Grantham Research Institute on Climate Change and the Environment

Adoption, incidence and welfare impacts of interest-free loans: evidence from solar PV

Leanne Cass, Misato Sato and Aurélien Saussay

January 2026

Grantham Research Institute on
Climate Change and the Environment
Working Paper No. 438

ISSN 2515-5717 (Online)

Grantham Foundation
for the Protection of the Environment

LSE The London School of Economics and Political Science

The Grantham Research Institute on Climate Change and the Environment was established by the London School of Economics and Political Science in 2008 to bring together international expertise on economics, finance, geography, the environment, international development and political economy to create a world-leading centre for policy-relevant research and training. The Institute is funded by the Grantham Foundation for the Protection of the Environment and a number of other sources. It has five broad research areas:

1. Climate change impacts and resilience
2. Cutting emissions
3. Financing a better future
4. Global action
5. Protecting the environment

More information about the Grantham Research Institute is available at: www.lse.ac.uk/GranthamInstitute

Suggested citation:
Cass L, Sato M and Saussay A (2026) *Adoption, incidence and welfare impacts of interest-free loans: evidence from solar PV*. Grantham Research Institute on Climate Change and the Environment Working Paper 438. London: London School of Economics and Political Science

Adoption, incidence and welfare impacts of interest-free loans: Evidence from solar PV

Leanne Cass[*], Misato Sato[†], and Aurélien Saussay[‡]

This version: January 2026

Abstract

Steep declines in solar PV costs alongside concerns about regressive subsidy incidence raise questions about whether, and how, to continue support. Leveraging administrative microdata on the near-universe of UK domestic PV, we employ a matched difference-in-differences design exploiting devolved UK policy to evaluate the zero-interest Home Energy Scotland loan. The loan increased household adoption and shifted take-up towards smaller systems. Distributionally, gains were broad and not concentrated among high-wealth or rural areas, delivering more equitable benefits than alternative PV subsidies. A loan-specific marginal value of public funds shows welfare gains at modest fiscal cost even in a low-solar potential setting.

JEL codes: H22, H23, H81, Q42, Q48, Q58
Keywords: Renewable Support Policies; Interest-free loans; Residential PV; Distributional impacts; MVPF

[*]University of Helsinki (leanne.cass@helsinki.fi)
[†]London School of Economics and Political Science (m.sato1@lse.ac.uk)
[‡]London School of Economics and Political Science and Sciences Po, OFCE (a.saussay@lse.ac.uk)
We thank MCS for providing access to their Installations Database. We are grateful to Lassi Ahlvik, Gavin Allan, Louise Bernard, Tobias Eibinger, Massimo Filippini, Ken Gillingham, Rob Metcalfe, Kimmo Palanne, Sugandha Srivastav, Marta Talevi, and Faye Wade, as well as audiences at the FEEM Seminar, PRINZ Seminar, 2023 FAERE Annual Conference, GRI Workshop, 2024 International Workshop on Empirical Methods (EMEE), NTNU Department of Economics Seminar, 2024 AERE Summer Conference, 2024 Atlantic Workshop on Energy and Environmental Economics (AWEEE), 2024 NAERE Annual Workshop, 2024 Toulouse Conference on the Economics of Energy and Climate, 2024 EEA Meeting, 2024 Early-Career Workshop in Empirical Environmental Economics in Bergen, Helsinki GSE Seminar, 2025 EAERE Annual Conference, and the 2025 CEPR Symposium on Climate Change and the Environment for insightful comments and feedback. LC, MS, and AS gratefully acknowledge support from the Grantham Research Institute

1 Introduction

After five decades of investments that began in the wake of the oil crisis, solar photovoltaic (PV) technology has become the cheapest source of new electricity in most countries and is poised for rapid expansion. The International Energy Agency forecasts a ten-fold increase in installed PV capacity each decade, with PV expected to become the largest installed power capacity worldwide by 2027, surpassing coal, natural gas and hydropower (IEA, 2022, 2023). Past government policies, including Germany's feed-in tariff in 2000, which quadrupled the PV market, played a key role in increasing deployment (Hoppmann, Huenteler and Girod, 2014) and advancing PV along the technology cost curve (Nemet, 2019). The dramatic decline in PV prices[1] raises hope for climate action, while sharpening the question of how much government support is still warranted, and in what form.

Governments worldwide continue to support solar. In the EU, solar received the largest share of renewable subsidies in 2023, at €21 billion (European Commission, 2025); in the UK, the British Energy Security Strategy (U.K. Government, 2022) set a target to expand capacity from 14 GW to 70 GW by 2035; while in China, coal-benchmark on-grid prices were guaranteed to encourage new wind and solar investments between 2021 and June 2025 (Myllyvirta, 2025). At the same time, policy instruments have shifted with falling technology costs and budget constraints: many jurisdictions have reduced or ended Feed-in-Tariffs (FiT), moving towards tenders and contracts for difference (Kilinc-Ata, 2016). Distributional fairness has also come to the fore: without attention to who benefits and who pays, support risks political backlash (De Groote, Gautier and Verboven, 2024).

We contribute new evidence to this discourse by empirically assessing a relatively under-examined, low-fiscal-cost instrument: an interest-free (soft) loan. By lowering borrowing costs and extending repayment periods, soft loans reduce upfront capital hurdles for household PV through a consumption-smoothing, financing channel. While loans are common in green investment programmes (Bertoldi et al., 2021), credible ex-post evidence on their effects on renewable adoption and incidence remains scarce. Prior

on Climate Change and the Environment, at the London School of Economics, and the Economic and Social Research Council grants Centre for Climate Change Economics and Policy (CCCEP) (ref. ES/R009708/1) and PRINZ (ES/W010356/1). MS and AS acknowledge support from the European Union (H2020-MSCA-RISE-2019, GEOCEP, 870245). AS gratefully acknowledges Leverhulme Trust for his Early Career Fellowship (ECF/2021/536). LC gratefully acknowledges support from the European Union (ERC GRETA, 101116659). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. For the purpose of open access, the authors have applied a Creative Commons attribution (CC BY) licence to any Author Accepted Manuscript version arising.

[1]The global weighted average levelized cost of electricity (LCOE) of utility-scale PV plants is estimated to have fallen by 77% between 2010 and 2018, from around USD 0.37/kWh to USD 0.085/kWh (IRENA, 2019).

work is largely theoretical or ex-ante model-based, for example, combining FiTs with soft loans (Mir-Artigues and Del Río, 2014), and modelling fiscal impacts of loan programmes, e.g. the German Building Rehabilitation Programme (Kuckshinrichs, Kronenberg and Hansen, 2010) and the UK solid wall scheme (Rosenow, Platt and Demurtas, 2014) [2]. We address this gap with new evidence from Scotland's Home Energy Scotland (HES) Loan.

Introduced in 2017, the HES Loan offers interest-free financing for household energy upgrades, including rooftop PV. Unlike means-tested schemes, this support was available to homeowners regardless of income. Crucially, it arrived as UK-wide support under the FiT declined: generation tariffs for new installations fell from 41.3 p/kWh (2010) to 3.79 p/kWh (2019), lengthening payback periods despite falling installation costs (Figure 1). During our study period (2017–2021), PV was eligible as a standalone measure under the HES Loan.[3]

Using a database from the Microgeneration Certification Scheme, which has near-universe coverage of UK domestic PV installations, we assemble administrative microdata on more than 1 million domestic PV installations in the UK from 2010 to 2021. We merge this data with key household characteristics that influence PV adoption rates, including local solar PV generation potential and property-value data as a proxy for localized household income (see Section 3). Using a matching-with-difference-in-differences design, we compare outcomes in Scottish localities (eligible for the HES Loan) with matched English localities (not eligible) before and after 2017. This quasi-experimental approach exploits the UK's devolved policy landscape and yields, to our knowledge, the first comprehensive causal assessment of an interest-free loan for household PV. To assess welfare impacts, we adapt the canonical marginal value of public funds (MVPF) welfare metric (Hendren and Sprung-Keyser, 2020; Hahn et al., 2024) to loans. In doing so we show, intuitively, that when the government is more patient than households, each pound of loan support delivers more than a pound of household benefit.

The analysis delivers several findings. First, the HES Loan increased PV adoption, and shifted system sizes, offsetting the decline in PV installations following substantial cuts in UK-wide support for renewable generation. Event-study estimates imply about 0.8 additional installations per LSOA per year in Scotland over 2017–2021 (building to roughly 1.4 by 2019), and the two-period DiD estimates imply about six additional installations per LSOA over the five year period, relative to matched English LSOAs where installations fell as FiT support waned. These gains are concentrated in small systems: the loan is

[2]These papers show that loans not only achieve budget neutrality but may even have a positive effect on public budgets for example through the employment effect or VAT revenues.

[3]Subsequent programme changes, outside our study window, added requirements for PV to be part of a package with heating and storage (from mid-2023).

associated with about +8.2 small versus +1.7 large additional installations per LSOA in the same period, and the mean annual generation of new systems declines by ~500 kWh, consistent with a shift from production-linked support towards an upfront financing instrument.

Second, contrary to the solar adoption inequality literature (e.g. Darghouth et al., 2022), we find the gains from the HES Loan were broadly shared across wealth groups, with larger proportional and absolute effects at the bottom of the distribution and stronger impacts in urban and rural-accessible areas, indicating non-regressive incidence. In particular, the average marginal effect of the policy is roughly 75% larger in the lowest decile compared to the highest decile (2.1 versus 1.2 additional installations).

Finally, the welfare analysis using an adapted MVPF methodology highlights the cost efficiency of zero-interest loans when private discount rates are high and credit constraints bind. Our loan-specific MVPF yields a baseline value of 2.7, and in sensitivity checks this value stays above 1 across across a wide range of assumptions. In sum, by studying multiple outcomes jointly – take-up, system size, distributional incidence, and welfare impacts – we speak to current policy priorities on effectiveness, cost, and fairness, and to the role of upfront-cost support in a changing subsidy mix.

This paper contributes to several literatures. First, we add to empirical evaluations of solar PV support policies. Prior work generally finds that financial incentives increase household adoption, for example 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).[4] Potential challenges and trade-offs associated with solar PV support policies highlighted by prior work include the cost effectiveness these schemes, low price sensitivity of households (Gillingham and Tsvetanov, 2019) and high discounting of future benefits (De Groote and Verboven, 2019; Talevi, 2022; Bollinger, Gillingham and Kirkpatrick, 2025), and poor targeting of marginal adopters (Snashall-Woodhams, 2019) or locations with high solar potential or CO_2 mitigation potential (Callaway, Fowlie and McCormick, 2018; Fowlie and Muller, 2019). We contribute in two ways: (i) by assessing an interest-free loan scheme for the first time in this context; and (ii) by conducting a detailed welfare analysis offering insights for instrument design and cost effectiveness when private discount rates are high and credit constraints bind.

Second, we revisit the distributional consequences of rooftop-PV support. Prior evaluations of FiTs and upfront rebates generally find regressive incidence, with benefits

[4] Other studies find market support policies such as interconnection standards and renewable portfolio standards to be effective at encouraging solar capacity (e.g. Krasko and Doris, 2013; Steward et al., 2014).

concentrated among high-income households (e.g. Barbose et al., 2020; Best, Chareunsy and Li, 2021; Borenstein, 2017; De Groote, Pepermans and Verboven, 2016; Hansen, Jacobsen and Gram-Hanssen, 2022; Jacksohn et al., 2019; O'Shaughnessy et al., 2021). In contrast, the interest-free loan we study exhibits non-regressive incidence: gains are broad and relatively larger in lower income areas. These distributional impacts of support policies are important because perceived fairness is a key determinant of public support for such policies (Huber, Wicki and Bernauer, 2020; Bergquist et al., 2022), without which policies may be short lived.

Third, we connect policy design to heterogeneous discounting and capital constraints. A large literature identifies consumers' apparent under-valuation of future energy savings when making investment decisions (e.g. Allcott and Greenstone, 2012; Gerarden, Newell and Stavins, 2017; Busse, Knittel and Zettelmeyer, 2013; Gillingham, Houde and van Benthem, 2021). In a similar vein, recent work calls to attention the pivotal role that credit constraints play in preventing investment in clean technologies (Lanteri and Rampini, 2025). Evidence on household PV adoption from Belgium and the UK documents very high implicit discount rates (around 15%) and low price sensitivity, implying that instruments which shift costs over time (e.g., production support paid upfront or loan-like support) can outperform production-only designs when private rates are high or credit is tight (De Groote and Verboven, 2019; Talevi, 2022). U.S. evidence similarly points to low price sensitivity and salient dynamics in adoption and timing decisions, underscoring the value of instruments that shift costs over time and reduce liquidity hurdles (Gillingham and Tsvetanov, 2019). We show that an interest-free loan can help to overcome these investment barriers.

Finally, we contribute to the emerging use of MVPF in environmental policy evaluation (e.g. Hahn et al., 2024; Bollinger, Gillingham and Kirkpatrick, 2025; Bernard et al., 2024) by developing and applying a loan-specific MVPF. Our formulation separates the net present value (NPV) transfer received by households from the government's NPV cost, making the financing channel explicit. This yields a transparent welfare metric for loan policies and complements existing comparisons of upfront versus production-based support.

The remainder of the paper is structured as follows. Section 2 provides an overview of the policy landscape for solar PV in the UK. Section 3 presents the data and Section 4 explains the empirical strategy. Section 5 presents the main results. Section 6 examines distributional impacts. Section 7 discusses mechanisms through a simple NPV framework. Section 8 develops the loan-specific MVPF and reports the welfare decomposition and sensitivities. Section 9 concludes.

2 Policy context

Over the past fifteen years, UK and devolved policies have supported household solar PV. The main UK-wide policy during our sample period is the Feed-in-Tariff scheme, which ran from April 2010 to March 2019. Under this policy, small-scale renewables such as solar PV systems of up to 5 MW capacity could receive a subsidy on every kWh generated, as well as an additional subsidy for every excess kWh exported back to the National Grid. Overall, UK-wide support fell markedly during our study window with contract lengths reducing from 25 to 20 years in 2012 and tariff rates for new systems declining quarterly (see Figure 1).

In 2017, the Scottish Government introduced the Home Energy Scotland (HES) Loan,[5] an interest-free loan for energy efficiency improvements and renewable technology installations including solar PV. This loan was available to all homeowners and private landlords, and not restricted by income. During 2017–2021, our sample period, PV was eligible as a stand-alone measure, and the PV loan cap rose from £2,500 to £5,000 in May 2018.[6] No analogous loan operated in England (further details in Appendix S1).[7] Our empirical strategy exploits this devolved nature of PV support in the UK, comparing Scottish localities (eligible for HES Loan) with matched English localities before and after 2017.

An important contextual aspect the HES Loan scheme in Scotland is that it was introduced against the backdrop of declining UK-wide support for household solar PV under the FiT scheme.[8] Besides an annual inflation adjustment in line with the Retail Price Index, FiT participants kept a fixed tariff for the contract term, but tariff offered to new installations fell substantially over time, from 41.3 pence per kWh in April 2010 to 3.79 pence per kWh in January 2019.[9] Panel A of Figure 1 illustrates this decline, and a relatively modest increase in the export tariff during this period, while Panel B shows that installation costs also fell over this period. Accordingly, despite lower expected annual net revenue from the scheme (Panel C), PV remained profitable by the end of the FiT

[5]For more information on the HES Loan, see the Home Energy Scotland webpage here.

[6]Post-period changes outside our estimation window include the addition of grants alongside loans in December 2022 (raising the cap to £6000 with a grant element when bundled) and a June 2023 rule requiring PV to be installed as part of a package with heating and storage.

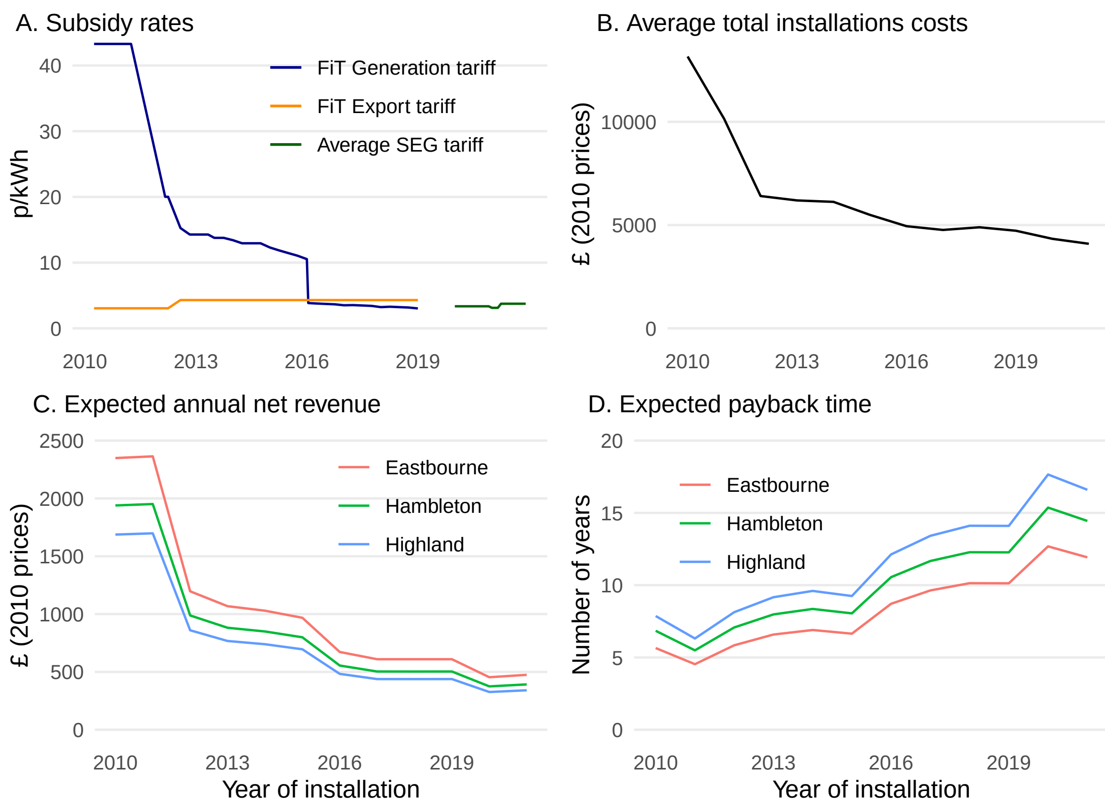
[7]The UK landscape did include other, means-tested programmes for low-income or fuel-poor households including ECO and Warmer Homes Scotland. However, not only did these predate the HES Loan, they also funded very few solar PV systems in practice. Therefore, we do not believe that these alternative policies pose a significant threat to our causal identification of the HES Loan impact.

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

[9]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.

scheme in March 2019. Payback periods for a 4 kW system lengthened (Panel D), yet, in 2018, remained below the expected 20-30 year system lifetime in both a low-insolation (Highland) and high-insolation (Eastbourne) local authority.

Figure 1: Expected profitability of a 3-4kW solar PV system under the UK-wide FiT scheme



Notes: Panel A illustrates Feed-in-Tariff (FiT) scheme tariffs as well as the average Smart Export Guarantee (SEG), as reported in Ofgem's 2023-2024 SEG Annual Report. Tariff rates are deflated to 2010 prices using the Retail Price Index. Panel B shows the average total installation costs of 3-4kW 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 3-4kW PV system under the FiT/SEG schemes for 3 representative Local Authority Districts (LADs). Highland in Scotland and has the lowest solar potential in the UK; Carlisle in the North of England 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. Expected annual net revenue is based on FiT/SEG scheme payments, and electricity savings (calculated using data on electricity prices from BEIS). We assume that 50% of the electricity generated by the system is exported back to the grid. These figures also assume that households are able to install a system at the optimal orientation and angle to maximize the PV system's generation. Annual net revenue is deflated to 2010 prices using the RPI. Expected payback time is the average total installation costs divided by expected annual net revenue.

In January 2020, the Smart Export Guarantee (SEG) was introduced to partially replace the FiT and encourage renewable technology investments, but the level of support was reduced as it pays only for exports to the grid, not for generation.[10] This shift reduced UK-

[10] 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 (those with at least 150,000 domestic electricity customers) are required to offer at least one tariff rate. Households are not

wide support relative to the early FiT years; meanwhile, in Scotland eligible households faced more generous overall support than comparable households in England thanks to the HES Loan. By comparing outcomes in England versus Scotland before and after the HES Loan scheme launched, we uncover the impact of continued versus declining policy support as the market for domestic solar PV matured.

3 Data and Descriptive Facts

The main data source used in this paper is a rich administrative database of household-level solar PV installations provided by the Microgeneration Certification Scheme (MCS). MCS creates and maintains standards for the certification of products, installers, and installations in the UK small-scale renewable energy sector. Obtaining MCS certification is necessary for households to be eligible for government support for renewable installations, including both the UK-wide FiT scheme subsidies (Ofgem, 2023*c*) and Scotland's HES Loan 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.

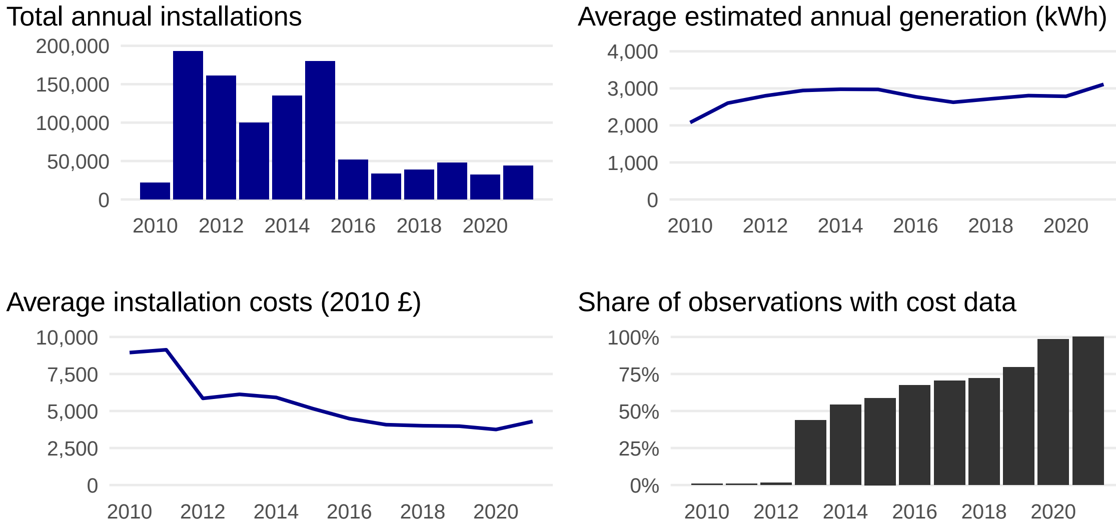
Our main data source is the MCS Installation Database over the period 2010-2021 (MCS, 2024). The data include 1.29 million small-scale renewable installations, 84% of which are solar photovoltaic (PV) systems. Given the certification requirements to benefit from renewable subsidies, we believe these data to encompass the near-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 address and postcode[11] of each installation. Furthermore, the total installation cost is reported for 42% of all solar PV installations on average across the sample period, with coverage increasing to almost 100% by the end of the period. After cleaning the sample by dropping observations with a non-domestic or commercial end-user as well as a handful of outliers in terms of the reported total capacity or estimated annual generation, we obtain a final sample of 1.04 million solar PV installations across the UK over 2010-2021.[12]

eligible for SEG payments if they already receive payments under a FiT scheme contract. As of December 2025, SEG tariff rates offered by UK energy suppliers range from 1.0 to 25 pence per kWh. Current SEG tariff rates are summarised by Solar Energy UK (2025). Also, in April 2022 the UK government introduced a zero-rate of VAT for solar panels, which runs until 2027.

[11] A UK postcode identifies an average of 15 properties, but can vary from 1 to around 100 properties.

[12] We drop observations with missing estimated annual generation, as well as those with greater than 20 kW total installed capacity, and those with less than 500 or greater than 30,000 annual kWh estimated annual generation. Inspection of the data suggests that some installations may have incorrect units for capacity or

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).

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, in line with the falling PV module prices globally.

Our empirical strategy to estimate the impact of Scotland's HES Loan scheme compares installations in Scotland versus England. Table 1 summarises the average cost and size of installations before and after the HES Loan was introduced in 2017 for the full sample as well as individually for England and Scotland. The overall number of solar PV installations in Scotland is much smaller, with a population size less than a tenth of England's. Installation rates per 1000 people before 2017 were higher in England (12.5) than in Scotland (10.1), but they dropped significantly more in England (2.6) compared to Scotland (6.5) after 2017. Average installation sizes and costs are similar across both nations, except in Scotland after 2017 when average system sizes drop notably.

annual generation, so we compute the ratio of estimated annual generation and total installed capacity, and drop observations with less than 200 annual kWh per kW. Finally, we impute as missing values observations of total installation costs that are above £400,000 and below £100.

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

	Full sample		England		Scotland	
	2010-2016	2017-2021	2010-2016	2017-2021	2010-2016	2017-2021
Number of installations	842,135	195,752	707,988	146,519	55,304	35,434
Installations per 1000 people	12.6	2.9	12.5	2.6	10.1	6.5
Installation Costs (2010 £)						
Mean	5,474	4,038	5,405	4,522	5,648	2,274
Std. Dev.	4,399	3,883	4,468	4,010	2,988	3,041
Estimated Annual Generation (kWh)						
Mean	2,816.7	2,822.7	2,784	3,069	2,823	1,749
Std. Dev.	1,816	2,157	1,802	2,228	1,502	1,433

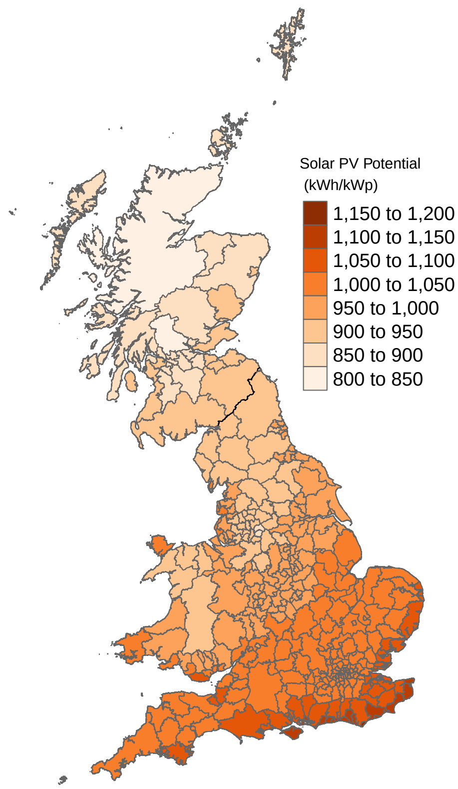
Notes: Installations per 1000 people are calculated based on 2021 populations. Installation costs are considered missing if they are recorded as zero or if they are an outlier (above the 0.1% percentile of observations). Costs are deflated to 2010 prices using the Retail Price Index (RPI).

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. We conduct our analysis at the level of Lower Layer Super Output Areas (LSOAs), which are statistical geographical areas designed to encompass 650 households on average. The entire UK is made up of 42,622 LSOAs, including 6,976 in Scotland.[13] To enable this matching, we collect data on 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 LSOA, illustrated in Figure 3 (World Bank, 2023). Next, we use the Energy Performance Certificates in England (DLUHC, 2024) and Scotland (Energy Saving Trust, 2024) to construct measures of LSOA-level housing stock characteristics, such as average square meterage, share of homes that are houses, and share of homes built after 1949. We also use the UK Department for Energy Security and Net Zero's data on postcode-level data electricity consumption (DESNZ, 2024)[14], as well as data on home ownership rates from the 2011 census (ONS, 2013; Scotland's Census, 2011). Finally, we construct an index of local average property value using real estate transaction data from the HM Land Registry and the Registers of Scotland (HM Land Registry, 2024; Registers of Scotland, 2024).

[13]The Scottish Government uses the term Data Zone for these small-area geographies. For simplicity we use LSOA to refer to both English LSOAs and Scottish Data Zones.

[14]We use postcode-level data on electricity consumption in 2015 and 2016 and aggregate to average annual consumption per LSOA.

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



Notes: This map shows solar PV generation potential (annual kWh per 1 kW peak installed capacity, kWh/kWp), based on the Global Solar Atlas database (World Bank, 2023). The dark border indicates the England-Scotland border. Solar potential is shown here at the LAD level for legibility, although in our analysis we use LSOA-level solar potential. LADs are local government administrative areas that are much larger than LSOAs (on average, LADs contain over 100 LSOAs).

We also utilize this real estate transaction value data in our distributional analysis of the impact of Scotland's HES Loan scheme. Granular income data is not readily available for the UK; while it is possible to obtain income estimates for Scotland at the LSOA level, 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 (HM Land Registry, 2024; Registers of Scotland, 2024). 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 HES Loan enactment (2012 to 2016).[15]

[15]Figure S2.7 in the Appendix verifies that this index correlates very well with household income in

4 Identification and Methodology

4.1 Empirical design

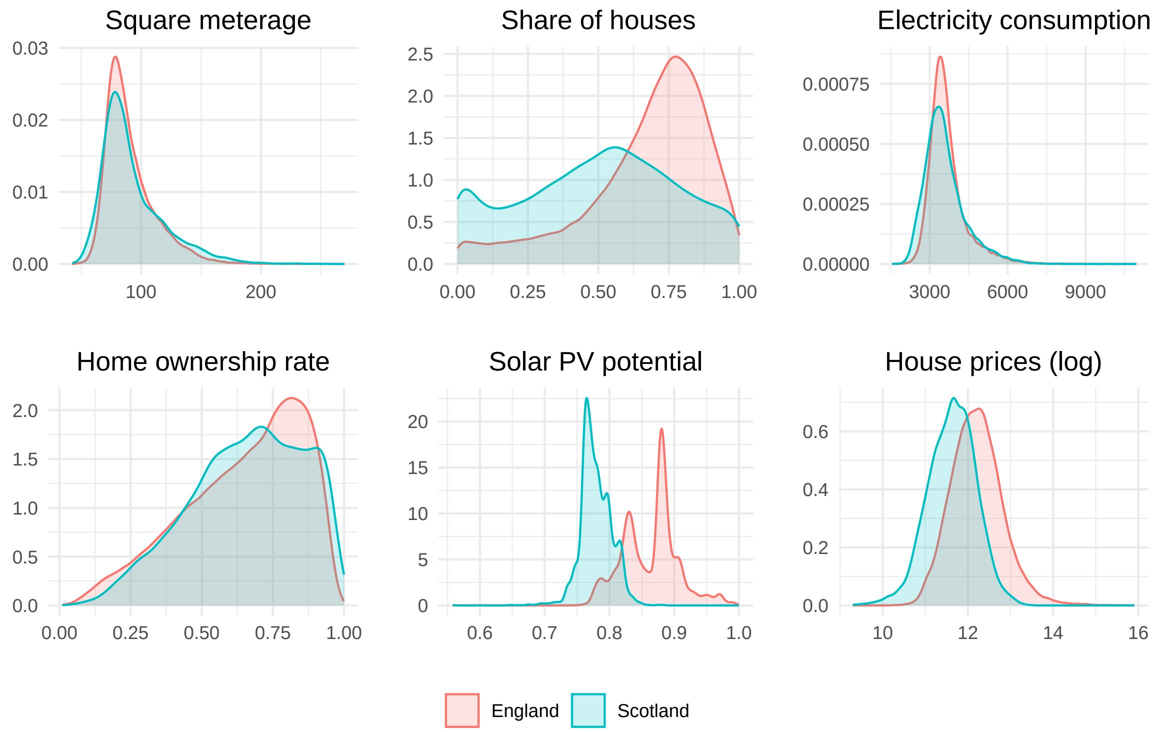
Our aim is to identify the causal impact of an interest-free loan on domestic solar PV installations in the UK. Our empirical strategy exploits policy variation across nations within the UK, in particular, the Home Energy Scotland Loan that was only available to Scottish residents and did not have a contemporary equivalent in England, Wales, or Northern Ireland.

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 relies 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 generation potential and household income, we expect that many English localities may be quite different than the typical Scottish locality. 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 Lower Layer Super Output Area (LSOA) level.

We match on LSOA-level covariates relevant to the propensity to adopt solar PV: characteristics of the local housing stock such as average square meterage and shares that are houses and that are built post-WWII; average electricity consumption; the 2011 home ownership rate; total installations during the pre-treatment period of 2010-2016; average house prices over 2012-2016; and solar PV production potential. Figure 4 presents the respective English and Scottish distributions for several of these covariates used to implement our matching strategy. These distributions are not entirely overlapping, particularly for solar PV potential. This incomplete overlap highlights the concern that a "naive" DiD approach without matching would involve comparing very different units in terms of propensity to adopt solar PV and would likely lead to violating the parallel trends assumption. Crucially, however, despite the differences between the Scottish and English distributions, we consistently observe significant areas of overlap, which ensures the feasibility of obtaining a subsample of Scottish and English LSOAs that are plausibly similar in terms of propensity to adopt solar PV.

Scotland, which is available at the LSOA level.

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



Notes: This figure shows kernel density plots of our key matching variables across LSOAs in England versus Scotland. The overlap in the distributions across the two countries provides a visual confirmation of the feasibility of our matching strategy. Note that for visual clarity this figure shows six of the eight covariates used in the matching procedure. The remaining covariates are the share of houses built after 1949 as well as the total number of installations in the pre-treatment (2010-2016) period.

In the following subsection we discuss the details of our matching strategy further, but first we highlight some 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, contrary to previous findings reported in California (e.g. Borenstein, 2017), we find that installations do not concentrate among top income deciles but rather in the middle of the income distribution (see Figure A.1). Next, as expected household solar PV installations are more frequent in areas with greater solar generation potential (see Figure A.2), although the weakness of this correlation suggests the importance of other factors as well.[16]

[16]As shown in Figure A.2, a 100 annual kWh/kWp increase in solar potential (equivalent to almost a two standard deviation increase in solar potential observed in UK LSOAs) is associated with 1.1 additional installations per 1,000 inhabitants.

4.2 Coarsened Exact Matching

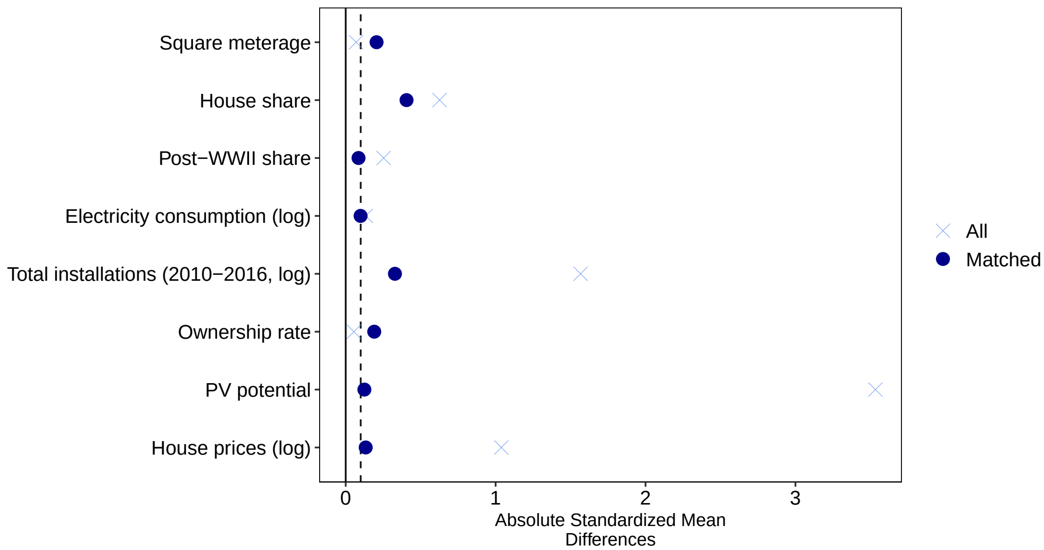
Implementing an efficient and effective matching strategy within our context faces two main challenges. First, the limited degree of overlap between the English and Scottish distributions for some covariates, particularly solar potential, raises difficulties in finding a strong match and implies that dropping some LSOAs from our estimation sample is necessary. Second, the large number of LSOAs (42k+) implies that the number of potential combinations of English and Scottish LSOAs to include in the estimation sample is very large, which is a significant computational burden for some matching algorithms. To overcome these challenges we use coarsened exact matching, which ensures a strong match by jointly balancing the sample across all covariates, and is also efficient with large sample sizes (Iacus, King and Porro, 2012).

Coarsened exact matching involves first coarsening the covariates into bins and then performing exact matching on the coarsened versions of the covariates (Iacus, King and Porro, 2012). If any bin does not include both control (English) and treatment (Scottish) units, then the units in that bin are discarded from the sample. In our context, this constraint implies we discard many LSOAs, such as sunny LSOAs in southern England for which we have no reasonable counterpart in Scotland in terms of solar potential. This process of sample restriction helps to ensure that we obtain an estimation sample in which the English and Scottish LSOAs are plausibly similar in terms of propensity to adopt solar PV. On the other hand, this constraint also means that a trade off exists between the size of the matc'hed sample and the number of covariates and the degree to which they are coarsened. As the number of covariates or bins increases, the potential for "empty" bins without both English and Scottish LSOAs increases, and so the size of the matched sample decreases. We iterate over several configurations for the number of bins for each covariate to reach a reasonable trade off between balance quality and sample size.[17]

Our matched sample covers 2,707 LSOAs, including 1,172 in England and 1,535 in Scotland, which corresponds to 24% of Scottish households and 3% of English households. Figure 5 presents the results of the matching procedure in terms of the absolute standardized mean difference between Scottish and English LSOAs across each covariate. The matching procedure makes strong improvements on balance quality relative to the full sample, particularly for pre-treatment installations, PV potential, and house prices. In our matched sample, the absolute standardized mean difference is 0.21 on average and is close to or below 0.1 for the majority of the covariates.

[17]See Figure S2.1 for a comparison of match quality across alternative specifications.

Figure 5: Covariate balance across the full versus matched sample of LSOAs



Notes: This figure shows the absolute standardized mean differences between LSOAs in Scotland versus England for each of the covariates included in our matching procedure. The light blue Xs show absolute standardized mean differences computed on the full sample of LSOAs, and the dark blue dots are computed on the matched sample. The dashed line at 0.1 indicates the conventional reference value for match quality assessment.

4.3 Difference-in-difference specification

After obtaining our matched sample of LSOAs, we run a difference-in-differences (DiD) analysis of outcomes in matched Scottish versus English LSOAs before versus after the HES Loan was introduced in 2017. While we also show results of the policy impact from a simple two-period DiD model using outcomes in the pre- and post-treatment periods, our preferred estimation approach is the following event-study specification:

$$Y_{it} = exp(\beta_t^{HESL} \mathbb{1}_{it}^{\text{HESL}} + \mu_i + \gamma_t) \times \epsilon_{it} \quad (1)$$

where Y_i represents the outcome variable for LSOA i at time t; $\mathbb{1}^{\text{HESL}}$ is a binary indicator variable equalling 1 from 2017 onwards if the LSOA is located Scotland (and therefore exposed to the HES Loan) and 0 otherwise; μ_i and γ_t are LSOA and year fixed effects, respectively; and ϵ_{it} is the error term, clustered at the matching subclass level. Our main dependent variables of interest are the number of solar PV installations, and the average estimated annual generation of new installations in an LSOA-year. The first outcome variable is a count variable and both outcome variables are non-negative, so our main results use a Poisson estimator for goodness-of-fit, and in robustness checks we also show results using the OLS estimator. Our primary coefficient of interest, β_t^{HESL}, captures the causal impact of the HES Loan in year t under the condition that the parallel trends assumption holds within our matched sample. Since our analysis discards some LSOAs 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 on the treated (ATT). 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 ATT is necessary to ensure a robust causal estimate.

5 HES Loan impact on adoption

We find that the Home Energy Scotland Loan had a positive and statistically significant impact on the number of domestic solar PV installations in Scotland. Figure 6 illustrates the main results from estimating the event-study specification (Figure 6a) and a two-period DiD specification (Figure 6b) on our matched sample of LSOAs.[18,19] In the event-study results in Figure 6a, the coefficients on the pre-2016 years serve as a placebo test, and suggest that in the years before the HES Loan was introduced installation numbers were the same or slightly lower in Scottish compared to English LSOAs.[20] After the HES Loan was introduced in 2017, a statistically significant increase in installations occurred in Scotland compared to England. These impacts progressively built up over 2017-2018, and our estimates imply that by 2019 Scottish LSOAs saw about 1.4 additional installations due to the policy. On average over 2017-2021, the HES Loan lead to 0.76 additional installations per LSOA per year, which is a doubling of the installation rate in 2016 of 0.73 installations per LSOA.[21]

The two-period DiD results in Figure 6b confirm and expand on the event-study results.[22,23] In these specifications we compare the total number and average size of in-

[18]See Tables B.3 and B.4 in Appendix B for these results in tables.

[19]In Appendix S3, we show that our results are robust to using a regression discontinuity (RD) design, and also discuss why the RD design is not our main identification strategy.

[20]In Table B.3, we show estimates for an alternative specification that replaces the pre-treatment year dummies with a linear time trend for these years interacted with the "Scotland" dummy. The results further suggest that before the HES Loan was introducted, solar PV adoption rates were the same or trending slightly downwards in Scottish compared to English LSOAs. Moreover, in Figure S2.5 in Appendix S2 we show results from implementing the pretrends tests in Roth (2022), which indicate that pretrends are unlikely to fully explain policy impacts that we find.

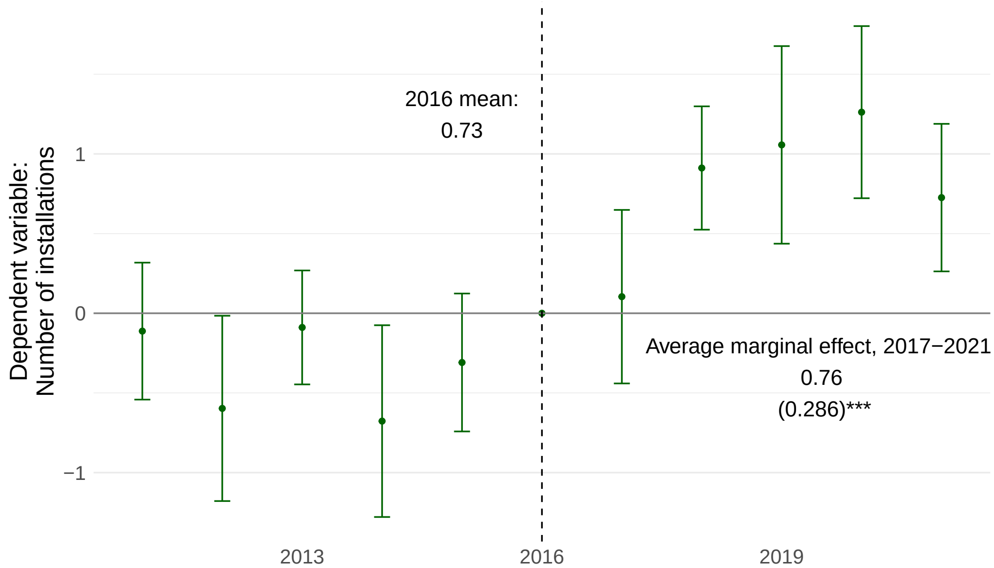
[21]As shown in Table B.3 and Figure S2.2, we obtain similar results using the OLS estimator.

[22]See Table B.4 for the results in a table.

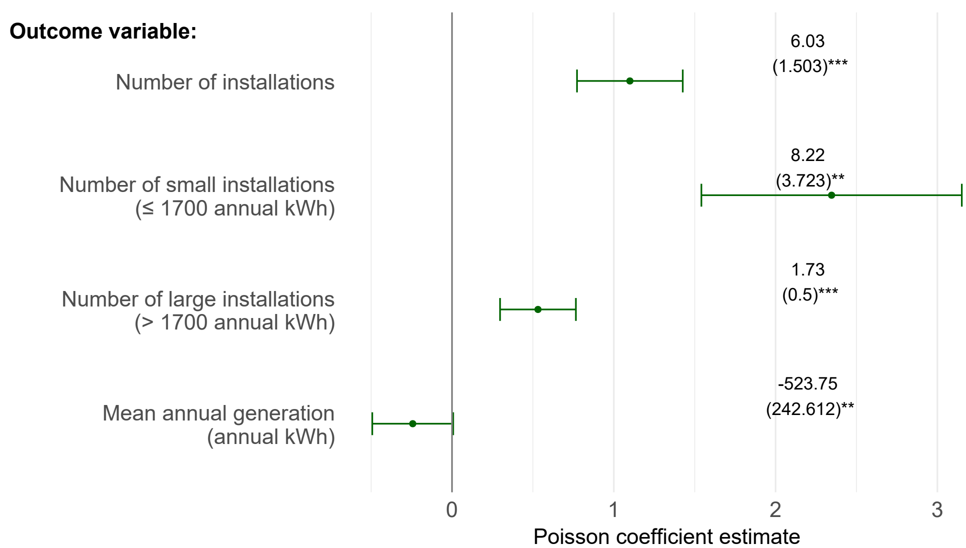
[23]We present 2-period DiD results to enable comparability with the distributional analysis in Section 6, which uses 2-period DiD to maintain statistical power. The 2-period DiD specification also allows us enough observations to use mean annual generation (kWh) of new installations per LSOA-period as an outcome variable.

Figure 6: Main results: Impact of HES Loan on number and size of PV installations

(a) Event-study results



(b) Two-period DiD results



Notes: Panel (a) shows Poisson coefficient estimates from an event-study specification for the annual number of installations per LSOA. See column (1) in Table B.3 for these results in a table. "2016 mean" refers to the mean outcome across English and Scottish LSOAs in 2016. "AME" refers to average marginal effect. Panel (b) shows Poisson coefficient estimates from a two-period (2011-2015 and 2017-2021) DiD specification for the total number and average size of installations per LSOA per period. See Table B.4 for these results in a table. The annotations in Panel (b) indicate average marginal effect estimates. Estimates are weighted using LSOA weights from the matching procedure, and standard errors are clustered at the matching subclass level. * $p \leq 0.10$, ** $p \leq 0.05$, *** $p \leq 0.01$

stallations in Scottish versus English LSOAs in the post-treatment (2017-2021) versus pre-treatment (2011-2015) period. The first row of this figure shows a slightly higher but similar estimate to the event-study results for the impact on number of installations, implying that the HES Loan led to 6 additional installations per LSOA across the 5 year period 2017-2021. The second and third rows of this figure show results restricted to small (≤ 1,700 annual kWh) and large (> 1,700 annual kWh) installations, respectively. These results indicate that the impact of the policy was heavily concentrated on small installations; while the HES Loan led to 1.7 additional large installations per LSOA over 2017-2021, small installations increased by 8.2 on average per LSOA during this period. We find similar results when we estimate the event study specification separately for small versus large installations.[24] Moreover, the fourth row of Figure 6b indicates that the mean annual generation of installations decreased by about 500 kWh on average following the policy's implementation. A non-causal analysis of installation costs suggests that costs also fell in line with this decrease in installation sizes.[25].

The decrease in installation sizes in Scotland following the introduction of the HES Loan could be driven by several factors. First, while the FiT scheme targeted large installations by paying larger subsidies the more a PV system generated, the HES Loan subsidy has a £5000 cap and therefore does not scale with the system size; overall, as the HES Loan was introduced in 2017 and the FiT scheme closed down in 2019, the relative benefit of installing a large system declined. Second, uptake of the loan may have been particularly strong for households preferring small installation sizes, such as urban or credit-constrained households living in small houses with limited rooftop space and/or low electricity consumption. The next section sheds some light on this hypothesis by exploring heterogeneity in the policy impact across urban versus rural LSOAs and across the wealth distribution.

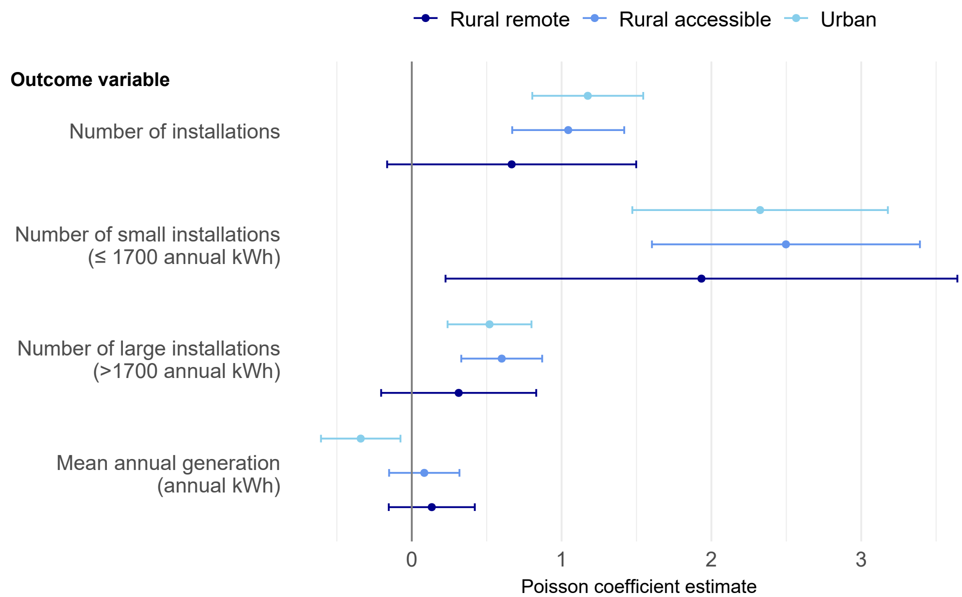
6 Who Benefited? Distributional analysis

A key political-economy concern with support for household PV is regressivity. Prior work documents unequal incidence under European feed-in tariffs (Grover and Daniels, 2017) and rebate-based programs including in California (Hughes and Podolefsky, 2015; Borenstein, 2017; Barbose et al., 2020; Lukanov and Krieger, 2019), but none have causally evaluated the distributional effects of soft loans to our knowledge.

[24]These split-sample event study results are illustrated in Figure S2.3).

[25]In Figure S2.4 we show that the distribution of installation costs before policy implementation (2011-2015) in England versus Scotland reveals no notable differences (left panel), but after the HES Loan became available to Scottish residents (2017-2021), the two distributions diverge strikingly (right panel)

Figure 7: Heterogeneity in HES Loan impact by urban versus rural LSOAs



Notes: This figure shows Poisson cofficient estimates from a two-period DiD specification that interacts the HES Loan treatment dummy with the urban-rural category of the LSOA. Standard errors clustered at the matching subclass level.

6.1 Urban versus rural heterogeneity

We assess the heterogeneous impacts across urban, rural-accessible and rural-remote LSOAs based on pre-2017 classifications (ONS, 2016; NRS, 2015).[26] Two-period DiD estimates (Figure 7) show that the HES Loan increased installations mainly in urban and rural accessible LSOAs. Small installations increase across all area types but particularly in urban LSOAs, which is the only group exhibiting a statistically significant decrease in the average annual generation. These findings contrast with previous evidence that solar PV uptake tends to be in low-density, suburban or rural areas (Balta-Ozkan, Yildirim and Connor, 2015; De Groote and Verboven, 2019; Graziano and Gillingham, 2015). One interpretation is that an interest-free loan that does not scale with system size relaxes financing frictions for households in small urban dwellings, tilting adoption toward smaller systems.

[26]Scotland and England do not use exactly the same urban-rural classification. We match the six category Scottish classification to the ten category English classification as follows. For urban areas, from Scotland we include large urban areas, other urban areas, accessible small towns, and remote small towns, and from England we include major conurbations, minor conurbations, city and towns, and city and towns in a sparse setting. For rural-accessible areas, from Scotland we include accessible rural areas, and from England we include towns and fringe, villages, and hamlets and isolated dwellings. For rural-remote areas, from Scotland we include rural remote areas and from England we include towns and fringe in a sparse setting, villages in a sparse setting, and hamlets and isolated dwellings in a sparse setting.

6.2 Wealth distribution analysis

To evaluate heterogeneous impacts of the HES Loan by income groups, we proxy for household income using an index of local property values[27] (see Section 3), and use data at a very granular geographical scale (Output Areas, or OAs, representing approximately 150 households).[28] The unconditional joint distributions of OA-level property values and PV installations in Scotland and England imply that installations are concentrated in wealthier areas in both countries (see Figure A.3 in the Appendix),[29] but a stark divergence is apparent after the introduction of the HES Loan in 2017. In England, as the FiT scheme wound down, installations plummeted across all wealth deciles, but the decline was smaller in the wealthiest OAs, and therefore installations became more unevenly distributed - the Suits Index increased from 0.21 to to 0.23.[30] In contrast in Scotland, installations shifted towards OAs at the low end of the property value distribution in particular becoming less regressive, and the Suits index improved from 0.41 to 0.27.

To test whether the post-2017 distributional shifts are causal, we return to the matching with difference-in-differences strategy, at the OA level. We restrict to OAs within the matched LSOAs used above and estimate the following specification using PPML, comparing installations in Scottish OAs with those in English OAs before versus after 2017:

$$y_{jdt} = exp(\sum_{d=1}^{10} \beta_d^{HESL} \delta_{jd} \times \mathbb{1}_{jt}^{HESL} + \mu_j + \gamma_t) \times \epsilon_{jdt}, \quad (2)$$

where y_{jdt} is installations (or total annual generation) in OA j and period t, and the OA is in decile d of the property value distribution. We use a 2-period panel, with pre-treatment (2011-2015) and post-treatment (2017-2021) defined as above. $\mathbb{1}_{jt}^{HESL}$ equals one for Scottish OAs in the post-treatment period, indicating exposure to the HES Loan scheme. δ_{jd} indexes property-value deciles. We control for OA (μ_j) and period (γ_t) fixed effects, and the error term, ϵ_{jdt}, is clustered at the matching subclass level.

Figure 8 shows positive effects across the distribution: installations rise in Scottish OAs in every decile relative to matched English OAs, with the largest gains in the poorest

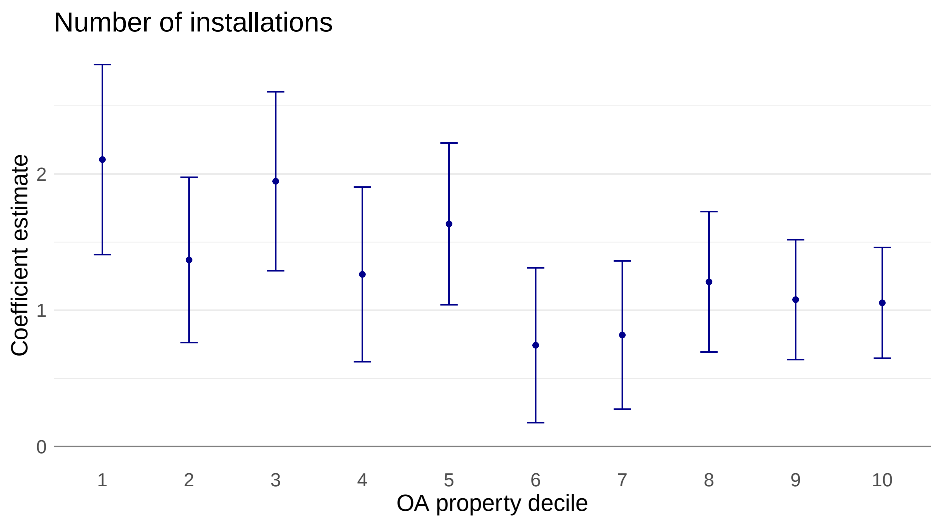
[27]Figure S2.7 shows that in Scotland, for which income data is available at the LSOA level, our LSOA property value index correlates strongly with LSOA income.

[28]OAs are the smallest statistical geographical units provided by the ONS, ensuring homogeneous populations in terms of wealth levels.

[29]We also plot Lorenz-like curves of the percentile rank of OA property values versus the cumulative share of PV installations in Figure S2.8. For both nations the curve is below the 45 degree line, which indicates that installations are unequally distributed and skewed towards wealthier LSOAs.

[30]The Suits Index is analogous to the Gini coefficient, except instead of comparing population share across the income distribution, in this case we compare the cumulative share of PV installations across the property-value distribution. See Table S2.1 for details on the Suits Index across countries and time.

Figure 8: Causal impact of the HES Loan in Scotland versus England by OA property value decile



Notes: This figure plot the estimation results for the specification given by Equation (2). See also Table B.6. The dependent variable is the number of new installations in an OA.

decile.[31] Interestingly, the impact in the poorest decile was roughly twice the impact in the richest decile. In levels, average marginal effects show correspondingly larger increases at the bottom deciles. Results are similar for total annual generation and when using OLS; t-tests confirm that the estimated effect for the poorest decile exceeds the highest across specifications (Appendix Tables B.6, S2.2).[32] These distributional difference-in-difference estimates suggest that the HES Loan's benefits were not regressively distributed across the wealth distribution at the OA level. Indeed, the policy likely played a role in the reduction in inequality in household solar PV across Scotland discussed above.

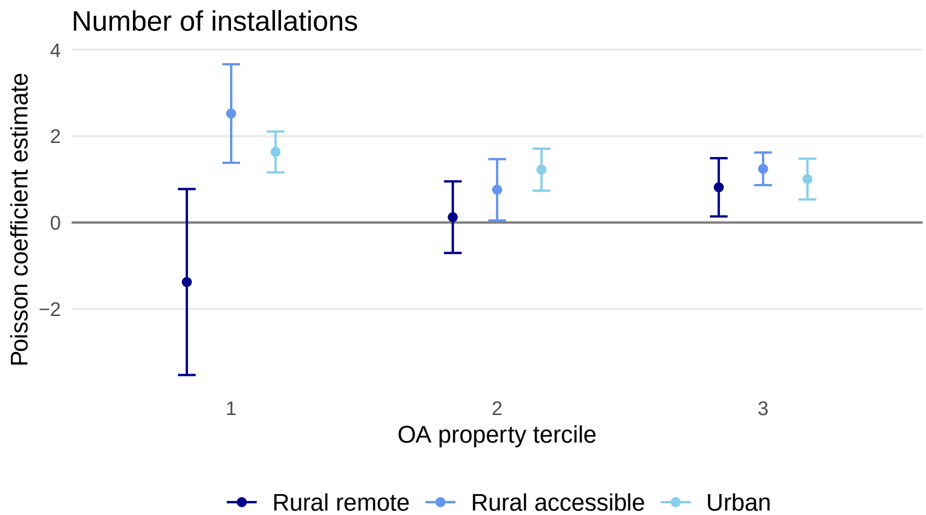
Previous findings for California (Borenstein, 2017; Lukanov and Krieger, 2019; Barbose et al., 2020), Switzerland (Feger, Pavanini and Radulescu, 2022), and the UK FiT scheme (Grover and Daniels, 2017) suggest that PV support policies can be regressive, with benefits accruing mainly to higher-income households. Our analysis of Scotland's HES Loan does not follow this pattern, at least across OA property values.[33] While installations remain skewed towards wealthier areas in both countries, the skew declines in

[31]See Table B.6 in the Appendix for more details and average marginal effects across Scottish OAs within each decile; this table also shows additional results using total annual generation installed as the outcome variable and using the OLS estimator.

[32]In Table S2.2, we run a series of t-tests to compare the effects of the HES Loan in the first decile compared to all other deciles of the property value distribution. We run these tests for both outcome variables and for both Poisson and OLS coefficient estimates. Across the specifications, the estimate for the poorest decile is consistently larger than and statistically significantly different from the estimate for all deciles from Q6 to Q10.

[33]An important caveat is that the HES Loan is only available to homeowners. Our analysis speaks to distribution within the homeowner population.

Figure 9: Impact of the HES Loan by property value tercile and urban-rural classification



Notes: This figure plots the estimation results for the specification similar to Equation (2), using terciles rather than deciles of the property value distribution and interacting these tercile-specific treatment effects with the urban-rural classifications of the Output Area (OA). The dependent variable is the number of new installations in an OA over 2017-2021. See Table B.7.

Scotland after 2017. In England, as FiT support waned, installations fell and the distribution became more regressive. These results highlight the role of policies that relax credit constraints and help with upfront costs in promoting more equitable access to solar PV.

Finally, we combine the distributional analysis with the urban-rural heterogeneity above. To maintain sufficient sample sizes for statistical power we use terciles rather than deciles of the property value distribution, and interact the decile-specific treatment effects with the OA's urban-rural category.[34] Figure 9 shows the Poisson coefficient estimates: the wealthiest tercile gains relative to England across all urban-rural categories; urban and rural-accessible OAs benefit across all terciles, with an especially large effect for the lowest tercile, and rural-remote OAs do not appear to benefit outside the upper tercile. Taken together, the HES Loan's contribution to equitable access is nuanced and heterogeneous across neighborhood types.

7 How the HES Loan promoted equitable adoption

In contrast to many other solar subsidies, a loan subsidy such as the HES Loan requires households to repay the loan principal to the government. The policy therefore incentivizes adoptions through a consumption-smoothing, financing channel: by lowering the cost of delaying payment of installation costs, it raises the net present value (NPV) of

[34] See Table B.7 for full results including those with total annual generation as the outcome variable and using the OLS estimator.

investing in PV. We formalise this intuition with a simple framework that assumes equal annual loan repayments and household-specific discounting. The NPV of taking a loan to install PV is given by the following:

$$NPV_h = \sum_{t=1}^{25} \frac{R_{ht}}{(1+r_h)^t} - \sum_{t=1}^{10} \frac{A_h}{(1+r_h)^t} - (C_h - L_h) \tag{3}$$

The first term in Equation 3 is the discounted annual net revenue (R_{ht}) that the household receives over the (assumed) 25-year lifetime of the PV system. This revenue includes electricity savings, operating expenses, and any subsidy payments received under the FiT or Smart Export Guarantee schemes (depending on the availability of these schemes in the year of installation). The second term is the discounted annual loan repayments under a loan interest rate of i. Under the assumption of equal annual repayments, these are $A_h = L_h \cdot \frac{i}{1-(1+i)^{-T}}$ for a private market loan, and simply $A_h = L_h/T$ for the HES loan . The loan principal, L_h, and the total installation costs, C_h, vary across households according to their system size choice, which we take as given for the purposes of this discussion. The final term, $C_h - L_h$, is the outstanding installation costs, C_h, that remain after receiving the loan in the first period.[35] Each household discounts future revenue and payments using their individual discount rate r_h. Empirically, this parameter captures not only a household's pure rate of time preference but also unobservable factors driving their consumption smoothing behaviours.[36]

Figure 10 is a stylized example of how households' discount rates impact the NPV under three payment options: upfront ($L_h = 0$); a private loan; and the HES Loan. For households with high implicit discount rates, the upfront option yields low (or even negative) NPV,[37] while any loan raises NPV by shifting costs into the future; setting the loan rate to zero increases NPV for all households, and proportionally more for those with higher r_h. This pattern helps rationalize our distributional findings: the HES Loan's gains are broad but strongest at the bottom of the property-value distribution and among

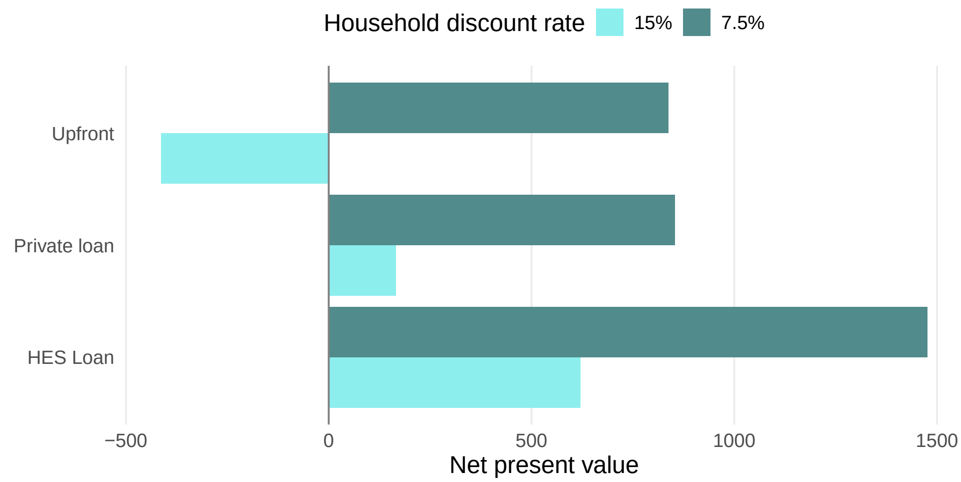
[35]The MCS data suggest that the maximum loan size of £5000 would cover 85-100% of costs for systems up to 4kW installed in 2017-2021. For simplicity, the analysis if Figure 10 assumes $C_h - L_h = 0$.

[36]In practice, we usually cannot observe household-level differences in borrowing costs (i), so empirically this heterogeneity is absorbed into the discount rate. Bollinger, Gillingham and Kirkpatrick (2025) call this parameter the "implicit" discount rate because it is the discount rate that rationalizes observed behaviours. The factors encompassed in the "implicit" discount rate may include borrowing costs, including binding liquidity or credit constraints, risk perceptions and preferences, households' marginal propensities to consume, and of course time-related factors such as myopia and impatience (Bollinger, Gillingham and Kirkpatrick, 2025).

[37]In our example, the NPV of paying all costs upfront is negative if the household has a discount rate of 15%, which aligns with Bollinger, Gillingham and Kirkpatrick (2025)'s estimate of the discount rate for low-wealth households adopting solar PV in California.

smaller systems, consistent with liquidity constraints and space or consumption limits in urban areas. It also fits the observed size effects: whereas the FiT scaled rewards with generation and thus favored larger, more productive systems, the HES Loan's fixed, non–size-scaled support tilts adoption toward smaller systems.

Figure 10: Net present value of 1-2 kW solar PV system by payment scenario



Notes: This figures shows the net present value of installing solar PV under different payment scenarios. We use 2019 FiT rates and average installation costs for 1-2 kW systems. We assume a 25 year PV system lifetime, a real electricity price of 0.16 p/kWh (2020 GBP) throughout this lifetime, zero annual operating expenditures, 50% of generation exported back to the grid, a private market loan interest rate of 7%, and annual solar generational potential of 908 kWh/kW, which is equivalent to the City of Edinburgh and roughly the Scottish average.

Previous literature on green technology adoption highlights the role of (implicit) discounting in household adoption rates.[38] In household solar PV specifically, several papers estimate high implicit discount rates that rationalize observed adoption rates: De Groote and Verboven (2019) and Talevi (2022) both find rates around 15% for Belgium and the UK respectively; Bollinger, Gillingham and Kirkpatrick (2025) estimate wealth-group-specific discount rates, with 15% for low-wealth households versus 10% for high-wealth households, showing that higher upfront cost subsidies can reduce inequality in the solar PV adoption.

A loan subsidy is therefore a particularly relevant context to study the role of dis-

[38]The large literature on the "energy-efficiency gap" points to household discount rates, in particular consumer myopia, as an explanation for under-investment in energy saving measures (Allcott and Greenstone, 2012; Gillingham and Palmer, 2014; Gerarden, Newell and Stavins, 2017; Allcott, Knittel and Taubinsky, 2015). Related work suggests that consumers may be myopic in valuing future vehicle fuel costs (Busse, Knittel and Zettelmeyer, 2013; Allcott and Wozny, 2014; Grigolon, Reynaert and Verboven, 2018; Gillingham, Houde and van Benthem, 2021). From a macroeconomic perspective, Lanteri and Rampini (2025) show that heterogeneity in financial constraints can generate unequal clean-technology adoption even holding environmental preferences constant.

counting, since it works entirely through consumption-smoothing, i.e. the interest rate and household discount rates. Our main finding that the HES Loan significantly increased installations underscores the importance of time preferences and related drivers of smoothing in green-technology adoption. While we cannot isolate which components of implicit discounting mattered the most, the stronger impact in low-wealth areas suggest channels salient for those households were important, e.g. tighter financial constraints.

Our results build on recent work linking implicit discount rates and financial constraints to equity and adoption (e.g. Bollinger, Gillingham and Kirkpatrick, 2025; Lanteri and Rampini, 2025) . While the FiT scheme targeted larger and more productive systems by scaling rewards with generation, the HES Loan's £5,000 cap is not tailored to such systems. Nevertheless, it raised adoption in a relatively equitable manner. Overall, these results point to the value of policies that help households to tackle upfront costs when seeking both effective and fair PV support (De Groote and Verboven, 2019; Bollinger, Gillingham and Kirkpatrick, 2025).

8 Welfare impact: Marginal value of public funds

We use the marginal value of public funds (MVPF) to assess the welfare impact of the HES Loan. The MVPF is the ratio of total net benefits across all groups to the net costs for the government (Hahn et al., 2024). An MVPF of one implies benefits equal costs, while a value above (below) one indicates that benefits exceed (fall short of) costs. The MVPF is a unified approach that allows for consistent welfare comparisons across a variety of policies, including those in other sectors such as education and health care (Hendren and Sprung-Keyser, 2020; Hahn et al., 2024). Beyond its comparability, the MVPF has further advantages over alternative metrics often used to assess environmental policies, such as social or government cost per ton of CO_2 abated, which often omit long-term costs and benefits (Hahn et al., 2024). Consistent with Hahn et al. (2024) and Hendren and Sprung-Keyser (2020) we begin from the standard expression:

$$MVPF = \frac{x \cdot d\tau + V \cdot dx}{x \cdot d\tau + \tau \cdot dx} = \frac{1 + \frac{V}{p}(-\epsilon)}{1 + \frac{\tau}{p}(-\epsilon)}, \tag{4}$$

where x denotes installed watts of PV, p is the price per watt, τ a per-watt subsidy, V the environmental benefits, and ϵ the price elasticity, which is the estimated behavioural response.

However, none of the policies analyzed in Hahn et al. (2024) are loans. A loan subsidy spreads costs and benefits over the full time horizon from award to repayment, hence valuing it requires using net present values. We therefore adapt Equation 4 to the loan setting by distinguishing the household NPV transfer per watt, s, from the government NPV cost per watt, c.[39] Letting ρ denote the probability of repayment, we define $s = p - \rho\, PV_h(p)$ and $c = p - \rho\, PV_g(p)$, where $PV_h(\cdot)$ and $PV_g(\cdot)$ are functions that transform the loan's principal amount into the present value of future repayments from the household's and government's perspectives, respectively.[40] Substituting s and c for τ and normalising components per £1 NPV transferred to consumers yields the following (see Appendix S4.1 for derivation):

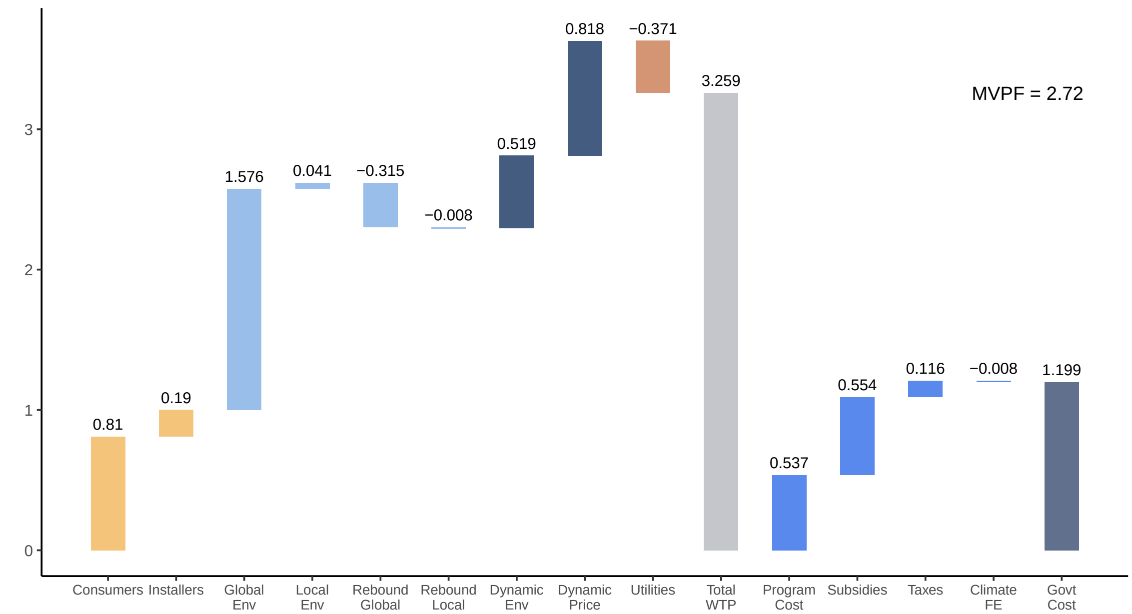
$$\text{MVPF} = \frac{1 + \frac{V}{s}(-\epsilon)}{\left(\frac{dc}{ds}\right) + \frac{c}{s}(-\epsilon)}. \tag{5}$$

This formulation differs from 4 in three ways. First, ϵ is with respect to a 1% change in the *NPV per watt* rather than the upfront cost. Second, the environmental and fiscal externality components of the MVPF, V and c are normalised by s i.e. the net present value of the subsidy value per watt for consumers, not the subsidy cost. Third, $dc/ds \neq 1$ because the government and households value future repayments differently. Under typical discounting assumptions the government is more patient ($r_g < r_h$), implying $dc/ds < 1$: the government can transfer £1 NPV to households at less than £1 NPV fiscal cost by bearing the waiting cost of repayment. Computing a specific value for $\frac{dc}{ds}$ requires making assumptions about discount rates and loan repayment schedules to define a specific functional form for $PV_h(\cdot)$ and $PV_g(\cdot)$. Assuming a 3.5% government discount rate following guidance in The Green Book (HM Treasury, 2022), a household discount rate of 7.5%, equal annual loan repayments, and zero default risk ($\rho = 1$), we obtain $\frac{dc}{ds} = 0.537$. The implied cost to the government to transfer £1 NPV to households is therefore only £0.54.

[39]For more details of this MVPF analysis, see Section S4 in the Appendix. Our calculations and assumptions follow Hahn et al. (2024) as closely as possible to ensure comparability, but to stay consistent with the context we follow The Green Book guidance and other UK government sources for many parameters. See Table S4.1 in the Appendix for a summary of our parameter assumptions and their sources.

[40]These functions capture the difference between how households versus the government value the future (i.e. their discount rates), which underpins the difference between s and c.

Figure 11: Marginal value of public funds



Notes: This figure breaks down each component of our baseline estimate of the MVPF of the HES Loan, with benefits (WTP) on the left side and government net costs on the right side. "Global" and "Local" refer to global and local environmental damages, and "Dynamic" refers to learning-by-doing effects. All components are normalized in terms of per £1 NPV transferred to consumers.

Behavioural response (elasticity). We obtain the elasticity with respect to the consumer's NPV per watt from our causal estimates of the impact of the HES Loan.[41] Specifically, we use the estimates from the event-study DiD (Equation (1)) with total additional annual generation (kWh) at the LSOA-year level as the outcome[42]. The predicted values from this model imply that the HES Loan led to 7,888 annual MWh of additional electricity generation installed in our matched Scottish LSOAs over 2017-2021, accounting for around 50% of observed additions in our matched Scottish LSOAs during this period.[43,44] Figure 11 illustrates the final values for each component of the MVPF under our baseline assumptions. The net benefits are shown on the left side of the figure and the government costs are shown on the right side of the figure, with all components are normalized in terms of per £1 NPV transfer for the consumer.

[41]For further details on how we compute the elasticity as well as all other components of the MVPF, see Section S4 in the Supplemental Information.

[42]Note that when using these estimates to compute the MVPF, we implicitly assume that the treatment effect of the HES Loan was the same in unmatched as in matched LSOAs.

[43]If we assume the same treatment effect in matched and unmatched Scottish LSOAs, the aggregate predicted additional annual production in Scotland is about 33 GWh, which is roughly 0.4% of annual domestic electricity consumption in Scotland (according to the Scottish government's energy statistics, total domestic energy consumption in Scotland was 8,604 GWh in 2022 (link)).

[44]Figure S2.6 illustrates the policy impact by showing our model's predictions for how much capacity was added with versus without the HES Loan, indicating that thanks to the policy capacity additions in matched Scottish LSOAs exceeded those in matched English LSOAs for the first time.

Baseline MVPF and decomposition. As illustrated in Figure 11, we account for a number components per £1 NPV transferred to consumers. On the benefit side, for the direct transfer to consumers, we assume the pass-through rate of £0.81 following Pless and van Benthem (2019), and the remaining £0.19 to installers. For avoided global and local environmental damages, we follow guidance from The Green Book on the projected emission intensity of the UK electricity grid and the social cost of carbon[45] yielding £1.58 and £0.04, respectively. The rebound effect (increased electricity consumption due to electricity cost savings from PV installations) leads to a reduction in global and local environmental damages of £0.32 and £0.008, respectively. Using the approach developed by Hahn et al. (2024) to value the learning-by-doing, the increase in cumulative deployment of solar PV systems due the the HES Loan leads to a decrease in solar PV market prices, yielding "dynamic price" benefits of £0.82 per £1 NPV transferred to consumers. Learning also means that future purchases of solar PV occur sooner than they would have without the HES Loan, leading to additional "dynamic" environmental benefits that we calculate are £0.52 per £1 NPV. Finally, we calculate a cost to utility companies of reduced profits due to the increase in household solar PV capacity of £0.24. All together, these willingness to pay components lead to a total net benefit of the HES Loan £3.39 per £1 transferred to consumers.

On the cost side, the direct cost of the HES Loan to the government is £0.54 as discussed (our dc/ds). The behavioural response to the policy also leads to a number of long-term fiscal externality costs for the government. More solar PV adoption leads to more FiT scheme subsidy payments; we calculate this to be £0.55 per £1 transferred to consumers via the HES Loan. Reduced utility profits due to more rooftop solar reduces taxes from utility companies, estimated at £0.07. Finally, the reduction in climate damages due to the policy benefits economic production and results in a positive fiscal externality (i.e. a negative cost) via an increase in taxes collected of £0.008. The total government net costs of the HES Loan are £1.16 per £1 NPV transferred to consumers. Combined, the estimated MVPF of the HES Loan is 2.72 indicating that the policy was welfare-improving, the MVPF being greater than 1.

[45]Our baseline MVPF estimate uses The Green Book's central scenario of an SCC starting at £253/tCO_2e SCC in 2020 and rising each year.

Table 2: MVPF: Sensitivity to alternative assumptions

Variant	MVPF
Baseline	2.72
Low SCC	2.19
High SCC	3.25
Marginal adopters	2.55
No transition to Net Zero	11.96
Lower elasticity (-1 s.e.)	2.27
Higher elasticity (+1 s.e.)	4.81
No learning-by-doing	1.59
High household discount rate	9.77
Credit-constrained households	2.51

Notes: This table compares our baseline estimates of the MVPF of the HES Loan to alternative assumptions about the social cost of carbon (SCC), the future emissions intensity of the UK electricity grid, the behvioural response to the HES Loan (elasticity), learning-by-doing effects, and household valuation of future benefits and the HES Loan.

Sensitivity. Table 2 shows the MVPF remains above 1 under a number of alternative assumptions, providing a high degree of confidence that the policy was welfare-improving. First, we use alternative trajectories for the social cost of carbon (SCC): in the low SCC scenario, which starts at £127/tCO_2e in 2020, the MVPF is 2.19, and in the high SCC scenario of £380/tCO_2e in 2020, the MVPF is 3.25. Second, if we assume that 50% of adoptions resulting from the policy are marginal[46], we obtain an MVPF of 2.55. Next, instead of assuming the UK power grid reaches Net Zero by 2050, we use an alternative "worst-case" scenario where the carbon intensity of the grid remains at 2025 levels of 0.21 kgCO_2 per kWh, and find that the MVPF of the HES Loan increases significantly to 11.96. We also compute the MVPF under elasticities that are 1 standard deviation below and above our main elasticity estimate; accounting for the statistical uncertainty in our elasticity estimate in this manner implies a confidence interval for our MVPF estimate ranging between 2.27 and 4.81. When we disregard potential learning-by-doing effects, the MVPF decreases to 1.59, implying that the HES Loan is still welfare-improving, but these dynamic effects play an important role in our baseline MVPF estimate.[47] Finally, we compute the MVPF under

[46]In our baseline calculations we assume all adoptions are infra-marginal following Hahn et al. (2024)'s approach for solar subsidies. However, our model predictions shown in Figure S2.6 suggest that around 50% of adoptions are marginal. Under this alternative assumption, we follow Hendren and Sprung-Keyser (2020) by assuming uniformly distributed willingness-to-pay (linear demand) across marginal adopters, which implies that the average value for marginal adopters of a £1 NPV transfer is £0.50 NPV. Taking the weighted average across infra-marginal and marginal adopters and applying the pass-through rate, the value of the direct transfer to consumers is $0.81 \times ((0.5 \times 1) + (0.5 \times 0.5)) = 0.61$ per £1 NPV transferred.

[47]For comparison, Hahn et al. (2024) find that the average MVPF for solar PV in their primary sample decreases from 2.26 to 1.45 when they disregard learning-by-doing effects.

a couple of alternative assumptions about households. If we assume that households have a very high discount rate of 15%, as suggested by the findings in Bollinger, Gillingham and Kirkpatrick (2025) and Talevi (2022), the MVPF is 9.77. If we calculate the elasticity under the assumption that households face binding credit constraints and private loans for solar PV are not available to them, then the MVPF decreases to 2.51.

Overall, the MVPF of the HES Loan compares favourably with other solar policies especially in the U.S., despite Scotland's lower insolation.[48] For comparison, Hahn et al. (2024) find that the "in-context" MVPFs of the U.S. subnational solar PV subsidies included in their primary sample range from 0.65 to 3.28 with an average of 2.26. Of course, the HES Loan is more recent policy initiative compared to earlier U.S. programmes, especially the California Solar Initiative, and the more recent decline in solar PV prices certainly helps to boost the relative cost effectiveness of the HES Loan. However, the value-for-money that the loan subsidy provides also plays a crucial role in this result.

9 Conclusion

This paper shows that an interest-free loan can be a cost-effective, welfare-increasing way to deliver higher deployment and long-run welfare gains, where public discounting is lower than private discounting and upfront costs impede adoption. We show this in the context of rooftop solar PV adoption, even in the famously unsunny setting that is Scotland. By operating through a consumption-smoothing channel, the HES Loan raised adoption without amplifying regressivity, and delivered welfare gains with a marginal value of public funds comfortably above one. Taken together, the evidence suggests that when technology costs are low and fiscal space is constrained, a well-designed zero-interest loan is a practical instrument for expanding access to clean technology while maintaining fiscal efficiency.

Our contribution is twofold. First, to our knowledge this is the first causal evaluation of an interest-free loan for residential renewable adoption. The design matters: shifting costs over time and lowering the borrowing rate directly relaxes liquidity constraints that bind more tightly for many households than for the public sector. In such contexts the government can transfer one pound of net present value to consumers at less than one pound of fiscal NPV cost, a feature that is absent in grant or tariff designs and that helps explain why the measured welfare bang-for-buck is strong. Second, we connect this

[48] For example, according to the Global Solar Atlas, the expected annual production per 1 kW residential solar PV capacity is 887 kWh in Edinburgh, Scotland and 1,734 kWh in Los Angeles, California. https://globalsolaratlas.info/map

mechanism to distributional performance. Whereas support for production (e.g. FiT) tend to benefit larger systems and higher-wealth households more, a capped, interest-free loan can broaden participation.

The findings also speak to instrument choice within a broader decarbonisation portfolio. In Scotland, small-scale rooftop PV is not the cheapest source of abatement when compared with, say, offshore wind. But the relevant counterfactual for policy is not a single-technology race to the lowest cost per tonne. Households face credit constraints; distributional objectives and political feasibility matter; and some dynamic benefits (e.g., learning-by-doing, supply-chain development) accrue outside narrow static cost metrics. Our welfare analysis indicates that, even in northern latitudes, the cost difference is acceptable when multiple objectives are pursued alongside abatement, including access, participation, and long-run learning. Overall, a key implication is that interest-free loans should take a more prominent place in the green technology adoption policy mix as costs fall, if the aim is broad uptake at low fiscal cost and without worsening regressivity.

References

Allcott, Hunt, and Michael Greenstone. 2012. "Is there an Energy Efficiency Gap?" *Journal of Economic Perspectives*, 26: 3–28.

Allcott, Hunt, and Nathan Wozny. 2014. "Gasoline prices, fuel economy, and the energy paradox." *The Review of Economics and Statistics*, 96(5): 779–795.

Allcott, Hunt, Christopher Knittel, and Dmitry Taubinsky. 2015. "Tagging and targeting of energy efficiency subsidies." *American Economic Review*, 105: 187–191.

Balta-Ozkan, Nazmiye, Julide Yildirim, and Peter M Connor. 2015. "Regional distribution of photovoltaic deployment in the UK and its determinants: A spatial econometric approach." *Energy Economics*, 51: 417–429.

Bank of England. 2025. "Data Series CFMBI73." Bank of England Database. Available at: https://wwwtest.bankofengland.co.uk/... SearchText=CFMBI73, Accessed 2025-09-17.

Barbose, Galen L, Sydney Forrester, Naïm R Darghouth, and Ben Hoen. 2020. "Income Trends among US Residential Rooftop Solar Adopters." Lawrence Berkeley National Laboratory, Berkeley, CA (United States).

Bergquist, Magnus, Andreas Nilsson, Niklas Harring, and Sverker C. Jagers. 2022. "Meta-analyses of fifteen determinants of public opinion about climate change taxes and laws." *Nature Climate Change*, 12(3): 235–240.

Bernard, Louise, Andy Hackett, Robert D Metcalfe, and Andrew Schein. 2024. "Decarbonizing Heat: The Impact of Heat Pumps and a Time-of-Use Heat Pump Tariff on Energy Demand." *NBER Working Paper Series*, 33036.

Bertoldi, Paolo, Marina Economidou, Valentina Palermo, Benigna Boza-Kiss, and Valeria Todeschi. 2021. "How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU." *Wiley Interdisciplinary Reviews: Energy and Environment*, 10: e384.

Best, Rohan, Andrea Chareunsy, and Han Li. 2021. "Equity and effectiveness of Australian small-scale solar schemes." *Ecological Economics*, 180: 106890.

Bollinger, Bryan, Kenneth Gillingham, and A Justin Kirkpatrick. 2025. "Valuing Solar Subsidies." *NBER Working Paper Series*, 33368.

Borenstein, Severin. 2017. "Private net benefits of residential solar PV: The role of electricity tariffs, tax incentives, and rebates." *Journal of the Association of Environmental and Resource Economists*, 4(S1): S85–S122.

Busse, Meghan R, Christopher R Knittel, and Florian Zettelmeyer. 2013. "Are consumers myopic? Evidence from new and used car purchases." *The American Economic Review*, 103: 220–256.

Callaway, Duncan S, Meredith Fowlie, and Gavin McCormick. 2018. "Location, Location, Location: The Variable Value of Renewable Energy and Demand-Side Efficiency Resources." *Journal of the Association of Environmental and Resource Economists*, 5(1): 39–75.

Darghouth, Naïm R, Eric O'Shaughnessy, Sydney Forrester, and Galen Barbose. 2022. "Characterizing local rooftop solar adoption inequity in the US." *Environmental Research Letters*, 17(3): 034028.

De Groote, Olivier, and Frank Verboven. 2019. "Subsidies and time discounting in new technology adoption: Evidence from solar photovoltaic systems." *American Economic Review*, 109(6): 2137–2172.

De Groote, Olivier, Axel Gautier, and Frank Verboven. 2024. "The political economy of financing climate policy—Evidence from the solar PV subsidy programs." *Resource and Energy Economics*, 77: 101436.

De Groote, Olivier, Guido Pepermans, and Frank Verboven. 2016. "Heterogeneity in the adoption of photovoltaic systems in Flanders." *Energy Economics*, 59: 45–57.

DESNZ. 2023. "Electricity Generation Costs 2023." Department for Energy Security and Net Zero. Available at: https://www.gov.uk/government/publications/electricity-generation-costs-2023, Accessed 2025-10-17.

DESNZ. 2024. "Subnational electricity consumption data." Department for Energy Security and Net Zero. Available at: https://www.gov.uk/government/collections/sub-national-electricity-consumption-data, Accessed 2024-07-15.

DESNZ. 2025*a*. "Annual domestic energy bills." Department for Energy Security and Net Zero. Available at: https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics, Accessed 2025-10-17.

DESNZ. 2025*b*. "Digest of UK Energy Statistics (DUKES)." Department for Energy Security and Net Zero. Available at: https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2025, Accessed 2025-10-17.

DLUHC. 2024. "Energy Performace of Buildings Register." Department for Levelling Up, Housing & Communities. Available at: https://epc.opendatacommunities.org/, Accessed 2024-07-15.

Energy Saving Trust. 2024. "Scottish Energy Performance Certificate Register." Energy Saving Trust. Available at: https://www.scottishepcregister.org.uk/, Accessed 2024-07-15.

European Commission. 2025. "2024 Report on Energy subsidies in the EU." Directorate-General for Energy, European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2025:17:FIN.

Feger, Fabian, Nicola Pavanini, and Doina Radulescu. 2022. "Welfare and redistribution in residential electricity markets with solar power." *The Review of Economic Studies*, 89(6): 3267–3302.

Fowlie, Meredith, and Nicholas Muller. 2019. "Market-Based Emissions Regulation When Damages Vary across Sources: What Are the Gains from Differentiation?" *Journal of the Association of Environmental and Resource Economists*, 6(3): 593–632.

Gerarden, Todd D, Richard G Newell, and Robert N Stavins. 2017. "Assessing the energy-efficiency gap." *Journal of Economic Literature*, 55: 1486–1525.

Germeshausen, Robert. 2018. "Effects of attribute-based regulation on technology adoption–the case of feed-in tariffs for solar photovoltaic." *ZEW-Centre for European Economic Research Discussion Paper*, 18-057.

Gillingham, Kenneth, and Karen Palmer. 2014. "Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence." *Review of Environmental Economics and Policy*, 8: 18–38.

Gillingham, Kenneth, and Tsvetan Tsvetanov. 2019. "Hurdles and steps: Estimating demand for solar photovoltaics." *Quantitative Economics*, 10(1): 275–310.

Gillingham, Kenneth T, Sébastien Houde, and Arthur A van Benthem. 2021. "Consumer myopia in vehicle purchases: Evidence from a natural experiment." *American Economic Journal: Economic Policy*, 13: 207–238.

Graziano, Marcello, and Kenneth Gillingham. 2015. "Spatial patterns of solar photovoltaic system adoption: the influence of neighbors and the built environment." *Journal of Economic Geography*, 15(4): 815–839.

Grigolon, Laura, Mathias Reynaert, and Frank Verboven. 2018. "Consumer valuation of fuel costs and tax policy: Evidence from the European car market." *American Economic Journal: Economic Policy*, 10: 193–225.

Grover, David, and Benjamin Daniels. 2017. "Social equity issues in the distribution of feed-in tariff policy benefits: A cross sectional analysis from England and Wales using spatial census and policy data." *Energy Policy*, 106: 255–265.

Hahn, Robert W., Nathaniel Hendren, Robert D. Metcalfe, and Ben Sprung-Keyser. 2024. "A Welfare Analysis of Policies Impacting Climate Change." *NBER Working paper Series*, 32728.

Hansen, Anders Rhiger, Mette Hove Jacobsen, and Kirsten Gram-Hanssen. 2022. "Characterizing the Danish energy prosumer: Who buys solar PV systems and why do they buy them?" *Ecological Economics*, 193: 107333.

Hendren, Nathaniel, and Ben Sprung-Keyser. 2020. "A unified welfare analysis of government policies." *The Quarterly Journal of Economics*, 135: 1209–1318.

HM Land Registry. 2024. "Price paid data." HM Land Registry. Available at: https://www.gov.uk/government/statistical-data-sets/price-paid-data-downloads, Accessed 2024-08-20.

HM Revenue & Customs. 2025. "Corporation Tax rates and allowances." UK Government. Available at: https://www.gov.uk/government/publications/rates-and-allowances-corporation-tax/rates-and-allowances-corporation-tax, Accessed 2025-10-17.

HM Treasury. 2022. "The Green Book: Appraisal and Evaluation in Central Government." May 2024 ed., UK Government.

Home Energy Scotland. 2022. "Home Energy Scotland Grant and Loan: in detail." Available at: https://www.homeenergyscotland.org/funding/grants-loans/detail/, Accessed 2023-10-13.

Hoppmann, Joern, Joern Huenteler, and Bastien Girod. 2014. "Compulsive policy-making—The evolution of the German feed-in tariff system for solar photovoltaic power." *Research Policy*, 43(8): 1422–1441.

Huber, Robert A., Michael L. Wicki, and Thomas Bernauer. 2020. "Public support for environmental policy depends on beliefs concerning effectiveness, intrusiveness, and fairness." *Environmental Politics*, 29(4): 649–673.

Hughes, Jonathan E, and Molly Podolefsky. 2015. "Getting green with solar subsidies: evidence from the California solar initiative." *Journal of the Association of Environmental and Resource Economists*, 2(2): 235–275.

Iacus, Stefano M, Gary King, and Giuseppe Porro. 2012. "Causal inference without balance checking: Coarsened exact matching." *Political Analysis*, 20(1): 1–24.

IEA. 2022. "Renewables 2022." IEA. Available at: https://www.iea.org/reports/renewables-2022.

IEA. 2023. "World Energy Outlook 2023." IEA. Available at: https://www.iea.org/reports/world-energy-outlook-2023.

IRENA. 2019. "Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects." International Renewable Energy Agency. Available at: https://www.irena.org/publications/2019/Nov/Future-of-Solar-Photovoltaic.

IRENA. 2023. "Renewable power generation costs in 2022." International Renewable Energy Agency. Available at: https://www.irena.org/ ... /IRENA_Renewable_power_generation_costs_in_2022.pdf.

Jacksohn, Anke, Peter Grösche, Katrin Rehdanz, and Carsten Schröder. 2019. "Drivers of renewable technology adoption in the household sector." *Energy Economics*, 81: 216–226.

Kilinc-Ata, Nurcan. 2016. "The evaluation of renewable energy policies across EU countries and US states: An econometric approach." *Energy for Sustainable Development*, 31: 83–90.

Krasko, Vitaliy A, and Elizabeth Doris. 2013. "State distributed PV policies: Can low cost (to government) policies have a market impact?" *Energy Policy*, 59: 172–181.

Kuckshinrichs, Wilhelm, Tobias Kronenberg, and Patrick Hansen. 2010. "The social return on investment in the energy efficiency of buildings in Germany." *Energy Policy*, 38(8): 4317–4329.

Lanteri, Andrea, and Adriano Rampini. 2025. "Financing the adoption of clean technology." *NBER Working Paper Series*, 33545.

Lukanov, Boris R, and Elena M Krieger. 2019. "Distributed solar and environmental justice: Exploring the demographic and socio-economic trends of residential PV adoption in California." *Energy Policy*, 134: 110935.

MCS. 2024. "MCS Installations Database." Microgeneration Certification Scheme.

Mir-Artigues, Pere, and Pablo Del Río. 2014. "Combining tariffs, investment subsidies and soft loans in a renewable electricity deployment policy." *Energy Policy*, 69: 430–442.

Myllyvirta, Lauri. 2025. "Analysis: Record solar growth keeps China's CO2 falling in first half of 2025." Carbon Brief, Available at: https://www.carbonbrief.org/analysis-record-solar-growth-keeps-chinas-co2-falling-in-first-half-of-2025/, Accessed 4 December 2025.

Nemet, Gregory F. 2019. *How solar energy became cheap: A model for low-carbon innovation.* Routledge.

NRS. 2015. "Urban Rural Classification – Scotland." National Records of Scotland. Available at: https://statistics.gov.scot/data/urban-rural-classification, Accessed 2024-08-20.

OECD. 2025. "Global Revenue Statistics Database." Organisation for Economic Co-operation and Development. Available at: https://www.oecd.org/en/data/datasets/global-revenue-statistics-database.html, Accessed 2025-10-14.

Ofgem. 2023*a*. "Energy Company Obligation (ECO3) Final Determination Report." Office of Gas and Electricity Markets. Available at: https://www.ofgem.gov.uk/transparency-document/energy-company-obligation-eco3-final-determination-report.

Ofgem. 2023*b*. "FIT Rates RPI Update 23-24." Office of Gas and Electricity Markets. Available at: https://www.ofgem.gov.uk/data/feed-tariff-fit-tariff-table-1-april-2023.

Ofgem. 2023*c*. "FIT Supplier Guidance."

Ofgem. 2024. "Smart Export Guarantee Annual Report – April 2023 to March 2024." Office of Gas and Electricity Markets. Available at: https://www.ofgem.gov.uk/transparency-document/smart-export-guarantee-annual-report-april-2023-march-2024.

ONS. 2013. "2011 Census: QS405EW (Tenure - Households)." Office for National Statistics. Available at: https://www.nomisweb.co.uk/census/2011/qs405ew.

ONS. 2016. "2011 Rural–Urban Classification (small area geographies)." Office for National Statistics. Available at: https://www.ons.gov.uk/ ... /2011ruralurbanclassification, Accessed 2024-08-20.

ONS. 2024. "Trends in UK business dynamism and productivity: 2024." Office for National Statistics. Available at: https://www.ons.gov.uk/economy/ ... /trendsinukbusinessdynamismandproductivity/2024, Accessed 2025-10-17.

O'Shaughnessy, Eric, Galen Barbose, Ryan Wiser, Sydney Forrester, and Naïm Darghouth. 2021. "The impact of policies and business models on income equity in rooftop solar adoption." *Nature Energy*, 6(1): 84–91.

Pless, Jacquelyn, and Arthur A van Benthem. 2019. "Pass-through as a test for market power: An application to solar subsidies." *American Economic Journal: Applied Economics*, 11(4): 367–401.

Registers of Scotland. 2024. "House Prices – Residential Properties Sales and Price." Scottish Government. Available at: https://www.ros.gov.uk/data-and-statistics/property-market-statistics/small-area-statistics, Accessed 2024-08-20.

Ros, Agustin J, and Sai Shetty Sai. 2023. "Residential rooftop solar demand in the US and the impact of net energy metering and electricity prices." *Energy Economics*, 118: 106491.

Rosenow, Jan, Reg Platt, and Andrea Demurtas. 2014. "Fiscal impacts of energy efficiency programmes—The example of solid wall insulation investment in the UK." *Energy Policy*, 74: 610–620.

Roth, Jonathan. 2022. "Pretest with Caution: Event-Study Estimates after Testing for Parallel Trends." *American Economic Review: Insights*, 4(3): 305–22.

Scotland's Census. 2011. "2011 Census: Output Area 2011." National Records of Scotland. Available at: https://www.scotlandscensus.gov.uk/documents/2011-census-table-data-output-area-2011/, Accessed 2024-07-15.

Scottish Government. 2019. "Home Energy Efficiency Programmes for Scotland: Delivery Report 2017/18." Available at: https://www.gov.scot/publications/home-energy-efficiency-programmes-scotland-delivery-report-2017-18/.

Scottish Government. 2020. "Warmer Homes Scotland programme: annual review 2018-2019." Available at: https://www.gov.scot/publications/warmer-homes-scotland-programme-annual-review-2018-19/documents/.

Snashall-Woodhams, Nicholas. 2019. "Targeting Solar Subsidies." Working Paper.

Solar Energy UK. 2025. "Smart Export Guarantee League Table." Available at: https://solarenergyuk.org/resource/smart-export-guarantee/, Accessed 8 Dec 2025.

Steward, Darlene, Elizabeth Doris, Vitaly Krasko, and Daniel Hillman. 2014. "Effectiveness of state-level policies on solar market development in different state contexts." National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Talevi, M. 2022. "Incentives for the energy transition: Feed-in tariffs, rebates, or a hybrid design." CESifo Area Conferences 2022: Energy & Climate Economics.

U.K. Government. 2022. "British Energy Security Strategy." U.K. Department for Energy Security & Net Zero and Prime Minister's Office 10 Downing Street and Department for Business, Energy & Industrial Strategy Policy Paper.

Warmworks. 2020. "Warmworks Annual Report 2019/20." Warmworks Scotland. Available at: https://www.warmworks.co.uk/wp-content/uploads/2022/04/Warmworks-Annual-Report-2019-20.pdf.

Warmworks. 2021. "Warmer Homes Scotland Annual Report 2020/21." Warmworks Scotland. Available at: https://www.warmworks.co.uk/wp-content/uploads/2022/03/Annual-Report-2020-21.pdf.

Warmworks. 2022. "Warmer Homes Scotland Annual Report 2021/22." Warmworks Scotland. Available at: https://www.warmworks.co.uk/wp-content/uploads/2022/06/Warmer-Homes-Scotland-2122-Annual-Report.pdf.

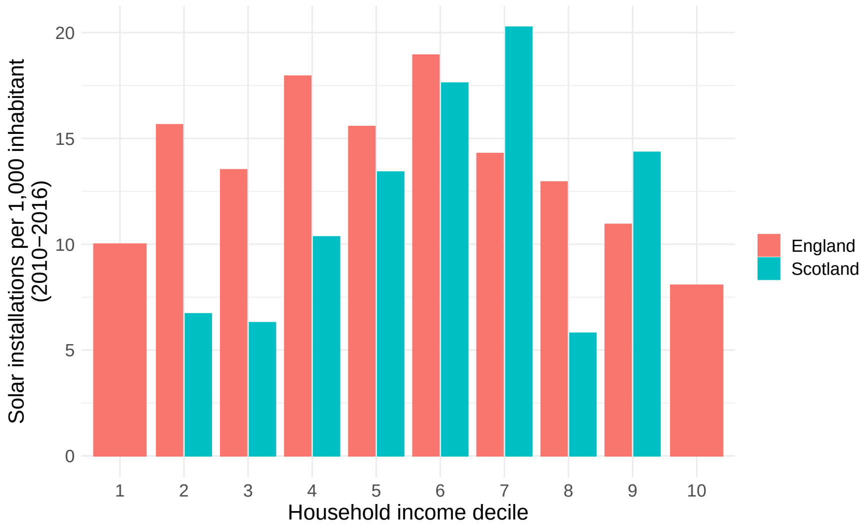
Way, Rupert, Matthew C Ives, Penny Mealy, and J Doyne Farmer. 2022. "Empirically grounded technology forecasts and the energy transition." *Joule*, 6: 2057–2082.

World Bank. 2023. "Global Solar Atlas." Washington, DC, Available at: https://globalsolaratlas.info, Accessed 2023-03-13.

World Bank. 2025. "World Development Indicators." Available at: https://databank.worldbank.org/reports.aspx?source=2series=NY.GDP.MKTP.PP.CD, Accessed 2025-10-14.

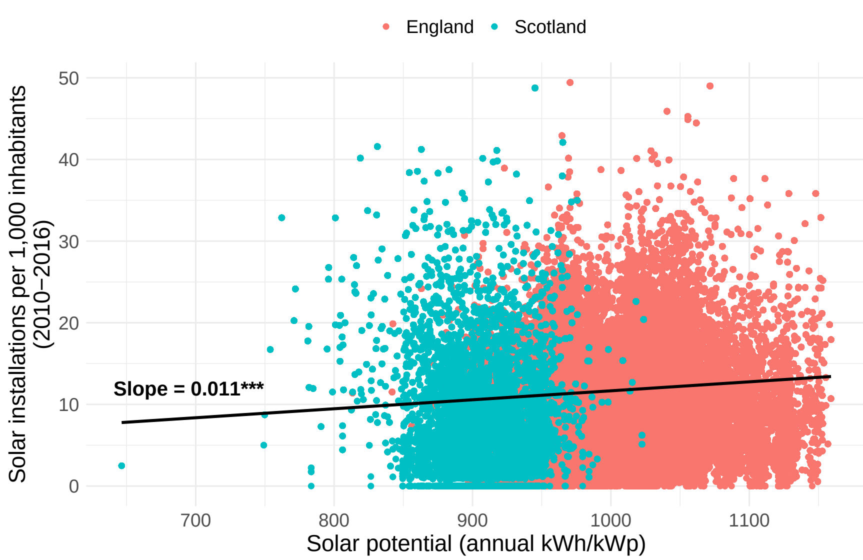
A Additional Figures

Figure A.1: Solar PV installations per household income decile (2010-2016)



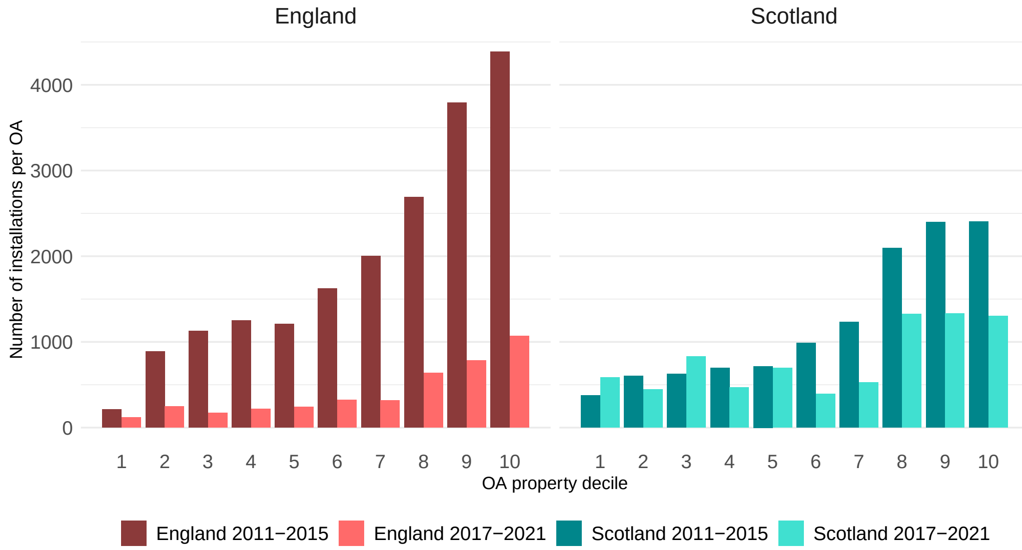
Notes: Income deciles are defined across the entire UK, then applied to English and Scottish households. Household income data obtained at the Middle-Layer Super Output Area (MSOA).

Figure A.2: Solar generation potential and pre-treatment PV installations



Notes: Solar generation potential obtained from the World Bank's Solar Atlas (2023). We aggregate the 1 km x 1 km solar potential gridded data to the LSOA level. The fitted line and slope indicate the results of a simple OLS regression of solar potential on total installations per 1,000 inhabitants during 2010-2016. * $p \leq 0.10$, ** $p \leq 0.05$, *** $p \leq 0.01$

Figure A.3: Unconditional distributions of installations per OA



Notes: This figure shows the count of installations per Output Area for England versus Scotland both before and after the HES Loan was introduced in 2017. Output Areas included are those within LSOAs in our matched sample.

B Additional Tables

Table B.3: Main event-study estimates

	Number of Installations			Total annual generation (kWh)		
	Poisson		OLS	Poisson		OLS
	(1)	(2)	(3)	(4)	(5)	(6)
2011 x Scotland	-0.112		-0.075	0.138		361.904
	(0.219)		(0.261)	(0.151)		(462.805)
2012 x Scotland	-0.597**		-1.338**	-0.070		-969.352
	(0.297)		(0.637)	(0.160)		(780.442)
2013 x Scotland	-0.089		-0.045	0.112		198.087
	(0.182)		(0.146)	(0.169)		(445.038)
2014 x Scotland	-0.677**		-1.046**	-0.417*		-2414.175**
	(0.307)		(0.465)	(0.252)		(1091.060)
2015 x Scotland	-0.309		-0.515*	-0.052		-861.088
	(0.221)		(0.311)	(0.144)		(667.197)
2017 x Scotland	0.104	0.480*	0.045	0.163	0.404**	252.681
	(0.278)	(0.264)	(0.162)	(0.207)	(0.193)	(291.609)
2018 x Scotland	0.912***	1.295***	0.636***	0.713***	1.001***	1130.521***
	(0.197)	(0.211)	(0.148)	(0.193)	(0.197)	(311.248)
2019 x Scotland	1.057***	1.447***	1.228***	0.887***	1.224***	2074.132***
	(0.316)	(0.330)	(0.291)	(0.229)	(0.217)	(506.938)
2020 x Scotland	1.262***	1.659***	0.888***	1.020***	1.405***	1549.180***
	(0.276)	(0.309)	(0.213)	(0.221)	(0.248)	(360.164)
2021 x Scotland	0.726***	1.130***	0.456***	0.541***	0.975***	901.518***
	(0.236)	(0.329)	(0.159)	(0.184)	(0.233)	(309.025)
Scotland x Year		-0.007			-0.048**	
		(0.036)			(0.023)	
N	28,281	28,281	28,281	28,281	28,281	28,281
R^2	0.451	0.449	0.237	0.797	0.796	0.299
Adj. R^2	0.421	0.419	0.16	0.797	0.796	0.228
Year FE	X	X	X	X	X	X
LSOA FE	X	X	X	X	X	X

Notes: This table shows the main event-study difference-in-difference results estimated on our matched sample of LSOAs. Columns (1) and (4) are the main specifications for each outcome variable, annual number of installations and total added annual generation (kWh) per LSOA. Columns (2) and (5) replace the year-specific pre-treatment (2011-2015) coefficients with a linear time trend for these years interacted with the Scotland dummy. Columns (3) and (6) show our baseline specification estimated using the OLS rather than Poisson estimator. In all columns the reference year is 2016, estimates are weighted using the LSOA matching weights, and standard errors are clustered at the matching subclass level. * $p \leq 0.10$, ** $p \leq 0.05$, *** $p \leq 0.01$

Table B.4: Main 2-period difference-in-differences estimates

	Number of installations	Number of small installations	Number of large installations	Mean annual generation
Panel A: Poisson coefficient estimates				
HES Loan	1.099***	2.346***	0.531***	-0.243*
	(0.166)	(0.410)	(0.119)	(0.127)
N	5,142	3,266	5,020	5,142
R^2	0.742	0.641	0.774	0.643
Adj. R^2	0.7	0.561	0.721	0.643
Period FE	X	X	X	X
LSOA FE	X	X	X	X
Panel B: OLS coefficient estimates				
HES Loan	6.343***	6.908***	1.781***	-494.882
	(0.961)	(1.241)	(0.490)	(303.886)
N	5,142	3,266	5,020	5,142
R^2	0.614	0.515	0.684	0.484
Adj. R^2	0.228	0.029	0.368	-0.033
Period FE	X	X	X	X
LSOA FE	X	X	X	X

Notes: This table shows 2-period difference-in-difference results estimated on our matched sample of LSOAs in Scotland versus England for 2011-2015 (pre-treatment) versus 2017-2021 (post-treatment). Outcome variables (indicated in the column header) are the total number or average size of installations per LSOA by 5-year period. The treatment variable, "HES Loan", is the interaction between being in Scotland and the post-treatment period. Small installations are those with estimated annual generation less than or equal to 1,700 kWh, and large installations are those with strictly greater that 1,700 kWh estimated annual generation. Estimates are weighted using the LSOA matching weights, and standard errors are clustered at the matching subclass level. * $p \leq 0.10$, ** $p \leq 0.05$, *** $p \leq 0.01$

Table B.5: Main urban-rural heterogeneity estimates

	Number of installations	Number of small installations	Number of large installations	Mean annual generation
Panel A: Poisson coefficient estimates				
HES Loan x Rural accessible	1.044***	2.497***	0.600***	0.083
	(0.190)	(0.455)	(0.137)	(0.119)
HES Loan x Rural remote	0.667	1.934**	0.313	0.133
	(0.423)	(0.869)	(0.263)	(0.146)
HES Loan x Urban	1.175***	2.325***	0.519***	-0.341**
	(0.188)	(0.434)	(0.143)	(0.135)
N	5,142	3,266	5,020	5,142
R^2	0.742	0.641	0.774	0.647
Adj. R^2	0.701	0.561	0.721	0.646
Period FE	X	X	X	X
LSOA FE	X	X	X	X
Panel B: OLS coefficient estimates				
HES Loan x Rural accessible	2.483	8.519***	-4.004***	189.727
	(2.271)	(2.234)	(1.050)	(291.247)
HES Loan x Rural remote	-3.524	5.628	-7.711***	333.309
	(4.906)	(4.350)	(2.355)	(376.738)
HES Loan x Urban	7.392***	6.574***	3.212***	-645.211**
	(0.947)	(1.303)	(0.523)	(316.548)
N	5,142	3,266	5,020	5,142
R^2	0.619	0.516	0.7	0.488
Adj. R^2	0.237	0.029	0.399	-0.026
Period FE	X	X	X	X
LSOA FE	X	X	X	X

Notes: This table shows heterogeneity in the 2-period difference-in-difference results by urban-rural classification of LSOAs in our matched sample across 2011-2015 (pre-treatment) versus 2017-2021 (post-treatment). Outcome variables (indicated in the column header) are the total number or average size of installations per LSOA by 5-year period. The treatment variable, "HES Loan", which is the interaction between being in Scotland and the post-treatment period, is interacted with each of the three urban-rural categories: urban, rural accessible, and rural remote. Small installations are those with estimated annual generation less than or equal to 1,700 kWh, and large installations are those with strictly greater that 1,700 kWh estimated annual generation. Estimates are weighted using the LSOA matching weights, and standard errors are clustered at the matching subclass level. * p ≤ 0.10, ** p ≤ 0.05, *** p ≤ 0.01

Table B.6: Output Area Distributional DiD results

	Number of installations			Total annual generation (kWh)		
	Poisson		OLS	Poisson		OLS
	Coefficients	AMEs	Coefficients	Coefficients	AMEs	Coefficients
HES Loan x Q1	2.106***	2.055**	3.599***	1.515***	10622.521***	6709.726***
	(0.356)	(0.833)	(0.625)	(0.284)	(3872.208)	(976.873)
HES Loan x Q2	1.369***	1.006**	2.300***	1.077***	7956.653**	5261.229***
	(0.309)	(0.418)	(0.497)	(0.272)	(3285.566)	(934.383)
HES Loan x Q3	1.946***	1.925**	3.316***	1.508***	13083.591***	6661.891***
	(0.335)	(0.753)	(0.717)	(0.260)	(4369.307)	(1091.602)
HES Loan x Q4	1.263***	0.933**	2.121***	0.926***	6091.191**	4571.581***
	(0.327)	(0.425)	(0.517)	(0.247)	(2486.916)	(760.678)
HES Loan x Q5	1.634***	1.403***	2.709***	1.101***	7552.454***	5098.593***
	(0.303)	(0.528)	(0.505)	(0.218)	(2465.203)	(708.536)
HES Loan x Q6	0.743**	0.464*	1.424***	0.285	1451.988	2612.950***
	(0.290)	(0.256)	(0.330)	(0.237)	(1388.939)	(584.115)
HES Loan x Q7	0.818***	0.532**	1.494***	0.359*	2104.41	2599.028***
	(0.277)	(0.264)	(0.319)	(0.198)	(1379.675)	(510.435)
HES Loan x Q8	1.209***	1.363***	1.640***	0.593***	5332.968**	1240.535*
	(0.263)	(0.511)	(0.483)	(0.185)	(2210.924)	(700.173)
HES Loan x Q9	1.078***	1.249***	1.249***	0.569***	5852.083***	466.115
	(0.224)	(0.425)	(0.404)	(0.140)	(1883.544)	(557.798)
HES Loan x Q10	1.054***	1.227***	1.177***	0.745***	8972.691***	1047.294
	(0.207)	(0.39)	(0.364)	(0.149)	(2536.732)	(697.492)
Observations	19032		19032	19032		19032
R^2	0.572		0.529	0.905		0.586

Notes: We estimate the heterogeneity in the 2-period (2011-2015 and 2017-2021) difference-in-differences results by decile (Q1 to Q10) of the property value distribution. Observations are at the level of Output Area (OA) by period and the sample covers OAs within our matched sample of LSOAs. Output Areas with zero installations for the entire sample period are dropped from the sample. HES Loan is the treatment dummy indicating that the OA is in Scotland and the period is 2017-2021. We estimate the model using both Poisson and OLS for two dependent variables: number of new installations and total annual generation potential installed. For the Poisson estimates we also show average marginal effects (AMEs) for treated (Scottish) OAs. All specifications include Output Area and year fixed effects. Estimates are weighted using the LSOA weights from the matching procedure, and standard errors are clustered at the matching subclass level. * $p \leq 0.10$, ** $p \leq 0.05$, *** $p \leq 0.01$

Table B.7: Distributional DiD: Heterogeneity by urban-rural classification

	Number of installations		Total annual generation (kWh)	
	Poisson	OLS	Poisson	OLS
Urban				
HES Loan x Urban x T1	1.635***	2.718***	1.184***	5675.215***
	(0.242)	(0.341)	(0.196)	(567.525)
HES Loan x Urban x T2	1.224***	2.098***	0.748***	4120.999***
	(0.248)	(0.353)	(0.187)	(522.374)
HES Loan x Urban x T3	1.006***	1.593***	0.476***	2419.026***
	(0.241)	(0.310)	(0.165)	(488.143)
Rural Accessible				
HES Loan x Rural Accessible x T1	2.524***	7.767*	2.167***	13980.373**
	(0.582)	(4.274)	(0.421)	(5807.020)
HES Loan x Rural Accessible x T2	0.758**	0.930*	0.430	1466.179
	(0.362)	(0.541)	(0.271)	(927.044)
HES Loan x Rural Accessible x T3	1.244***	1.310***	0.755***	-459.238
	(0.193)	(0.462)	(0.130)	(740.716)
Rural Remote				
HES Loan x Rural Remote x T1	-1.378	1.339***	-0.409	3321.830***
	(1.099)	(0.364)	(1.106)	(1239.990)
HES Loan x Rural Remote x T2	0.124	0.538	-0.049	403.822
	(0.423)	(0.440)	(0.267)	(932.727)
HES Loan x Rural Remote x T3	0.815**	0.190	0.555**	-1981.556
	(0.344)	(0.681)	(0.240)	(1341.495)
Observations	19032	19032	19032	19032
R^2	0.572	0.530	0.905	0.589

Notes: We estimated the heterogeneity in the 2-period (2011-2015 and 2017-2021) difference-in-differences results by the tercile (T1 to T3) of the property value distribution interacted with the urban-rural classification of the area. Observations are at the Output Area by period level and the sample covers OAs within our matched sample of LSOAs. HES Loan is the treatment dummy, indicating that the OA is in Scotland and the period is 2017-2021. We estimate the model using both Poisson and OLS for two dependent variables: number of new installations and total annual generation potential installed. All specifications include Output Area and year fixed effects. Estimates are weighted using the LSOA weights from the matching procedure, and standard errors are clustered at the matching subclass level. * p ≤ 0.10, ** p ≤ 0.05, *** p ≤ 0.01

Supplemental Information

S1 Additional details on the policy context

During our post-treatment period of 2017-2021, the HES Loan was unique among Scotland's support schemes for household energy investments because it is available to all homeowners regardless of income. However, other policy schemes exist in the UK that provide support for low-income, energy-poor households to make energy investments. While solar PV is within the remit of some of these other policies, they mainly focus on energy efficiency and heating system upgrades, and their own reporting indicates that the number of Scottish households receiving funding for solar PV is very small. 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 PV installations have been funded. For example, during the third phase of the scheme, ECO3, which ran from December 2018 to March 2022, less than 150 solar PV systems were funded across all of England, Scotland, and Wales (Ofgem, 2023*a*).

The Scottish government provides additional sources of funding for vulnerable households to make energy investments through policies such as the Area-based schemes (since 2013) and the Warmer Homes Scotland (WHS) scheme (since 2015).[49] Similar to the ECO scheme, these Scottish policies mainly focus on insulation and heating systems, but solar PV is also within the remit of the WHS scheme.[50] Nevertheless, annual reports indicate that in practice the WHS scheme has funded very few solar PV systems. The 2018-2019 annual report indicates that the scheme funded only five solar PV systems in the 2017-2018 fiscal year, and none in the 2018-2019 year (Scottish Government, 2020). Similarly, while the 2019-2020 and 2020-2021 annual reports on the WHS scheme do not directly report the number of solar PV systems funded during these fiscal years, the figures provided on total measures delivered suggest that over 95% of the roughly 3,000 to 3,500 measures delivered each year are related to heating and insulation (Warmworks, 2020, 2021).[51] In

[49] 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. The Area-based schemes are delivered by local authorities.

[50] The 2017/18 annual report on Home Energy Efficiency Programmes (HEEPS) for Scotland, explains that "Warmer Homes Scotland takes a 'whole house' approach to energy efficiency, often installing multiple measures to ensure homes are warmer and cheaper to run. More than 40 measures are available under this scheme including new energy efficient boilers combined with thermostatic heating controls, Air Source Heat Pumps, Solar PV and loft and cavity insulation," (Scottish Government, 2019)

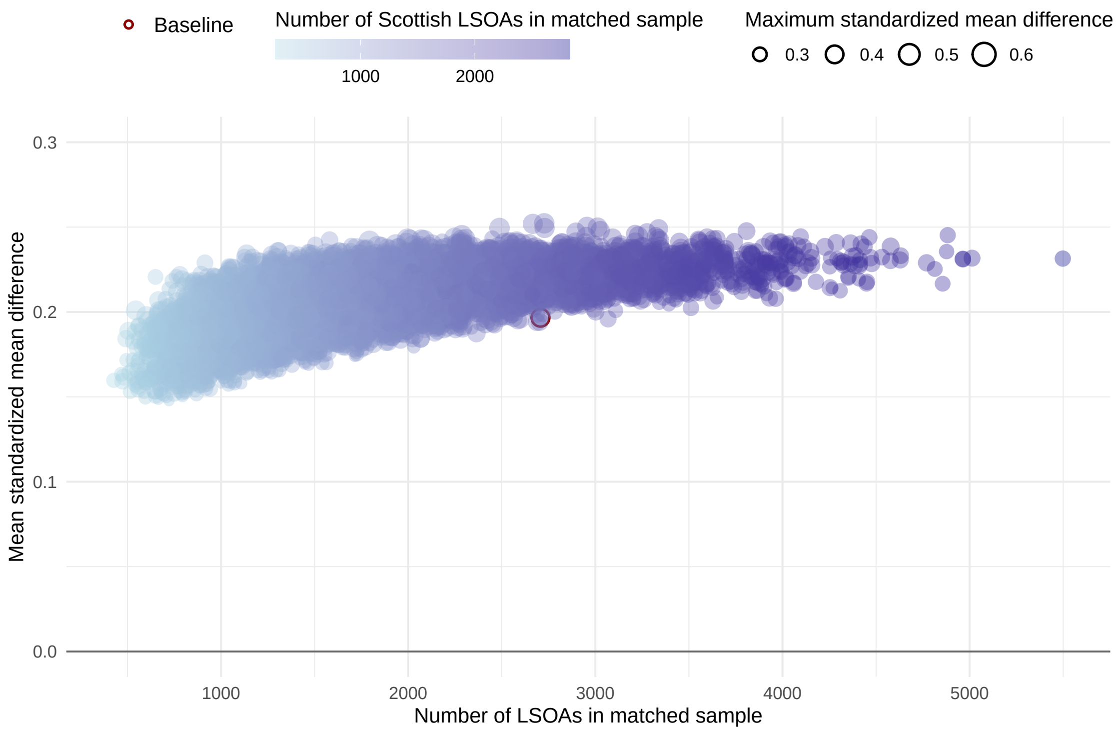
[51] The remaining portion of measures funded is simply tagged as "Other".

the 2021-2022 fiscal year, total measures funded by the WHS scheme increased to over 5,000, and the annual report indicates that only about 80 of these measures were solar PV (Warmworks, 2022).

While a small possibility exists that some low-income Scottish households are "treated" through these alternative policy schemes, we do not think that these other policies pose a major threat to the identification of the causal impact of the HES Loan. Not only does annual reporting on these schemes indicate that the number of solar PV systems funded by these policies was very small, but also the ECO scheme and Warmer Homes Scotland existed before the HES Loan was introduced, making it unlikely that these other policies can explain the increase in solar PV installations in 2017-2021 relative to pre-treatment periods.

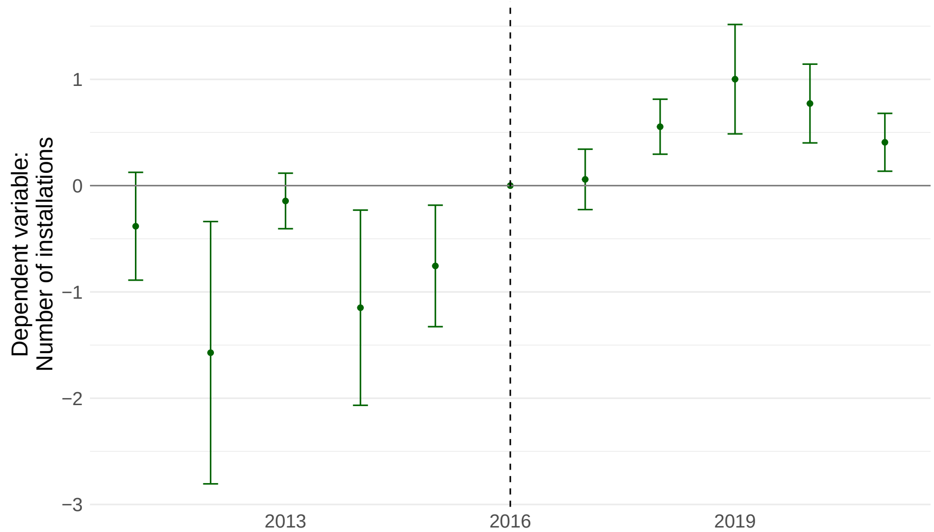
S2 Supplementary Tables and Figures

Figure S2.1: Comparing match quality across alternative specifications



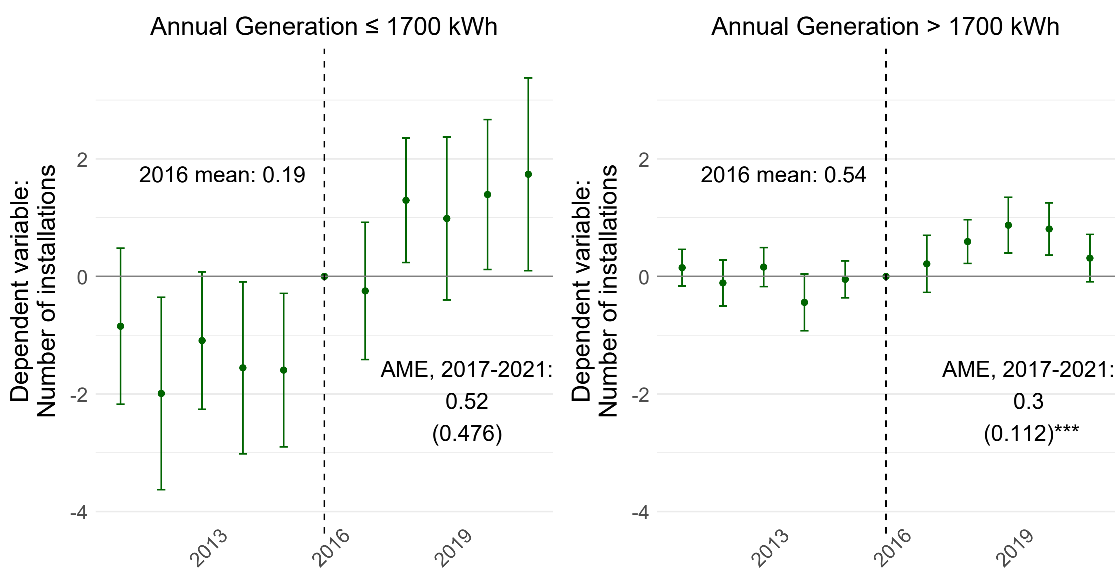
Notes: Each point represents the outcome of a single coarsened exact matching specification. The specifications shown use the same covariates as in our baseline matching specification (outlined in red in this figure), and include all permutations that have 8 or 10 bins for the solar potential variable, 3 to 10 bins for the log of house prices, and 3, 4 or 5 bins for each of the remaining covariates (pre-treatment installations, average house square meterage, house share, home ownership rate, log of average electricity consumption, and share of homes constructed after 1949). The x-axis indicates the total number of LSOAs included in the matched sample, and the y-axis indicates the average across all covariates of the absolute standardized mean difference between Scottish versus English LSOAs in the matched sample. The size of the point indicates the maximum of this measure across the covariates, and the colour of the point indicates the number of Scottish LSOAs included in the sample.

Figure S2.2: Robustness: Main results using OLS estimator



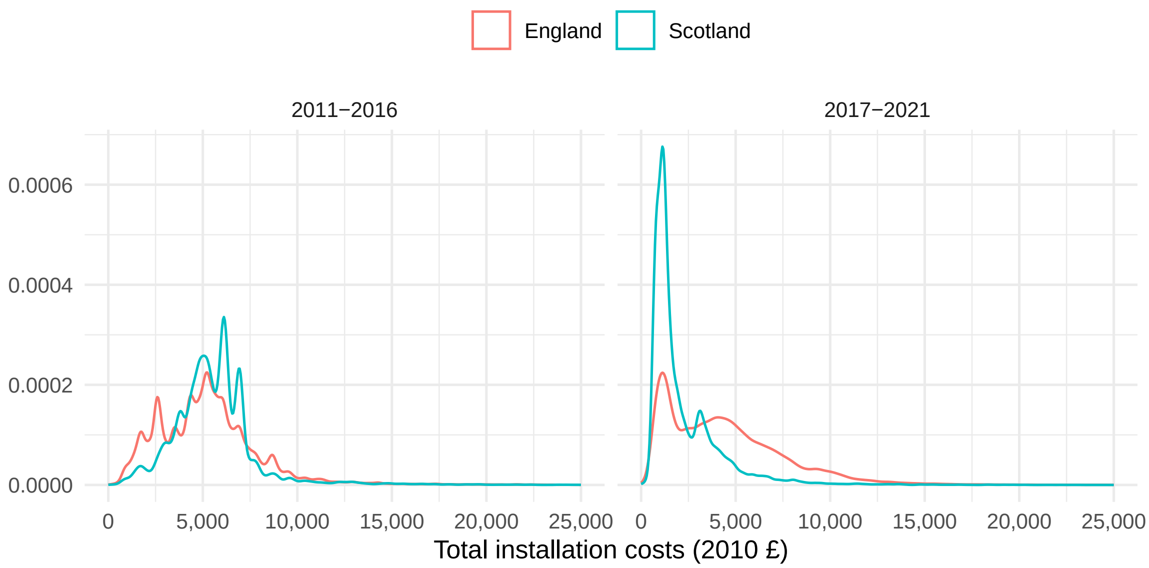
Notes: This figure shows OLS coefficient estimates from an event-study specification (Equation 1) using the annual number of installations per LSOA as the dependent variable. See column (3) in Table B.3 for further details on these results.

Figure S2.3: Impact of the HES Loan on the number of installations by installation size



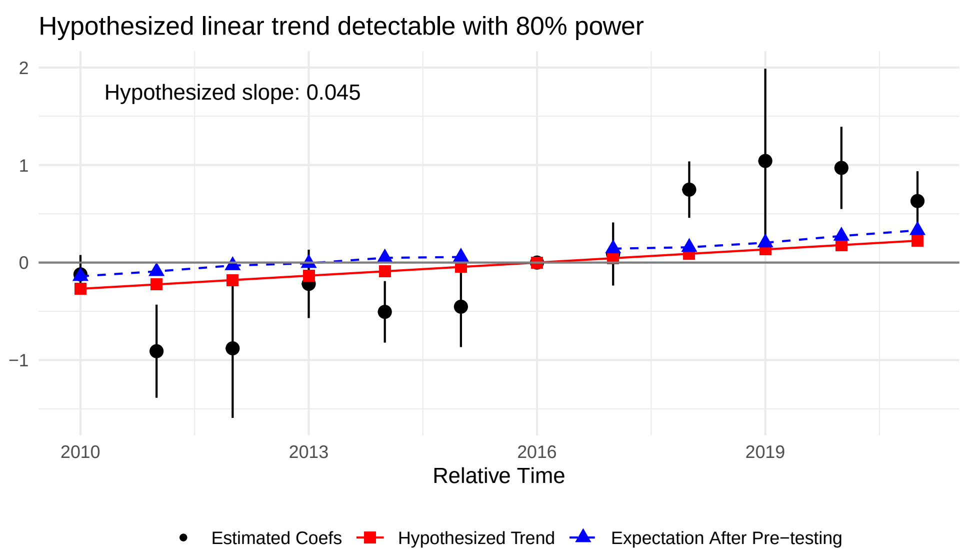
Notes: We estimate the event-study difference-in-differences specification separately for the impact of the HES Loan on small (≤ 1,700 estimated annual kWh) and large (≤ estimated annual kWh) solar PV installations. "2016 mean" refers to the mean outcome across English and Scottish LSOAs in 2016. "AME" refers to average marginal effect. Estimates are weighted using the LSOA weights from the matching procedure, and standard errors are clustered at the matching subclass level. * p ≤ 0.10, ** p ≤ 0.05, *** p ≤ 0.01

Figure S2.4: Distribution of total installation costs in England and Scotland, before and after the HES Loan



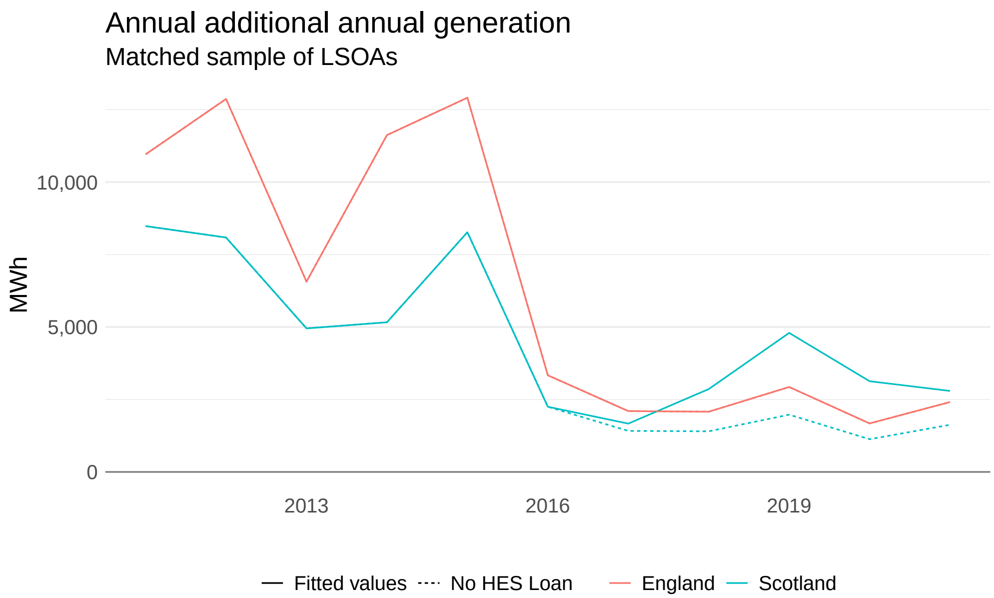
Notes: This figure shows kernel density plots for total installation costs (deflated using the retail price index) in England versus Scotland. Panel (a) covers the pre-treatment period (2011-2015), and panel (b) covers the HES Loan period (2017-2021).

Figure S2.5: Parallel trends test: How big would a violation of parallel trends need to be to detect it 80% of the time?



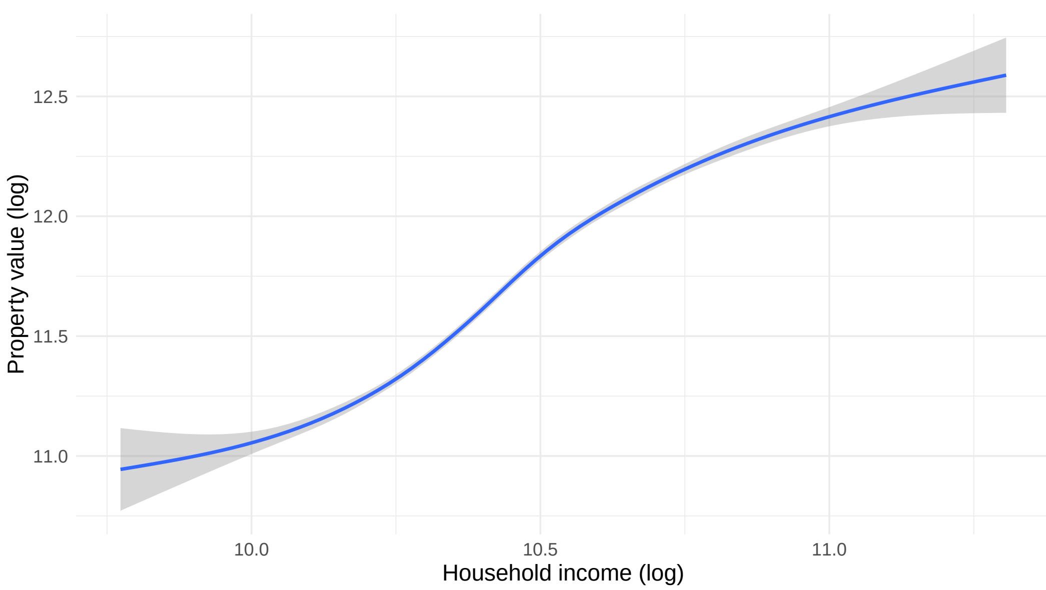
Notes: This figure tests for robustness of our main results to pretrends following the approach in Roth (2022). The dependent variable is number of installations per LSOA. The expectation after pre-testing (shown in blue) indicates the expected coefficients conditional on not finding a significant pre-trend if in fact the hypothesized trend (shown in red) is true.

Figure S2.6: Predicted additional generation with versus without the HES Loan



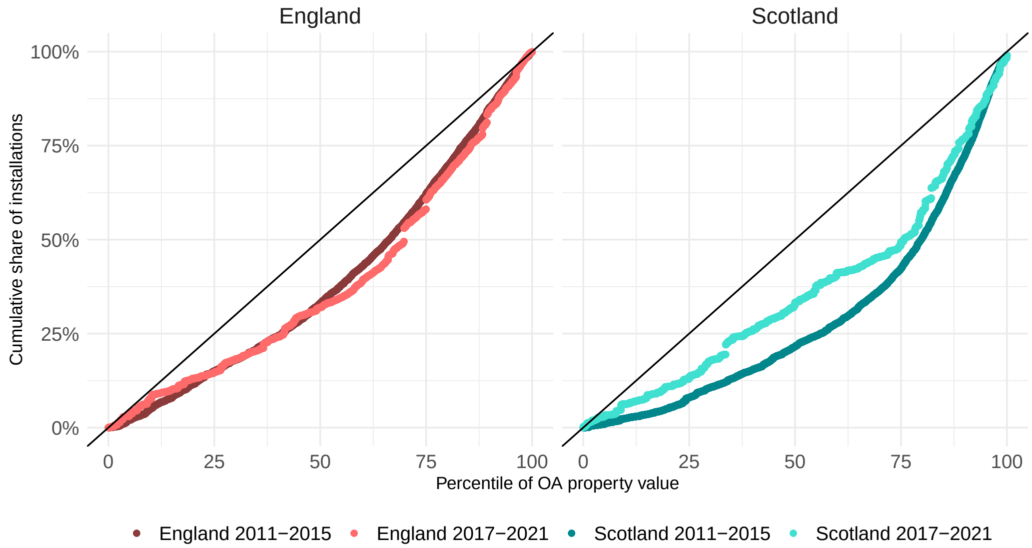
Notes: This figure plots the predicted value for total additional annual generation installed per year across all LSOAs in the matched sample in England versus Scotland and with versus without the HES Loan. The predictions are obtained from an event-study DiD specification with total added annual generation (kWh) per LSOA per year as the dependent variable.

Figure S2.7: 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 S2.8: Joint distribution of LSOA-level property value and installations



Notes: This figure is a Lorenz-like curve illustrating the percentile rank of OAs on the x-axis, and the cumulative share of solar PV installations on the y-axis. For comparison, the 45°line indicates hypothetical perfect equality in the distribution of installations across OAs. Includes OAs within our matched sample of LSOAs.

Table S2.1: Suits Index

	Number of installations		Total annual generation	
	2011-2015	2017-2021	2011-2015	2017-2021
England	0.213	0.230	0.249	0.289
Scotland	0.412	0.272	0.443	0.313

Notes: We calculate the Suits Index (analogous to the Gini coefficient) to assess the concentration of solar PV installations across the property value distribution. The sample includes Output Areas in our matched sample of LSOAs. A Suits Index value closer to zero indicates more equality, and a value closer to 1 indicates more concentration in wealther OAs.

Table S2.2: Distributional DiD: T-tests for equality with first decile

	Number of installations		Total annual generation	
Property decile	Poisson	OLS	Poisson	OLS
1	–	–	–	–
	–	–	–	–
2	-0.736*	-1.299*	-0.438	-1448.497
	(0.421)	(0.771)	(0.32)	(1186.913)
3	-0.159	-0.283	-0.006	-47.835
	(0.424)	(0.913)	(0.353)	(1385.573)
4	-0.843**	-1.478**	-0.588*	-2138.144*
	(0.41)	(0.728)	(0.344)	(1216.308)
5	-0.472	-0.89	-0.413	-1611.132
	(0.327)	(0.635)	(0.287)	(1076.383)
6	-1.363***	-2.175***	-1.229***	-4096.775***
	(0.37)	(0.625)	(0.311)	(1025.384)
7	-1.288***	-2.105***	-1.155***	-4110.698***
	(0.328)	(0.587)	(0.261)	(932.929)
8	-0.897**	-1.959***	-0.921***	-5469.191***
	(0.366)	(0.737)	(0.286)	(1141.226)
9	-1.028***	-2.35***	-0.945***	-6243.611***
	(0.344)	(0.679)	(0.261)	(1013.736)
10	-1.052***	-2.422***	-0.769***	-5662.431***
	(0.309)	(0.633)	(0.259)	(1107.315)

Notes: Using the distributional DiD results shown in Table B.6, we run a series of t-tests for equality of each decile-specific coefficient estimate with the estimate for the first decile of the property value distribution (Q1). * $p \leq 0.10$, ** $p \leq 0.05$, *** $p \leq 0.01$

S3 Robustness: Border Regression Discontinuity Design

We also 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. Although it is not our preferred specification, the RD design serves as an important source of validation for our main results.[52]

[52] 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 severely limits the potential to assess distributional and other heterogeneous impacts using the RD design.

We estimate the following RD design on the sample of postcode districts within 10km of the England-Scotland border (Figure S3.1, left panel):

$$Y_b = \alpha + \beta D_b \times \mathbb{1}_b^{\text{Scotland}} + \gamma \mathbb{1}_b^{\text{Scotland}} \epsilon_b \tag{6}$$

where Y_b represents the outcome variable for postcode districts in distance bin b to the border. Our outcome variable is the total number of PV installations over the 5-year treatment period (2017-2021). D_b is the distance (in 500 metre bins) from the border, and $\mathbb{1}_i^{\text{Scotland}}$ is a binary indicator variable equalling 1 if the postcode area is in Scotland and 0 otherwise; and ϵ_b is the error term. Our coefficients of interest, β and γ, capture difference in total installations in Scotland versus England, which is the causal impact of the policy under the assumption of covariate balance across the border.

Figure S3.1: Border Regression Discontinuity design and results

Notes: The left panel illustrates the sample of postcode districts included in within 10km bandwidth used in the RD design. The centre and right panels show the results of the regression discontinuity design for the pre-treatment (2011-2016) and post-treatment (2017-2021) periods, respectively. The x-axis indicates distance from the England-Scotland border (metres, positive values indicate locations in Scotland), the dashed line indicates the border itself, and the y-axis indicates the total number of installations during the period. Points indicate observations for 500 metre bins. The lines illustrate the OLS regression of distance on the total number of installations.

Figure S3.1 illustrates the sample of postcode districts within the 10km bandwidth (left panel) and presents the estimation results (centre and right panels). Despite the

Second, we believe that difference-in-differences with matching provides a more robust basis for causal inference compared to the RD design. The England-Scotland border has existed for hundreds of years, and therefore could be correlated with variables such as housing stock and household characteristics. 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 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 other variables such as house prices and home ownership rates. Our main design can be interpreted as a more sophisticated version of the RD design because it accounts for these additional covariates.

significantly reduced sample size, the border discontinuity design corroborates our main findings in terms of direction and magnitude. Close to the border, the HES Loan has led to approximately 20 additional installations in Scotland compared to England over 2017-2021, and the policy mitigated the decline in installations that occurred after 2016.

S4 MVPF details

S4.1 Derivation: From the canonical MVPF to loans

Starting from Equation 4,

$$\text{MVPF} = \frac{x \cdot d\tau + V \cdot dx}{x \cdot d\tau + \tau \cdot dx},$$

we define a loan-specific net present value (NPV) transfer to consumers, $s \equiv p - \rho\, PV_h(p)$, and the government's NPV cost, $c \equiv p - \rho\, PV_g(p)$, where p is the upfront price per watt, ρ is the repayment probability, and $PV_h(\cdot)$ and $PV_g(\cdot)$ are the present values of repayments from the household and government perspectives, respectively. Replacing τ with (s, c) and normalising per £1 of NPV transfer to consumers gives

$$\text{MVPF} = \frac{x\, ds + V\, dx}{x\, dc + c\, dx} = \frac{1 + \frac{V}{s}\frac{dx}{d\ln s}\frac{d\ln s}{ds}}{\frac{dc}{ds} + \frac{c}{s}\frac{dx}{d\ln s}\frac{d\ln s}{ds}} = \frac{1 + \frac{V}{s}(-\epsilon)}{\left(\frac{dc}{ds}\right) + \frac{c}{s}(-\epsilon)},$$

where $\epsilon \equiv \frac{d\ln x}{d\ln s}$ is the elasticity with respect to the consumer's NPV per watt. This yields Equation 5 in the main text.

As discussed in the main text, this loan specific framework allows for the possibility that the NPV of the transfer is not equivalent for both households and the government. A transfer of £1 NPV from the household's perspective costs the the government $\frac{dc}{ds}$, which may differ from £1 if the government has different time preferences relative to households. To arrive at a specific value for the $\frac{dc}{ds}$, we begin by simplifying; both c and s are functions of p, the upfront price per watt, therefore:

$$\frac{dc}{ds} = \frac{dc/dp}{ds/dp}$$
$$\frac{dc}{ds} = \frac{1 - \rho \cdot dPV_g(p)}{1 - \rho \cdot dPV_h(p)},$$

where $PV(p)$ is the present value of loan repayments as a function of the upfront price per watt. This functional form depends on our assumptions about the loan repayment schedule. We assume of a fully amortized loan with equal annual repayments. The HES Loan offers zero interest payments, so the annual loan repayments per watt are $\frac{p}{T}$, where T is the length of the loan repayment period. As a result we have:

$$PV_h = p \sum_t \frac{1}{(1+r_h)^t} \qquad PV_g = p \sum_t \frac{1}{(1+r_g)^t}$$
$$dPV_h = \sum_t \frac{1}{(1+r_h)^t} \qquad dPV_g = \sum_t \frac{1}{(1+r_g)^t}$$

Therefore, under these assumptions for the loan repayment schedule, we have

$$\frac{dc}{ds} = \frac{1 - \rho\left[\sum_t \frac{1}{(1+r_g)^t}\right]}{1 - \rho\left[\sum_t \frac{1}{(1+r_h)^t}\right]}. \tag{7}$$

S4.2 Details on calculations

Behavioural response (elasticity). To apply the MVPF framework, we must convert our causal estimate of the behavioural response to the HES Loan into an elasticity of solar PV demand with respect to a 1% change in the NPV per watt of solar PV capacity ($-\varepsilon$ in Equation 5). From the event study DiD model with total additional annual generation (kWh) as the dependent variable, we obtain the coefficient estimates on the annual (2017-2021) HES Loan treatment dummies (see Equation 1), which are the estimated annual semi-elasticities with respect to the HES Loan. To convert theses semi-elasticities with respect to the treatment dummy into price elasticities, we divide these semi-elasticities by the percentage change in the NPV per watt due to the HES Loan.

To compute the change in NPV per watt due to the HES Loan, we start with observed installation costs from the MCS data for systems smaller than 5 kW installed in Scotland between 2017 and 2021. For each observation we compute the difference in the NPV per watt of paying for the installation using the HES Loan versus a private market loan. In doing so, we assume fully-amortized loans with equal annual payments over the 10-year repayment period, and for private market interest rates we use the average annual interest rate for short-term loans, as reported by the Bank of England[53]. This calculation results in installation-level changes in the NPV per watt due to the HES loan. We aggregate these installation-level changes into average annual changes by taking the weighted average across years, using installed capacity as weights. We then convert these annual changes

[53]Specifically, we use data series CFMBI73 from (Bank of England, 2025).

in the NPV per watt into percentage changes by dividing by the post-subsidy lifetime cost per watt (described below) and taking the log of this ratio.

Finally, for each year from 2017-2021, we divide our estimated semi-elasticity with respect to the HES Loan dummy by the calculated percentage change in the NPV per watt due the HES Loan, resulting in annual elasticity estimates. Taking the average across all years, we obtain a final elasticity with respect to the NPV per watt of -1.68.

Table S4.1: MVPF parameter assumptions and sources

Parameter	Baseline assumption	Source
Elasticity, ϵ	-1.68	Calculated from DiD estimates
Household discount rate, r_h	7.5%	Assumption
Utility discount rate	8%	Assumption
Social discount rate, r_g	3.5%	HM Treasury (2022)
Social discount rate (health), $r_{g,health}$	1.5%	HM Treasury (2022)
Default risk $(1-\rho)$	0%	Assumption
Rebound rate	20%	Hahn et al. (2024)
Lifetime (NPV) cost per watt, s	£0.49	Calculated based on MCS (2024)
PV system lifetime	25 years	Assumption
Private market loan interest rate*	6.39% (2020)	Bank of England (2025)
Share of PV production exported	50%	Assumption
Social cost of carbon*, £/tCO_2e	£253 (2020)	HM Treasury (2022)
Emissions intensity of electricity*	0.293 kgCO_2e/kWh (2020)	HM Treasury (2022)
Local air quality damage from electricity*	£0.0015/kWh (2023)	HM Treasury (2022)
Pass-through rate	81%	Pless and van Benthem (2019)
Learning rate, θ	-31.9%	Way et al. (2022)
Retail electricity price (Scotland)	£0.25/kWh	Calculated from DESNZ (2025*a*)
Average utility LCOE	£0.098/kWh	Calculated from DESNZ (2023, 2025*b*)
Utility markup rate	27%	ONS (2024)
Tax rate on utility companies	25%	HM Revenue & Customs (2025)
UK share of global economy	2.3%	Calculated from World Bank (2025)
UK tax-to-GDP ratio	33%	OECD (2025)
Private share of climate damages	50%	Follows Hahn et al. (2024)'s assumption

Notes: The * indicates parameters that vary by year.

Lifetime (NPV) cost per watt. All components of the MVPF are calculated in terms of per £1 NPV transferred to consumers. In practice, this means dividing each benefit and cost component of the MVPF by the consumer's "lifetime" cost per watt (i.e. s in Equation

5). To calculate s, we start with observations in the MCS data of installations of less than 5kW made in Scotland between 2018 and 2021. We compute the annual weighted average real cost per watt, using capacity as weights (as usual we use the retail price index to deflate nominal prices). We then calculate the lifetime post-subsidy cost per watt by (i) subtracting the discounted stream of FiT scheme subsidy payments (we assume 50% of generation is exported back to the grid and therefore earns the export subsidy), and (ii) adding the additional NPV per watt due to paying for the installation via the HES Loan rather than a private market loan (as calculated for the elasticity and explained above). Taking the weighted average of the resulting annual values across 2018-2021, we obtain a lifetime (NPV) cost per watt for consumers of £0.49.

Willingness to pay. The net benefits of the HES Loan include the direct transfer to consumers, directly avoided global and local environmental damages, additional environmental damages due to a rebound effect in household electricity consumption, dynamic environmental and price benefits due to learning-by-doing effects, and utility profit losses.

Mechanically, the value of the direct transfer to consumers is £1 NPV per £1 NPV transferred.[54] However, we assume an incomplete pass-through rate of 81% (Pless and van Benthem, 2019), and therefore £0.19 per £1 transferred is captured by installers, and the remaining £0.81 transferred is captured by households

To compute the avoided global environmental damages due to the policy, we follow The Green Book guidance for the annual long-run marginal emissions factors (kg CO_2e per kWh) for domestic electricity consumption in the UK (HM Treasury, 2022).[55] Using observed solar generation potential (annual kWh per kW) in Scotland in the MCS data[56], we convert these emissions factors into tonnes of CO_2-equivalent emissions avoided per 1 watt of solar PV installed, and then multiply these values using The Green Book's central scenario for the social cost of carbon.[57] We then use The Green Book's recommended

[54]In our baseline calculations we assume all adoptions are infra-marginal following Hahn et al. (2024)'s approach for solar subsidies. In the sensitivity analysis we calculate the MVPF under the alternative assumption that 50% of adoptions are marginal (as discussed in the main text and illustrated in Figure S2.6, this assumption aligns with predicted outcomes from our DiD model). Following Hendren and Sprung-Keyser (2020), we assume uniformly distributed willingness-to-pay (linear demand) across marginal adopters, which implies that the average value for marginal adopters of a £1 NPV transfer is £0.50 NPV. Taking the weighted average across infra-marginal and marginal adopters and applying the pass-through rate, the value of the direct transfer to consumers is $0.81 \times ((0.5 \times 1) + (0.5 \times 0.5)) = 0.61$ per £1 NPV transferred.

[55]These values reflect the projected trajectory for the UK to achieve Net Zero by 2050

[56]To compute solar generation potential, we take the weighted mean of average annual kWh per kW observed in matched Scottish LSOAs across 2017-2021, using total additional generation installed in the LSOA-year as weights.

[57]The Social Cost of Carbon is increasing each year, reflecting the benefit of mitigating now rather than later. The Green Book provides SCC values up to 2050; to extend beyond this year we follow their guidance by applying a 1.5% real annual growth rate.

discount rate of 3.5% to compute the net present value of the avoided global damages over the lifetime of the solar PV system, which we assume is 25 years. Dividing this value by the lifetime cost per watt (s) and multiplying by the elasticity results in global environmental damages avoided of £1.58 per £1 NPV transferred to consumers through the HES Loan.

For the avoided local environmental damages due to the HES Loan, we use with The Green Book's values for the national average of air quality damages due to electricity (pence per kWh). Once again we convert these values to damages per watt of solar PV installed using our measure of solar generation potential from the MCS data. We compute the net present value of these damages over the 25-year PV lifetime, in this case using a discount rate of 1.5%, which follows The Green Book's guidance to discount health damages at this rate (HM Treasury, 2022). Dividing by the lifetime cost per watt (s) and multiplying by the elasticity, we have £0.04 avoided local environmental damages per £1 NPV transferred to consumers.

We follow Hahn et al. (2024) by assuming a rebound rate of 20%. We simply multiply this rate by the environmental benefits per £1 NPV transferred, and obtain global and local environmental damages (i.e. negative benefits) due to the rebound effect of -0.32 and -0.008, respectively.

Once again following Hahn et al. (2024), we calculate two dynamic "learning-by-doing" effects of the HES Loan. The dynamic price (DP) effect captures the benefit of reduced solar PV prices due the policy's impact on cumulative solar PV installations, and the dynamic environmental (DE) effect captures the avoided environmental damages due to the policy's impact on pulling forward future solar PV installations as a result of the price decrease. We calculate DP and DE as the discretized version of equations derived in Hahn et al. (2024), summing over 2020 to 2200:

$$DP = \theta\epsilon(t^*)^{\theta\frac{(1+\epsilon)}{(1-\epsilon\theta)}} \sum_{t=t^*}^{2200} \frac{(t+t^*)^{\theta\frac{(1+\epsilon)}{(1-\epsilon\theta)}-1}}{(1+r_g)^t},$$

$$\text{where } t^* = \frac{X_{2020}}{x_{2020}(1-\epsilon\theta)}$$

$$DE = \frac{-\epsilon^2\theta}{(1-\epsilon\theta c(X(t^*))} t^{*-\frac{\epsilon\theta}{1-\epsilon\theta}} \sum_{t=t^*}^{2200} \frac{(t+t^*)^{\frac{2\epsilon\theta-1}{1-\epsilon*\theta}} V_t}{(1+r_g)^t}$$

θ is the learning rate (i.e. the elasticity of marginal cost with respect to cumulative production of solar panels); we use -0.319 following Hahn et al. (2024)'s assumption from

Way et al. (2022). ϵ is our estimated elasticity with respect to NPV per watt. X_{2020} and x_{2020} are cumulative and static global solar panel production in 2020, which we take from IRENA (2023) as 713,918 MW and 128,050 MW, respectively. $c(X(t^*))$ is the cost per watt in 2020; for this parameter we use the average cost per watt calculated from the MCS data using observations of systems less than 5 kW in Scotland between 2017 and 2021. V_t is the environmental damages avoided for a system installed in year t. We take the discounted sum of these damages over the 25 year lifetime of solar panels, and in doing so we extend the social cost of carbon to 2200 using a 1.5% real annual growth rate, as recommended by The Green Book.[58]

The final net benefit included in our MVPF calculation is utility profit losses due to the increased solar PV capacity caused by the HES Loan. We follow the approach in Hahn et al. (2024) to estimate utility profits per kWh as the difference between the retail price of electricity and the levelized cost of electricity (LCOE), taking into account markups and taxes.[59] We obtain an average retail electricity price of £0.25/kWh using UK National Grid data on average variable unit price and fixed costs of electricity in 2024 in Scotland based on a reference consumption level of 3,400 kWh per year (DESNZ, 2025*a*).[60] We also subtract the average 2021 Smart Export Guarantee tariff (£0.04/kWh) from this price because utilities (rather than the government) are responsible for these payments to consumers (Ofgem, 2024).

We obtain LCOEs for fuel and technology types from the UK Department for Energy Security and Net Zero (DESNZ, 2023, 2025*b*). We take the weighted average of LCOEs, using each fuel-technology group's share of total electricity production in 2024 as weights, resulting in an average LCOE of £0.098/kWh. We add £0.05/kWh transmission and distribution costs, which we calculate from the average fixed costs for our reference consumption level of 3,400 kWh. We assume a markup rate for utilities of 27%[61] and a 25% tax rate on utilities.[62] Together, these parameter values lead to a WTP per kWh for utility companies of $(0.25 - 0.04 - (0.098 + 0.05)(1 + 0.27)) \times (1 - 0.25) = 0.016$.

We multiply this value by 80% to account for the 20% rebound rate, convert to watts using average kWh per watt observed in the MCS data in Scotland over 2017-2021, and then take the discounted sum over the 25 year PV lifetime.[63] Finally, dividing this discounted sum of profit losses by the consumer's lifetime cost per watt (s) and multiplying by the

[58] See guidance on post-2050 values here.

[59] We abstract from the issue of foreign ownership of UK utility companies.

[60] As usual we deflate all nominal prices using the retail price index.

[61] We use the mean markup on intermediate consumption reported in ONS (2024).

[62] We use the main rate for companies with profits over £250,000 reported in HM Revenue & Customs (2025).

[63] We assume an 8% discount rate for utility companies.

elasticity leads to a loss in utility profits of £0.24 per £1 NPV transferred to consumers.

Government net costs. The net costs to the government from the HES Loan are the direct cost of the subsidy transfer to households, the fiscal externality costs of additional FiT scheme subsidy payments, the fiscal externality costs of reduced taxes from utility companies due to their reduced profits, and the fiscal externality costs of increased tax revenue due to the long-term decrease in climate damages as a result of the HES Loan.

As discussed above, the cost to the government to transfer £1 NPV to consumers is given by the term $\frac{dc}{ds}$ in Equation 5. Plugging our parameter assumptions for the government and household discount rates (3.5% and 7.5%, respectively) as well as default risk (0%) into the functional form that we derive for this term in Section S4.1, we obtain $\frac{dc}{ds} = 0.537$. Due to the government's high level of patience relative to consumers, the cost to the government to transfer £1 NPV to consumers is only £0.54 NPV.

In addition to this direct government cost, we account for several fiscal externality costs that result from HES Loan. First, we calculate the cost of additional FiT scheme subsidies due to the added solar PV installations that result from the HES Loan. We start by computing the net present value of the FiT scheme subsidies per watt over the 25 year lifetime. We use the average tariff rates over 2017 to 2021 and assume that 50% of production is exported back to the grid and therefore also benefits from the export subsidy (Ofgem, 2023*b*).[64] Next, we divide this value by the lifetime cost per watt (s) to obtain the fiscal externality per £1 NPV. Finally, we account for the behavioural response to the HES Loan by multiplying this fiscal externality by the pass-through rate and the elasticity to obtain a fiscal externality cost due to increased FiT scheme payments of £0.55 per £1 NPV transferred to consumers under the HES Loan scheme.

Next, we calculate the fiscal externality costs of reduced tax revenue from utility companies due to the reduction in utility company profits. We start with utility companies' willingness to pay of £0.016 per kWh, which we calculated as part of the benefits of the policy to utilities (explained above). We multiply this value by 80% to account for the 20% rebound in electricity consumption, convert to watts, and then take the discounted sum of this WTP per watt over the 25 year PV lifetime. We divide this sum by the lifetime cost per watt (s) and multiply by the tax rate on utility companies (25%) to obtain the tax revenue per per £1 NPV. Finally, we multiply this value by the pass-through rate and the elasticity, resulting in lost tax revenues of £0.074 per £1 NPV transferred to consumers under the HES Loan scheme.

[64]Note that the FiT scheme ends in 2019, so by taking the average tariff rate we make the simplifying assumption of uniform subsidy rates across 2017-2021.

The final fiscal externality cost included in our assessment of the MVPF for the HES Loan is the change is government tax revenue due to the decrease in climate damages as a result of the HES Loan. First, following Hahn et al. (2024)'s approach, we compute the incidence rate of global climate damages on the UK government as the product of three parameters: (i) a 2.3% share for the UK in the global economy, which we take as the average of the UK's share of global PPP GDP across 2017-2021 from the World Development Indicators (World Bank, 2025); (ii) a tax-to-GDP ratio in the UK of 33%, which obtain take from the OECD Global Revenue Statistics database (OECD, 2025); and (iii) a 50% share of climate damages that are private market damages and therefore impact tax revenues, which follows Hahn et al. (2024)'s own assumption. These parameter values lead to a 0.38% incidence rate of climate damages on the UK Government. Next, we multiply this incidence rate by the sum of global environmental damages and dynamic (global) environmental damages avoided per £1 NPV transferred to consumers to obtain the climate fiscal externality of -£0.008.