fuel-poor and low-income households through the Area-based schemes (since 2013) and the Warmer Homes Scotland (WHS) scheme (since 2015). The WHS scheme focuses mainly on energy efficiency improvements such as insulation and heating systems, though solar PV is also available under the scheme (HEEPS Report, 2017-2018). Eligibility for WHS funding requires that households live in a house with a poor energy efficiency rating and either receive a means-tested benefit or are 75+ years of age and have no working heating system.

While the ECO scheme and other similar policies focus on low-income, energy-poor households, middle- and high-income households outside of Scotland have no access to policy support for the upfront costs of installing a solar PV system. Strictly speaking, our quasi-experimental design is most effective for identifying the effect of the HESL scheme on middle- and high-income households, since these households are not "treated" by any other similar policy. Nevertheless, the lack of focus on solar PV in the ECO, Nest, and WHS schemes limits the degree to which even low-income households outside of Scotland can be "treated" by a policy similar to HESL scheme.

[12] The main focus of this scheme is heating systems and insulation improvements. In 2021-22, solar PV made up just 0.6% of installed measures (Nest Annual Report 2021-22, page 9).

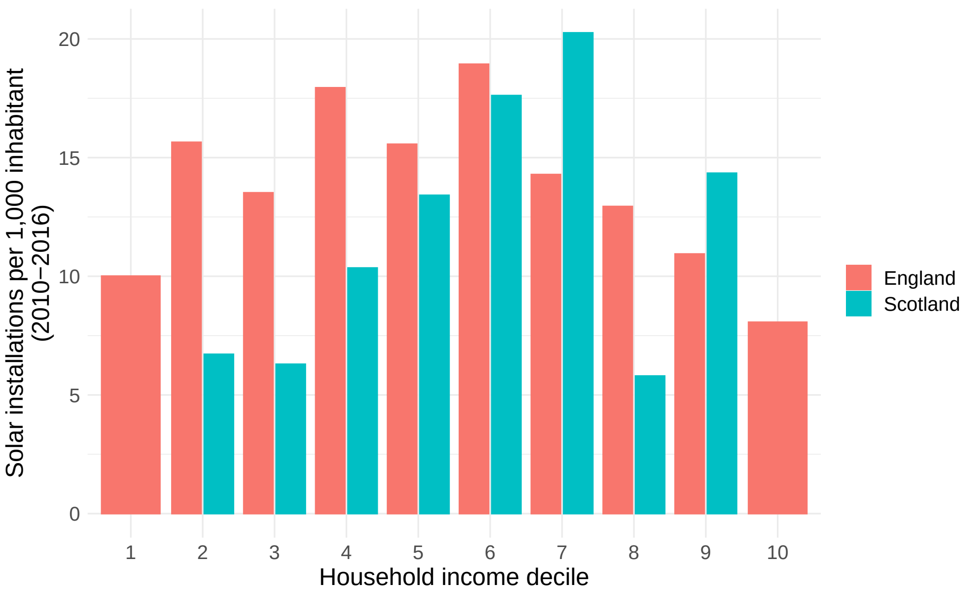
B Solar PV covariates

Figure B.1: Solar PV installations as a function of population density (2010-2016)



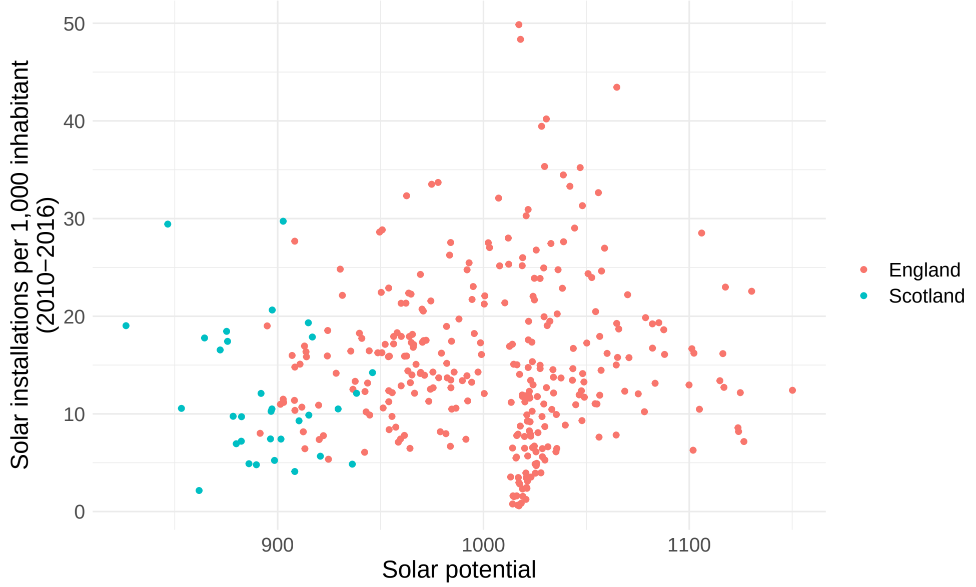
Notes: Each dot represents on Local Authority District, located in England or Scotland. Population data obtained from the UK ONS.

Figure B.2: Solar PV installations per household income decile (2010-2016)



Notes: Income deciles are defined across the entire UK, then applied to English and Scottish households. Household income data obtained at the Middle-Layer Super Output Area (MSOA).

Figure B.3: Solar PV installations as a function of solar potential (2010-2016)



Notes: Solar potential obtained from the World Bank's Solar Atlas (2023). The 1 m x 1 km solar potential grid data was then aggregated to the Local Authority District level.

Figure B.4: Vote for the Green Party in the 2014 European Parliamentary Elections

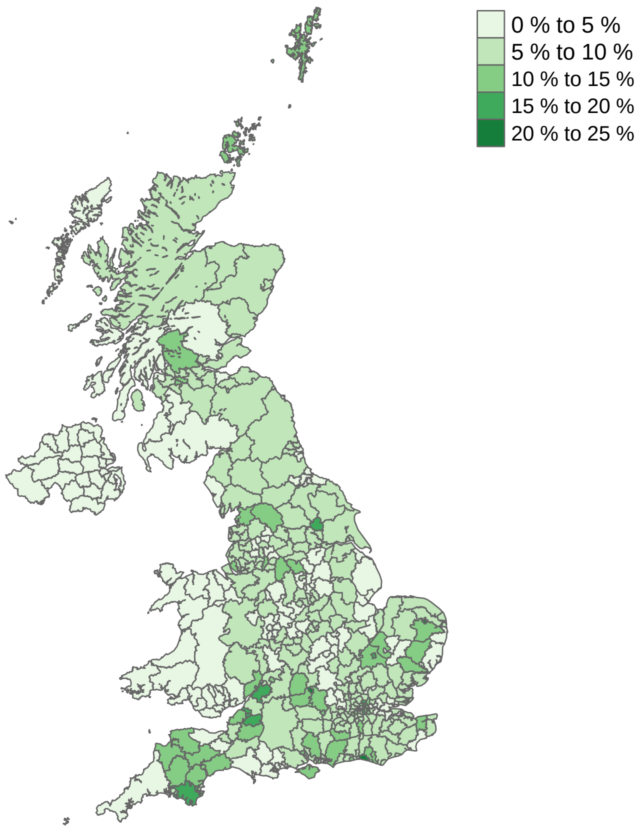
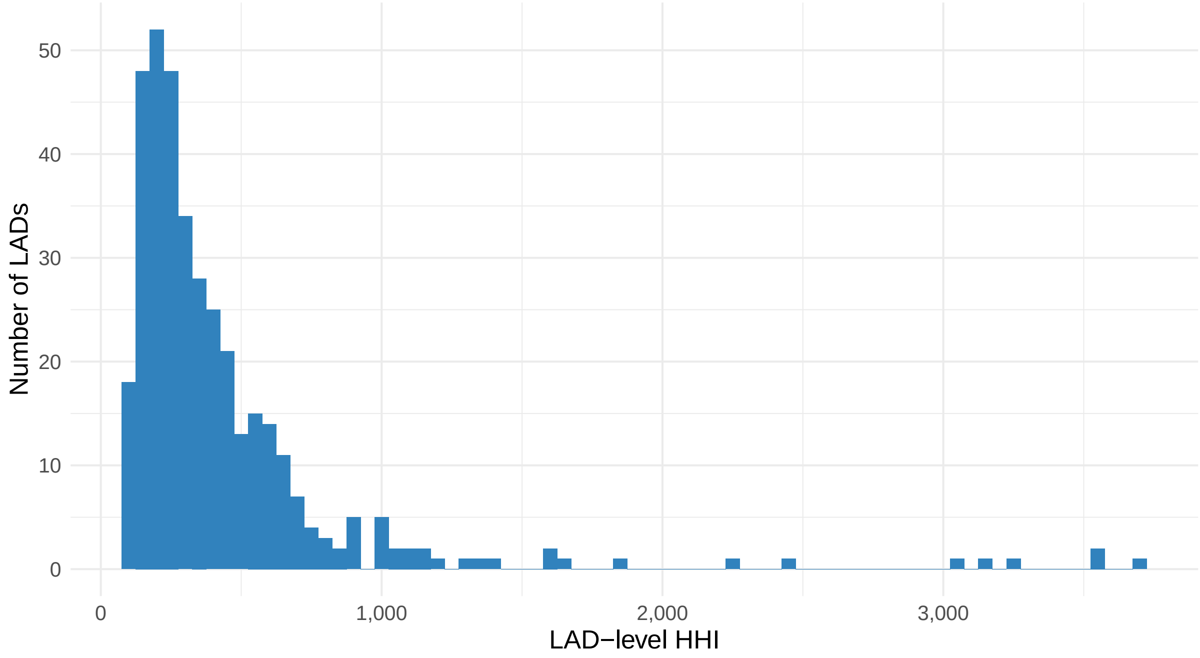


Figure B.5: Distribution of LAD-level HHI



C Complementary results

Figure C.1: Distribution of total installation costs in England, before and after the implementation of the HESL

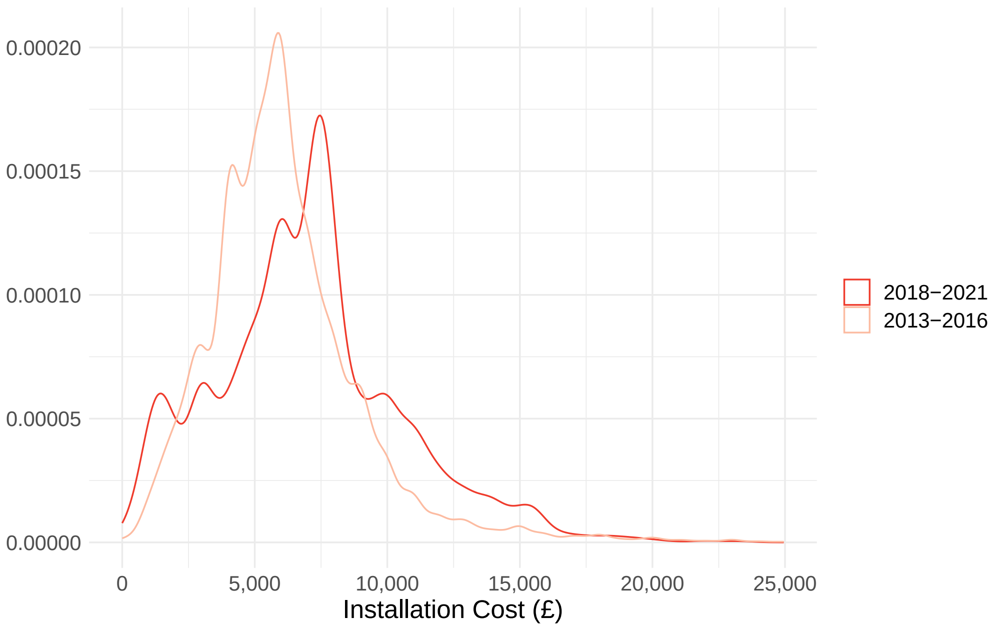
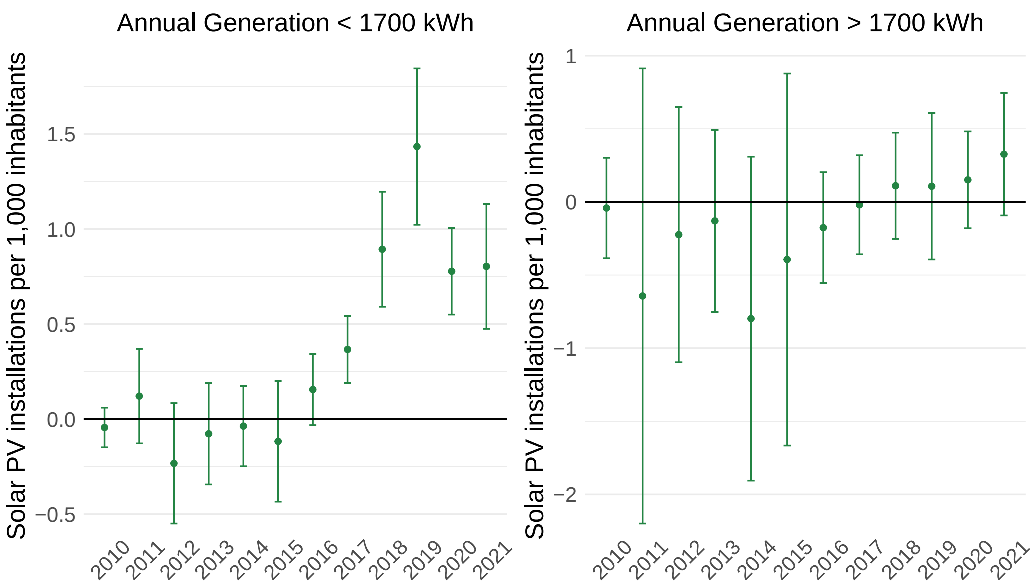


Table 3: Balance table: Full versus matched sample

	Full sample			Matched Sample		
	Means Scotland LADs	Means England LADs	Std. Mean Diff.	Means Scotland LADs	Means England LADs	Std. Mean Diff.
Matching variables						
PV potential	0.78	0.87	-4.15	0.79	0.80	-0.20
Household income (log)	9.75	9.82	-0.57	9.77	9.79	-0.19
Population (log)	11.75	11.89	-0.18	11.88	11.75	0.17
Population density	476.55	1675.45	-1.60	728.42	873.34	-0.19
Total installations (2010-2016, log)	7.17	7.51	-0.36	7.18	7.36	-0.19
Ownership rate	0.64	0.66	-0.21	0.63	0.64	-0.15
Green vote	0.07	0.08	-0.16	0.07	0.07	0.12
Other variables						
Total annual generation (2010-2016, log)	15.24	15.59	-0.36	15.27	15.45	-0.19
Number of LADs	32.00	309.00		16.00	16.00	

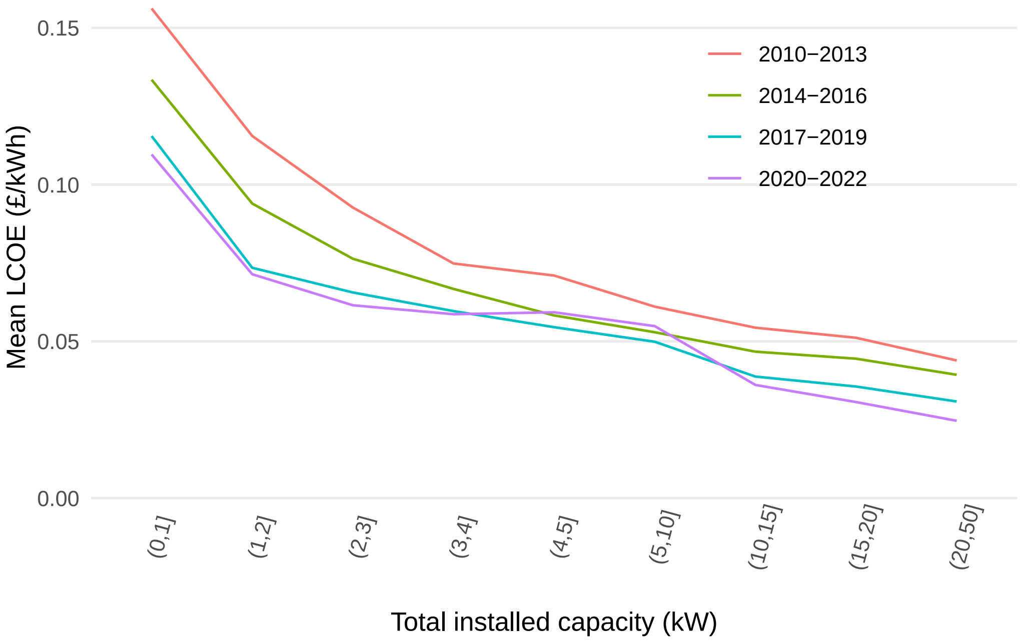
Notes: This table compares LAD-level means in Scotland versus England for the full sample of LADs and for the sub-sample of LADs obtained from the cardinality matching procedure. "Matching variables" indicates variables used in this matching procedure. "Std. Mean Diff" indicates the standardized difference in the means between Scottish versus English LADs from the relevant sample.

Figure C.2: Impact of the HESL on the number of installations by installation size



Notes: The dependent variable in both panels is the number of solar PV installations per 1,000 inhabitants. The left-hand panel presents results estimated on the sub-sample of installations generating less than 1,700 kWh annually, while the right-hand panel considers installations generating more than 1,700 kWh per year.

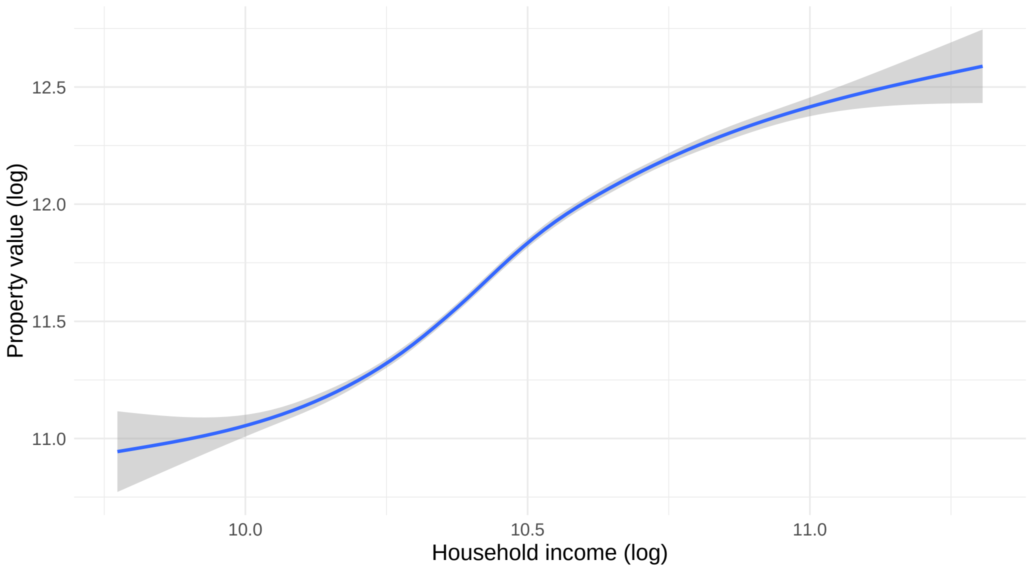
Figure C.3: LCOE as a function of total installed capacity



Notes: These LCOE are calculated from the installation capacities and total installation costs observed in the MCS dataset. They represent averages across the whole United Kingdom.

D Distributional analysis

Figure D.1: Correlation between household income and average property values at the LSOA level in Scotland



Notes: Average property values computed as the average of all residential real estate transactions observed in an LSOA between 2012 and 2016 (included). Average household income for the years 2014 and 2016 provided at the LSOA level in Scotland by the UK ONS.

Figure D.2: Joint distribution of LSOA-level property value and installations

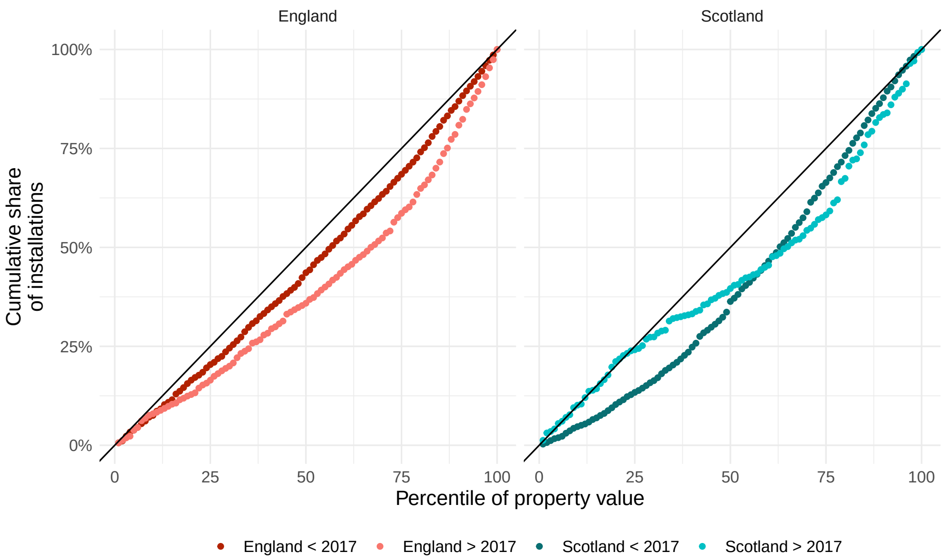


Figure D.3: Unconditional distributions of installations per LSOA