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Decarbonising residential heating: local conditions and spatial spillovers driving heat pump uptake

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ABSTRACT

Air source heat pumps are the principal means of decarbonising residential heating. What drives local uptake of heat pumps? We present and examine a unique, highly disaggregated, spatial-temporal dataset for heat pump diffusion across Great Britain at the local authority level from 2010 to 2020. We find average total installed cost of 1075 £/kW and a negative learning rate of −3.3 %, with most installations in owner-occupied houses. Using spatial econometric models, we investigate how local conditions drive heat pump installations. We find early adopting local areas tend to be rural, off the gas grid, with prior use of solid fuel or oil for heating, and participate in renewable and community energy projects. Early adopting areas benefit from a combination of more readily accessible properties, low-carbon energy skills, and local supply chains. We find robust evidence of spatial spillover effects that show early adopting areas serve as deployment test beds, indirectly stimulating deployment in contiguous areas. We reason that spatial spillovers are driven by installer availability and local supply chains materialised around installation activity. We estimate for every three heat pumps installed, one heat pump is subsequently installed in a neighbouring local authority with less advantageous conditions. This implies an important policy trade-off for low-carbon heat between maximising effectiveness (incentivise early adopters) and widening equality of access (support later adopters). Concerted policy action to tackle fragmented supply chains and skills shortages which inflate installation costs of heat pumps relative to gas boilers is also urgently needed.

1. Introduction

Buildings accounted for 31 % of global final energy demand in 2019 of which 70 % was in the residential sector (IPCC, 2022). From 1990 to 2019, CO_2 emissions from buildings increased globally by 50 % (IPCC, 2022). The UK's residential sector remains the largest contributor (37 %) to national greenhouse emissions, against a backdrop of rapidly falling emissions in energy supply and manufacturing (59 % and 53 % respectively from 1990 to 2019) (Agnolucci and Arvanitopoulos, 2019; ONS, 2021). Space heating accounts for around two thirds of final energy consumption in UK homes. The decarbonisation of heat is therefore a major and urgent policy challenge to sustain progress towards net-zero emission targets.

Heat pumps that extract ambient heat from the ground or air for circulation in radiant heat systems are among the principal solutions for the decarbonisation of residential heating (IPCC, 2022). Within Europe, the UK has the highest share of gas use for residential heating (86 % in 2020) (English Housing Survey, 2022), followed by the Netherlands and Italy with 68 % and 52 % respectively (IPCC, 2022). Conversely, the UK has among the lowest shares of heat pump deployment with approximately 1.5 heat pump installations per 1000 households in 2021, compared to 50 per 1000 households in market leaders such as Norway (EHPA, 2022). This can be explained largely by higher capital costs compared to other countries, and relatively high taxes and levies on electricity compared to gas (Rosenow et al., 2023). However, this general argument does not explain the wide heterogeneity in heat pump adoption observed between different areas (Fig. 1).

A unique contribution of our study is to present and examine highly disaggregated spatial-temporal data for heat pump diffusion throughout Great Britain (GB) at the local authority level from 2010 to 2020. This is the first in-depth spatial and temporal analysis of heat pump diffusion

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List of abbreviations

(BRES)	Business Register and Employment Survey
(CO2)	Carbon Dioxide
(CoP)	Coefficient of Performance
(CPI)	Consumer Prices Index
(BEIS)	Department of Business, Energy and Industrial Strategy
(DESNZ)	Department of Energy Security and Net Zero
(EPC)	Energy Performance Certificate
(EU)	European Union
(SLX)	Exogenous Spatial Effects Model
(GB)	Great Britain
(GW)	Gigawatt
(GVA)	Gross Value Added
(IDBR)	Inter-Departmental Business Register
(IPCC)	Intergovernmental Panel on Climate Change
(kW)	Kilowatt
(LSOAs)	Lower Layer Super Output Areas
(MCS)	Microgeneration certification scheme
(MW)	Megawatt
(ONS)	Office for National Statistics
(Ofgem)	Office of Gas and Electricity Markets
(OLS)	Ordinary Least Squares
(PAYE)	Pay As Your Earn
(RHI)	Renewable Heat Incentive
(SIC)	Standard Industrial Classifications
(SEM)	Spatial Error Model
(SAR)	Spatial Lag Model
(VAT)	Value Added Tax
(UK)	United Kingdom

that employs linear and spatial econometric methods to account for the role of property and household characteristics on heat pump adoption. We also estimate spatial spillover effects between areas with varying energy capabilities and competences.

We use two datasets, one obtained through a Freedom of Information request from Ofgem (the Office of Gas and Electricity Markets), the UK's energy market regulator, and a publicly available one derived from the energy ministry, BEIS (Department of Business, Energy and Industrial Strategy).[1] Both datasets originate from the Renewable Heat Incentive (RHI) scheme, which was the UK's principal policy instrument to support heat pump adoption until the start of 2022. We focus on air source (or 'air-to-water') heat pumps that capture heat from ambient air and transfer it to a circulating fluid as these account for 87 % of all heat pumps units sold in the UK to 2020, and for 85 % of those incentivised by the Renewable Heat Incentive (RHI) scheme (BEIS, 2020). We refer to air source heat pumps simply as 'heat pumps' hereafter.

We focus on four interrelated research questions (RQ) that build a holistic understanding of the local dynamics driving heat pump deployment:

RQ1: What types of homes are heat pumps installed in? We contribute to the empirical literature on the tenure and property characteristics of households adopting heat pumps. Our findings highlight substantial challenges in stimulating wider uptake, specifically in urban settings.
RQ2: What are the cost dynamics of heat pump deployment? Economies of scale and learning effects are expected to reduce costs. However, we provide evidence that GB is an exception and contribute to the limited empirical understanding of cost dynamics for heat pumps.
RQ3: What are the characteristics of local areas that are early adopters of heat pumps? Scant empirical evidence on the profile of early adopters hinders the development of targeted policy frameworks. Our results inform this discussion on the trade-offs between effectiveness and equality of access.
RQ4: What explains the spatial diffusion of heat pump installations over time? Spatial spillovers have been observed for other low-carbon and renewable technologies, but remain underexplored for heat pumps. We provide supportive evidence of such spillovers and examine the underlying supply and demand mechanisms that drive them.

Studies of the decarbonisation of residential heating use either statistical and case study analysis of historical data (*ex-post*) or future-oriented simulation modelling (*ex-ante*). These *ex-ante* approaches rely on assumptions about the drivers of heat pump adoption which should be grounded in historical evidence.[2] Our study falls within the *ex-post* tradition and provides valuable insights for calibrating *ex-ante* modelling projections.

Ex-post studies assess historical heat pump adoption and policy effectiveness using statistical and econometric methods, but rarely examine the local drivers of heat pump adoption. An exception is Zhang et al. (2024) who examine spatial diffusion of heat pumps in Swiss municipalities and find urban-rural disparities and spatial clusters. However, their use of linear regression despite spatial autocorrelation raises concerns about robustness. Their analysis also lacks a temporal dimension and does not consider factors such as low-carbon energy skills, previous heating technologies, cost dynamics, and spatial spillovers, which we addressed in our study.

Ex-post analyses of heat pump deployment without a spatial dimension are available for global, European, and US markets. Globally, Rosenow et al. (2022a) show that market penetration is higher in colder countries. In Europe, Winskel et al. (2024) show wide variation in observed cost dynamics between lead markets (Sweden, Switzerland) and followers (UK). Rosenow et al. (2023) attributes low market penetration in the UK to the higher differential between electricity and gas costs. Within Europe, Finland is a leading market for heat pump deployment. Sahari (2019) exploits local variation in electricity prices to show their influence on heat pump adoption. Hannon (2015) conducts a comparative analysis of the UK and Finnish heat pump markets, highlighting Finland's leadership in this area. Focusing on Ireland, Kelly et al. (2016) explore the comparative performance of heat pumps against residential heating technologies. In the US, Davis (2024) finds little correlation between income and heat pump deployment. This includes conversions in older homes (Anderson and Kirkpatrick, 2024). At the state level, Shen et al. (2021) show that introducing heat pumps increases the price premium in the housing markets of 23 US states, indicating a market preference for electrified space heating. *Ex-post* market studies also assess policy effectiveness. For example, Shen et al. (2022) find that rebate programs in North Carolina are more effective for middle-income households than for low- and high-income groups. Barnes et al. (2024) find that policy incentives in the UK have been insufficiently strong and designed without broad stakeholder buy-in.

We contribute to this evidence base through a highly differentiated analysis of local conditions associated with heat pump adoption alongside a generalisable economic analysis of installation cost dynamics. Our study contributes to the literature by providing robust econometric and

[1] In 2023, the energy-related competencies in BEIS were moved into a newly formed Department of Energy Security and Net Zero (DESNZ).

[2] For an overview of the related *ex ante* studies refer to SI-A.3.

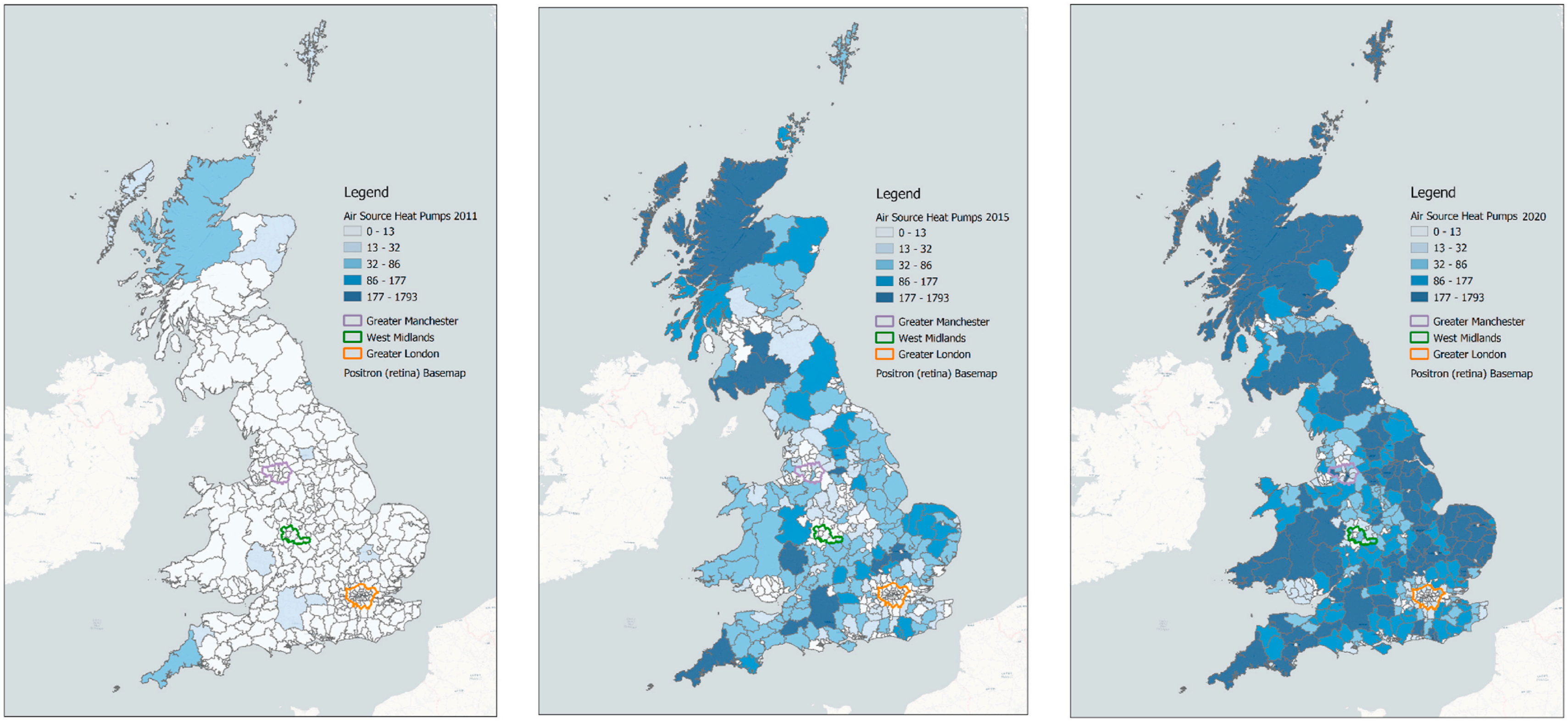

Fig. 1. Cumulative number of heat pumps installed in 380 local authority areas in Great Britain for 2011, 2015, and 2020, based on data from Ofgem (the Office of Gas and Electricity Markets) accessed through a Freedom of Information Act request. We also provide a timelapse of cumulative annual heat pump deployment across Great Britain's local authority areas from 2010 to 2020 in the animation Online Resource 1 attached with the Supplementary information (SI). For comparison purposes, we include Fig. B3 on population density by local authority in the SI.

visual evidence of spatial spillover effects, through which early adopting areas – likely to be rural, off-grid, and reliant on solid fuel – influence later-adopting regions, primarily through local supply chains and increased construction activity.

With the explicit spatial dimension to our analysis, we also contribute to a growing literature on the spatial characteristics of energy transitions. This includes studies that confirm the importance of peer or neighbourhood effects in stimulating adoption of low-carbon technologies like solar PV (Mundaca and Samahita, 2020; Palm, 2017), electric vehicles (Pettifor et al., 2017), energy retrofits (Noonan et al., 2013), heat pumps (Min and Mayfield, 2023), and green buildings (Qiu et al., 2016). In a joint study of solar PV, electric vehicle and heat pump diffusion spatially in the US, Min (2025) find highly localised peer effects that are strongest at distances of 150–250 m, in less densely populated rural areas, and during early adoption stages. Our work offers a unique bridge between these granular spatial studies of social influence and the market-level studies that consider economic factors and policy effectiveness.

2. Economic and technological characteristics of heat pumps

2.1. Technological characteristics

A fridge extracts heat from inside and releases it outside using a heat exchanger and a refrigerant cycle of compression and expansion. A heat pump works in reverse, transferring thermal energy from outside to inside with minimal electricity. Air source heat pumps use an external unit, ground- or wall-mounted, to extract ambient heat from the air. Ground source heat pumps draw heat from underground pipes, where temperatures are more stable. In 2021, 94 % of the 2.2 million heat pumps sold in Europe were air source (Rosenow et al., 2022). In the UK, air source heat pumps typically provide both heating and hot water ('air-to-water'), while less common 'air-to-air' systems, more popular in the US, can also cool spaces but do not provide hot water.

2.2. Cost dynamics

Although heat pumps have similar operating and maintenance costs, their upfront fixed costs are about three times higher than gas boilers, averaging £9–10,000 in the UK compared to £2–3000 for gas boilers (Winskel et al., 2024). Upfront costs rise further if upgrades to the radiant system or energy-efficiency improvements are needed before installation. However, lower variable costs can offset this. Manufacturing economies of scale and learning effects as installation experience accumulates can drive both equipment and installation costs down. Learning or experience curves are widely used to describe these cost reductions observed in energy technologies as cumulative installed capacity (a proxy for 'experience') increases (Steffen et al., 2020). The learning rate is the percentage reduction in cost per doubling of cumulative capacity. Studies show learning rates up to 18–26 % for ground source heat pumps in countries like Switzerland and the Netherlands (Winskel et al., 2024).

While heat pump costs (£/kW) are generally expected to decrease as the market grows (Renaldi et al., 2021), report negative learning rates of −2.3 % for air source heat pumps in the UK from 2010 to 2019, defying these expectations. Our results confirm this finding. We present and discuss this further below.

2.3. Policies and incentives

Enabling policy frameworks, including financial incentives, are key to supporting early deployment of low-carbon technologies like heat pumps, helping them compete with fossil-fuel incumbents (Shen et al., 2022). Grants, subsidies, tax rebates, and low interest loans are commonly used in many countries to offset high upfront costs for households (Rosenow et al., 2022). Increasing taxes on high-carbon gas relative to increasingly low-carbon electricity should further help improve the cost differential of operating a heat pump compared to a gas boiler (Rosenow et al., 2023).

In the UK, the principal policy instrument for heat pump adoption until recently was the Renewable Heat Incentive (RHI), introduced in 2014 after the Renewable Heat Premium Payment (RHPP) in 2011. The RHI offered grants and quarterly payments over seven years to homeowners, private and social landlords, and tenants (with permission from owners) installing renewable heating systems (Ofgem, 2021). Lowes et al. (2019) argue that RHI tariffs for heat pumps were set lower than needed for market expansion, as policymakers feared high budget costs from imported units, similar to what occurred with solar PV feed-in tariffs. The RHI scheme required building efficiency improvements for low-performing properties before heat pump installation. Retrofit challenges contributed to lower-than-expected heat pump uptake of the RHI in the UK (Snape et al., 2015).

The RHI scheme closed in March 2, 022[3] and was replaced by the Boiler Upgrade Scheme, a capital grant scheme that covers the majority share of upfront costs to ensure affordability relative to gas boilers. Since August 2023, this scheme has covered £7500 of air source heat pump installation costs.

3. Data

3.1. Heat pump installations

Through a Freedom of Information Act request submitted to Ofgem, we obtained access to anonymised data for residential heat pump installations in GB from 2010 to June 2020 under the UK's domestic RHI scheme. The Ofgem dataset provides disaggregated information per installation on property type (house, flat, and bungalow), property tenure (owned and rented), installation year, total installation cost, total heat demand, estimated annual heat generation, and installed capacity.[4] We have detailed information for 47,108 heat pumps installed in GB over the period 2010–2020. As noted, we use the term 'heat pumps' throughout the data and analysis sections to refer to air source heat pumps (air-to-water). Heat pumps in GB are solely used for heating in the winter, so cooling services possible with air-to-air heat pumps are not relevant to our study.

An alternative publicly available data source for heat pump deployment is the BEIS RHI dataset which provides summary information on total numbers of accredited RHI installations by technology type over 2014–2020. The BEIS dataset breaks down total installations by local authority area only for 2020, due to confidentiality constraints, given the small number of heat pumps installed in some local authorities. Although the BEIS dataset reports the cumulative installed capacity per local authority for all types of heat pumps installed, it does not disaggregate capacity for individual technology types (e.g., air vs ground source). So compared to the Ofgem dataset, it does not have a temporal dimension, and it lacks additional information on installed capacity, property type, and so on. We use the BEIS dataset in two ways: first, as a benchmark to assess the validity of our spatial allocation strategy for matching installations to local authority areas; second, as a general validity test on the robustness of the empirical findings.

The Ofgem dataset includes spatial information on the postal town for each heat pump installation. We matched postal towns to corresponding local authority areas which is the spatial resolution for our analysis. To check robustness of our spatial allocation strategy, we compared the cumulative number of heat pumps per local authority area in 2020 from the BEIS dataset to the spatially allocated Ofgem data. Overall, we identified the corresponding local authority for 45,505 heat

[3] Full details of the RHI are provided in SI-A.1. and Table A1.

[4] We provide a detailed overview of the employed data cleaning methodology in the SI-B.1.

pumps installed in GB from 2010 to 2020 in the Ofgem dataset.

Fig. 1 presents the spatial distribution of the cumulative number of heat pumps installed in 2010, 2015, and 2020 across the 380 local authority areas in England, Wales, and Scotland (comprising GB). We also provide a timelapse of cumulative annual heat pump deployment across GB's local authorities from 2010 to 2020 in the animation Online Resource 1 attached with Supplementary information (SI). Deployment of heat pumps over this period is predominantly concentrated outside the major metropolitan areas in which available space for locating heat pumps is more limited (particularly for flats rather than houses) and a higher proportion of homes are connected to the gas network.

Fig. 1 shows that certain local authority areas[5] function as test beds for early adoption of heat pumps. Animation Online Resource 1 shows that neighbouring local authority areas catch up gradually over time. This suggests a positive spatial spillover effect from early adopting areas to neighbouring areas in proximity. Similar patterns of positive spatial spillover have been observed in the diffusion of solar PV systems in the UK, also known as 'solar clusters' (Schaffer and Brun, 2015). We formally test for the existence of positive spatial spillover effects in the diffusion of heat pumps using spatial econometric techniques specified in the following section. We expect to find evidence of spatial spillover from 'core' early adopting to 'periphery' later adopting local authorities due to supply chain materialisation as well as peer effects.

3.2. Local conditions associated with heat pump installations

We use independent variables for local conditions that we expect to be associated with heat pump deployment. Table 1 summarises variables measuring property and household characteristics, low-carbon energy capabilities and competences, and market characteristics. We expand below on independent variables used in our analysis.

3.2.1. Property characteristics and household characteristics

Starting with property characteristics, heat pumps require outdoor space for siting equipment, so we expect higher deployment in houses and rural areas (McKinsey & Company, 2022) and lower deployment in urban and metropolitan areas, particularly in flats including those in multi-family buildings (Raslan and Ambrose, 2022). To account for demographic characteristics, we use the percentage of Lower Layer Super Output Areas (LSOAs) per local authority classified as rural, suburban, and metropolitan, based on the UK census. Additionally, we control for the share of flats per local authority using UK census data.[6]

Second, as gas is the dominant cost-competitive form of heating in the UK, we expect higher heat pump deployment in areas with limited or no access to the gas grid where heat pumps can substitute for expensive oil boilers or solid fuel heating systems.[7] To account for this, we use data from BEIS on the percentage of properties not connected to the gas grid per local authority. Additionally, we control for alternative heating systems, focusing on solid fuel (e.g., wood, coal) and oil. Using UK census data, we account for the percentage of properties per local authority with solid fuel and oil-based central heating.

Third, as heat pump installations commonly require costly and disruptive changes to the internal building fabric (e.g., hot water cylinders, underfloor pipe network, efficiency improvements), we expect higher uptake in areas with higher share of new build properties. We account for the share of new building stock per local authority using data from Consumer Data Research Centre and Scottish Government Statistics, covering properties built between 1983 and 2015, the most recent

[5] Dumfries and Galloway, Highlands, Outer Hebrides, Cornwall, Mid Suffolk, West Oxfordshire, Forest Heath, Hambleton, Lewes, South Cambridgeshire, etc.

[6] Areas with high share of flats are primarily metropolitan areas, and thus we use these variables interchangeably in our regression models.

[7] Given off-grid areas are primarily rural, we use these variables interchangeably in our regression models.

Table 1
Variables measuring local conditions we expect to be associated with heat pump installations.

Independent variables	Metric employed and data source in parenthesis
Property and household characteristics	
Limited access to gas	% of properties not connected to the gas grid per local authority in 2018 (Source: BEIS LSOA estimates of properties not connected to the gas network)
New building stock	% of properties that were built per local authority after 1983 till 2015 (Source: Consumer Data Research Centre and Scottish Government Statistics)
Heat pump cost	Average total installed real cost per kW (£1000, 2019 base year, deflated using CPI) per local authority from 2010 to 2020 (Source: Ofgem accessed through Freedom of Information Act request)
Soil fuel central heating	% of properties using solid fuel (e.g., wood, coal) for central heating per local authority (Source: UK census 2011) [a]
Oil central heating	% of properties using oil for central heating per local authority (Source: UK census 2011) [a]
Flats	% of flats per local authority (Source: UK census 2011) [a]
Mean household income	Mean gross disposable household income (£1000) per local authority from 2010 to 2016 (Source: ONS Regional Gross Disposable Household Income) [b]
Rural	% of rural Lower Layer Super Output Areas (LSOAs) per local authority (Source: UK census 2011) [a]
Suburban areas	% of suburban Lower Layer Super Output Areas (LSOAs) per local authority (Source: UK census 2011) [a]
Metropolitan areas	% of metropolitan Lower Layer Super Output Areas (LSOAs) per local authority (Source: UK census 2011) [a]
Low-carbon energy capabilities and competences	
Renewable energy (RE) projects – distributed (or residential)	Cumulative number and total capacity (MW) of active renewable power generation projects with Feed-in-Tariffs (FiT) per 1000 households per local authority from 2011 to 2020 (Source: Ofgem FiT installation report)
Home energy audits	% households with Green Deal Assessments per local authority - cumulative to 2017 (Source: BEIS household energy efficiency statistics) [c]
Energy efficiency	% households with EPC rating C or above per local authority – mean for England and Wales from 2011 to 2020, and for Scotland from 2011 to 2018 (source for England and Wales: Energy Performance of Buildings Certificates; source for Scotland: Scottish House Condition Survey)
Community energy projects	Cumulative number of community energy projects per 1000 households per local authority from 2010 to 2020 (Source: Community Energy Hub and Community Energy Scotland)
Volunteering rate	% of people that have volunteered in the last 12 months per local authority - mean for 2011, 2013, and 2017 (Source: UK Understanding Society (University of Essex, Institute for Social and Economic Research, NatCen Social Research, 2019)) [d]
Market characteristics	
Employment	Average number of employees for 5-digit industrial classifications (SIC) related to heat pump deployment per 1000 households per local authority from 2010 to 2020 (source: Business Register and Employment Survey (BRES)). [e]
Local businesses	Number of local units in the broad industrial sector of production (SIC 05–39) per 1000 households per local authority from 2014 to

(continued on next page)

Table 1 (*continued*)

Independent variables	Metric employed and data source in parenthesis
Economic activity	2019 (source: Inter Departmental Business Register (IDBR)) [b] Average gross value added (Chain Volume Index £1000) for broad industrial sectors of production (SIC 01–39) per 1000 households per local authority from 2011 to 2018 (source: ONS Regional GVA by industry) [b]

For detailed descriptive statistics for all variables used in this study, see Table B3 in SI-B.2.

[a] This is the latest UK Census data available for the period assessed in our analysis.

[b] The specified dataset provides spatially disaggregated information employing the same boundaries employed for the allocation of heat pumps during the specified years. Subsequent chronological changes in the boundaries used to spatially disaggregate the specified dataset do not allow us to appropriately match it with the dependent variable.

[c] Green Deal Assessments are home energy audits mainly for homeowners. They are used to identify recommended cost-effective efficiency and low-carbon measures, improve thermal comfort, and energy bills (Pettifor et al., 2015). The UK Government Green Deal scheme run from 2012 to 2017.

[d] The UK Understanding Society dataset reports volunteering rate at the local authority level for the specified years. Access to this dataset requires obtaining a Special License.

[e] We account for employment for SIC codes 33200, 35300, 41100, 41201, 41202, 42220, 43210, 43220, 43290, 43999, 46520, 46740. BRES is the only official source for employee estimates by local authority at 5-digit SIC level. IDBR and ONS regional GVA are available at 2-digit SIC level. BRES does not cover for very small business not registered for VAT or PAYE.

age band available by the Scottish Government Statistics.

Concerning household characteristics, given the higher upfront costs of heat pumps compared to gas boilers, and the fact that RHI incentives are amortised over seven years post-installation, we expect more installations in areas with higher average household income and fewer capital constraints. We derive mean gross disposable income per local authority from 2010 to 2016 using ONS data. Additionally, as heat pumps are long-term investments and RHI incentives benefit property owners, we expect more installations in owner-occupied areas. We obtained ownership data for properties with heat pumps from the Ofgem RHI dataset.

3.2.2. *Low-carbon energy capabilities and competences*

First, as heat pump installations require skilled, experienced service providers for emerging low-carbon technologies (e.g., installers, engineers, plumbers), we expect higher uptake in areas with stronger supply chain capabilities and competences. We cannot measure this directly, so we use proxies. We account for the number and capacity of residential solar PV installations, obtained from the Ofgem Feed-in-Tariffs database, that records all active renewable energy generation projects per LSOA and is a UK government initiative designed to promote the uptake of small-scale distributed renewable energy projects (up to 5 MW). We expect that large numbers of these energy-related activities indicate accumulated technical expertise, environmental consciousness, and willingness to adopt new technologies such as heat pumps.

Second, as heat pump adoption requires motivated households willing to take technology risks and bear incremental costs, we expect higher installations in areas with more interest in energy-related home improvements. As a proxy, we use numbers of home energy audits such as the Green Deal Assessment, which help homeowners identify cost-effective efficiency and low-carbon measures for improving thermal comfort and reducing energy bills (Pettifor et al., 2015; Morton et al., 2018). By accounting for the percentage of properties with a Green Deal Assessment per local authority, we additionally control for relevant supply chain expertise (e.g., EPC assessors). Additionally, we measure energy-efficiency improvements by including the percentage of properties with an EPC rating C or higher per local authority.

Third, as early adopters of low-carbon technologies influence later adopters through trusted peer-to-peer networks that reduce perceived risks (Wolske et al., 2020; Vrain and Wilson, 2021), we expect higher uptake in areas with higher social capital. We use voluntarism as a proxy for social capital, which reflects civic engagement and strong social networks (Scrivens and Smith, 2013). We use data from the UK Understanding Society dataset that measures the percentage of people per local authority who engaged in voluntary activities in the last 12 months (University of Essex, Institute for Social and Economic Research, NatCen Social Research, 2019). As bottom-up initiatives, community energy projects also embody strong citizen participation and local ownership of low-carbon energy assets (Devine-Wright, 2019).[8] We directly include all community energy projects in GB as an alternative proxy for peer influence in heat pump adoption (Arvanitopoulos et al., 2022).

3.2.3. *Market characteristics*

We expect areas with more active heat pump installers in local supply chains to have higher heat pump uptake. We do not have spatially-explicit data on heat pump installer density or activity, so as a proxy we use the number of employees (Business Register and Employment Survey (BRES)) per local authority for 5-digit industrial classifications (SIC) related to heat pump deployment (see notes in Table 1). BRES is the only official source for employee estimates by local authority at 5-digit SIC level, but it excludes very small businesses not registered for VAT or PAYE, and thus has the limitation that it might not control for availability of local skilled trades working under sole trader status. Additionally, we use the number of local businesses and levels of economic activity in the broad industrial sector of 'production'.[9] Gross value added (GVA) for 'production' is derived from the ONS Regional GVA dataset, and local business counts in the 'production' sector come from the Departmental Business Register (IDBR). However, both IDBR and ONS GVA data are only available at the 2-digit SIC level, limiting the interpretability of these variables for heat pump deployment.

4. Methods

We use econometric methods to assess the explanatory power of property, household, low-carbon energy, and market characteristics (independent variables) over the spatial and temporal diffusion of heat pump installations at the local authority level (dependent variable). Section 4.1 begins with a cross-section model to address research questions 1 (RQ1): '*What types of homes are heat pumps installed in?*', and 2 (RQ2): '*What are the cost dynamics of heat pump deployment?*'. In section 4.2, we focus on the spatial dimension, using a spatial error model to investigate research question 3 (RQ3): '*What are the characteristics of local areas that are early adopters of heat pumps?*'. We opt for this model to address spatial correlation that could otherwise bias estimates. In section 4.3, we estimate two spatial regression models, accounting for endogenous and exogenous spillover effects, exploring research question 4 (RQ4): '*What explains the spatial diffusion of heat pump installations over time?*'. Finally, we conduct extensive sensitivity tests, including alternative model specifications to avoid overspecification from correlated variables (e.g., low access to gas, rural areas), as discussed in section 5.

[8] For an interactive GIS map of community energy projects included in this analysis (Rae et al., 2021), see: https://www.energyrev.org.uk/app_plugins/Maps/V4/index.html#5/57.681/-2.856. For a detailed analysis on the spatial diffusion of community energy projects in the UK, see Arvanitopoulos et al. (2022).

[9] ONS incorporates under the broad industry sector of 'production' SIC industrial code classifications 1–39. IDBR uses a slightly differentiated classification for 'production' using SIC industrial code classifications 5–39.

4.1. Cost and size dynamics of heat pump diffusion

We use the following linear regression model to examine the relationship between heat pump adoption, home tenure, and property characteristics over time:

$$y_j = \alpha + X_j\beta + \delta_j + u_j \tag{1}$$

where y_j denotes the dependent variable for heat pump installations j (41,716 observations). We use two distinct dependent variables: one accounts for cost dynamics (£/kW), and the second accounts for size dynamics (kW/unit).[10] As discussed in section 2.2, the choice of dependent variables is motivated by the literature on learning curves (Jakob et al., 2019; Renaldi et al., 2021; Steffen et al., 2020; Weiss et al., 2008). Focusing on cost dynamics allows us to compare our findings with similar studies, while also expanding the literature by investigating the impact of property and ownership characteristics. By specifying both cost and size dynamics as dependent variables, we examine how cost relative to capacity, and capacity in absolute terms, are associated to these characteristics, providing comprehensive understanding of heat pump market in GB.

X_j is a vector of independent variables including dummies for property type (i.e., house, or flat), and tenure type (i.e., owner occupied).[11] The constant parameter α accounts for dummies not included in the model (i.e., social landlords for tenure type, and bungalows property type). Year dummies, δ_j, control for year fixed effects[12] on installations from 2010 to 2019, and u_j represents the regression residuals.

4.2. Local conditions associated with heat pump diffusion

We examine the relationship between local conditions at local authority level and heat pump diffusion. Our dependent variable is the cumulative number of heat pumps installed per 1000 households in each local authority from 2010 to 2020. The independent variables capture local conditions expected to explain spatial variation in installations (Table 1, section 3.2). Visual inspections and descriptive statistics suggest spatial spillovers between neighbouring local authority areas (Fig. 1, Online Resource 1). We use a spatial autoregressive model (Anselin, 2003) to account for spatial dependence in residuals (equations (2) and (3)), the dependent variable (equation (4)), and the vector of independent variables (equation (5)). Separate regression models are estimated for each case of spatial correlation.

Given we want to explicitly control for spatial correlation and the corresponding spillovers, logit models used in related studies (e.g., Arvanitopoulos et al., 2022) are not suitable for the purpose of our study. Following Gibbons and Overman (2012) and Corrado and Fingleton (2012) insights, we refrain from over-emphasising model specification testing and goodness-of-fit measures in identifying the best performing spatial regression model. Instead, we develop our model selection strategy driven by our underlying expectations on the relationship between local conditions and heat pumps diffusion. Nonetheless, we include a model comparison table (SI-D.2., Table D4) that shows information criteria and test statistics for spatial regressions models and supports our modelling approach.

Starting with the spatial error model (SEM), we control for spatial correlation in the residuals of the model:

$$y_i = \alpha + X_i\beta + u_i \tag{2}$$

$$u_i = \lambda W u_i + \varepsilon_i \tag{3}$$

where y_i stands for the dependent variable, i.e., the cumulative number of heat pumps installed per 1000 households per local authority $i = 1, .., 380,$ from 2010 to 2020; α is the constant parameter; X_i is the vector of independent variables (Table 1); and u_i stands for the regression residuals. In equation (3), we introduce $\lambda W u_i$, the spatial lag vector that accounts for spatial correlation in residuals between contiguous local authorities. The weighting matrix W is binary, taking the value 1 for local authorities that are geographically adjacent and 0 otherwise. This design implies that geographic proximity matters, assuming spatial spillovers occur between directly adjacent local authorities, given that skilled trades availability and peer effects tend to be localised. We expect to find a strong spillover effect between contiguous local authority areas, as visually supported in Online Resource 1. The parameter λ captures the magnitude and significance of spatial dependence in the disturbance. We estimate the model using the Generalised 2 Stage Least Square (G2SLS) nonlinear estimator.

As a robustness test, we estimate a panel regression model that accounts for temporal variation. This dataset is unbalanced due to data constraints, as not all variables are available for the entire time period, while censorial variables lack time variation. Where possible, we replace variables with relevant proxies (discussed in SI-D.3.) and results remain consistent, supporting the robustness of our methodology.

4.3. Spatial spillovers in heat pump diffusion

The spatial error model accounts for spatial dependence in the residuals, but it does not explain the nature of spillover effects. To identify the drivers, we specify two distinct spatial regression models. The spatial lag model (SAR) captures endogenous spillovers by including a spatially lagged dependent variable (equation (4)). Separately, we specify a model with a spatial lag of the independent variables to identify exogenous spillover effects (equation (5)). We do not to employ models that simultaneously incorporate spatially lagged dependent variable and spatially autocorrelated error term (SAC model), or both spatially lagged dependent and independent variables (spatial Durbin model). These modes are criticised in the literature for identification problems in distinguishing endogenous from exogenous interactions effects (Gibbons and Overman, 2012; Elhorst and Vega, 2013).

SAR (equation (4)) captures spillover effects for the dependent variable, controlling for whether heat pump deployment in one local authority indirectly influences deployment in contiguous authorities:

$$y_i = \alpha + \rho W y_i + X_i\beta + u_i \tag{4}$$

where y_i stands for the dependent variable, i.e., the cumulative number of heat pumps installed per 1000 households per local authority $i = 1, .., 380,$ from 2010 to 2020; α is the constant parameter; and X_i is the vector of independent variables. $\rho W y_i$ represents the spatial lag vector controlling for the spatial spillover effect of the dependent variable between contiguous local authorities, and ρ is the corresponding spatial dependent parameter. The weighting matrix W is binary, taking the value 1 for local authorities that are geographically adjacent and 0 otherwise. So, $\rho W y_i$ denotes the endogenous interaction of the dependent variable, and ρ captures the magnitude and significance of the spillover effect. u_i stands for the regression residuals. We use the Generalised 2 Stage Least Square (G2SLS) nonlinear estimator to estimate the model.

Although SAR captures spatial autocorrelation, it does not explain the exogenous causes of the observed spillover effect. The identified endogenous spillover effect could result from omitted variable bias and thus be misleading (Corrado and Fingleton, 2012). Thus, we use the model in equation (5) to further support the identified spatial spillovers and pinpoint their exogenous causes. This model captures the spillover effect of the independent variables, controlling for whether specific

[10] For descriptive statistics on cost and size dynamics variables see Table B1, in SI-B.1.

[11] We do not incorporate all property and tenure type dummies to avoid dummy variable trap, which would lead to perfect multicollinearity. We include the ones that we are more interested in, based on our expectations.

[12] Year fixed effects are dummy variables that control for factors which vary across years but remain constant across other units within each year.

conditions in one local authority indirectly influence heat pump deployment in contiguous local authorities:

$$y_i = \alpha + X_i\beta + WZ_i + u_i \quad (5)$$

y_i stands for the dependent variable, i.e., the cumulative number of heat pumps installed per 1000 households per local authority $i = 1, .., 380$, from 2010 to 2020; α is the constant parameter; and X_i is the vector of independent variables. The spatial lag vector WZ_i captures hypothesised transmission channels of spillover effects to contiguous local authorities by incorporating specific independent variables used to identify the demand and supply dynamics of heat pump diffusion. Section 5.3 provides a detailed discussion of how WZ_i vector is used to develop a plausible strategy for identifying spillover effects and interpreting the spatial diffusion dynamics of demand and supply. We estimate the model with the use of the Generalised 2 Stage Least Square (G2SLS) nonlinear estimator.

5. Results

5.1. RQ1. What types of homes are heat pumps installed in?

The number of heat pump installations in GB increased from 1000 in 2010 to about 47,100 in 2020, with annual rates increasing by almost 90 % from 2010 to 2019 (Fig. B2, SI-B.1.). Most heat pumps are installed in houses (67 %), of which 70 % are owner-occupied, as heat pumps require outdoor space for siting equipment. Bungalows account for 26.8 % of installations, and flats for 6.2 %. Regarding tenure type, most heat pumps are installed in owner-occupied properties (62.5 %), with the remaining installations in social housing (34.6 %), and a small proportion in privately rented properties (2.8 %). This is reasonable as heat pumps are long-term investments, and RHI incentives accrue to the heat pump and property owner. Landlords have no incentive to install heat pumps, as they have to pay installation costs and do not benefit from reduced energy bills, as these are paid by tenants.

Rented properties tend to have lower levels of energy efficiency (Lang et al., 2021). The observed low installation rate in rented properties underscores this and highlights the challenges in stimulating adoption in rented properties. Concerning social landlords, the observed adoption rate (34.6 %) is primarily driven by unique cases of local authorities with increased share of heat pumps installed by social landlords, as seen in Dumfries and Galloway.[13] Experienced social landlords with substantial real estate portfolios can influence market dynamics in local areas by capitalising on existing supply chains and local expertise.

5.2. RQ2: What are the cost dynamics of heat pump installations?

Total installed cost includes both equipment and on-site ('balance of plant') installation costs. The mean total installed real cost from 2010 to 2020 in our sample is 1075 £/kW. Initially, it decreases to 924 £/kW in 2014, before increasing to its highest price of 1300 £/kW in 2020 (see Fig. 2). This is comparable to Renaldi et al. (2021) who found mean total installed cost from 2010 to 2019 of 933 £/kW, with a decreasing trend to 2013, and thereafter increasing to 2019.[14] As discussed in section 2.2, we find that total real costs for heat pumps are substantially more expensive compared to the those for condensing gas boilers estimated by

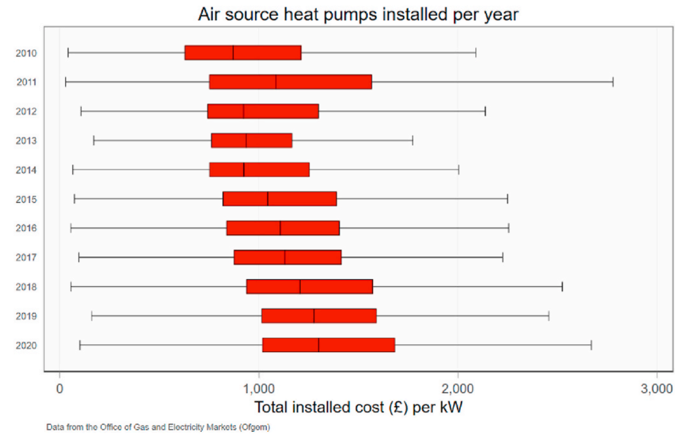

Fig. 2. Total installed real cost (£) per kW for air source heat pumps installed in Great Britain per year from 2010 to 2020.
Notes: Monetary values are deflated using the Consumer Price Index with 2019 as base year. Source: Ofgem RHI dataset (see text for details). Box shows interquartile range, whiskers show min and max. Outliers are excluded.

Renaldi et al. (2021) at 30 £/kW,[15] which functions as a barrier to the wider diffusion of heat pumps. However, it should be noted that heat pumps can have smaller capacities than gas boilers depending on their sizing.

It is important to disentangle what drives the observed total cost increases. There were 33 manufacturers active in the UK heat pump market in 2019, including small players with less than 1 % market share (BEIS, 2020). UK-based manufacturers (e.g. Mitsubishi, Global Energy Systems, Big Magic Thermodynamic Box and Star Renewables) accounted for 31 % of all heat pumps, indicating potential for competitive dynamics within the UK heat pump production sector, which could keep production costs down. Indeed, UK data from 2010 to 2019 on heat pump prices from manufacturers, distributors, and online equipment stores, show a 24 % decrease in equipment costs while cumulative capacity increased by 70 % in the same period (Renaldi et al., 2021). This means that rising total costs over time have been primarily driven by increasing on-site installation cost, which could be attributed to the historically increasing skills mismatch and shortages,[16] particularly for skilled trades and process, plant, and machines operatives (Sunley et al., 2021). Tracking down empirically skills shortages is particularly difficult as official data on skills and occupations at a granular geographical level do not exist (Brunello and Wruuck, 2021). We focus instead on monitoring existing low-carbon energy capabilities and competences (as discussed in section 3.2.2).

Replicating Renaldi et al. (2021), we estimate the learning curve for heat pumps in the UK and expand their analysis by one more year of observations (i.e., 2020) (Fig. 3). We estimate a −3.3 % learning rate, comparable to that of −2.3 % in (Renaldi et al., 2021).[17] Our lower value can be explained by the uptick in total installed cost in 2020. As discussed in section 2.2, cost data from other European countries shows

[13] Dumfries and Galloway is the local authority in GB with the second-largest deployment of Community Energy (CE) projects (26 compared to an average of 1 project across GB), which suggests potential association between expertise gained through Community Energy projects (for which we control for in the econometric analysis) and the involvement of social landlords in heat pump deployment.

[14] Fig. C1 in SI-C.1. Visually depicts heat pump cost (£/kW) per year estimated in this study compared to the equivalent cost dynamics estimated in (Renaldi et al., 2021).

[15] Using data from Switzerland, Jakob et al. (2019) estimated that cost for natural gas condensing combi boilers reduced from 122€/kW in 1980 to 40€/kW in 2018.

[16] Skills mismatch is the gap between supply and demand for specific skills typically observed with a reference to a geographic unit, while skills shortage corresponds to the inability of employers to recruit staff with required skills (Brunello and Wruuck, 2021). Skill shortages could exacerbate supply-side scarcities leading to cost increases.

[17] Renaldi et al. (2021) obtain total installed cost for heat pumps installed in the UK from the Microgeneration Certification Scheme (MSC) Installations Database that provides assessment certificates, which are part of the RHI application process.

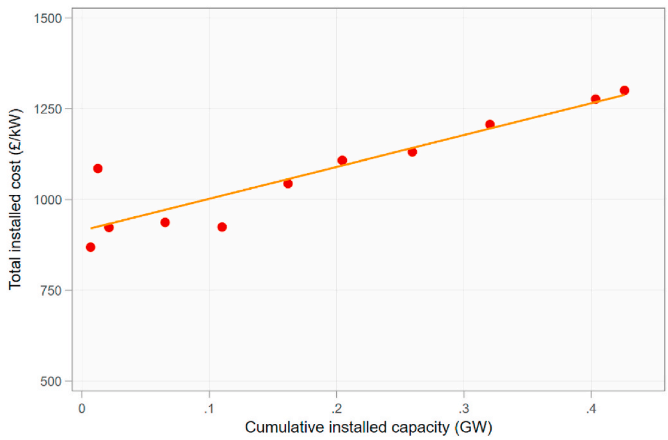

Fig. 3. Learning curve for air source heat pumps based on total installed real cost (£/kW) and cumulative capacity (GW) from 2010 to 2020.
Notes: Each data points reports an observation for each year from 2010 to 2020. The learning rate −3.3 % is comparable to (Renaldi et al., 2021)'s estimate of −2.3 % using data from 2010 to 2019. Monetary values are deflated using the Consumer Price Index with 2019 as base year. For more information on the learning curve see SI-C.1.

positive learning rates (Jakob et al., 2019) which helps explain the significantly lower uptake of heat pumps in the UK (Rosenow et al., 2022). For example, Switzerland exhibits a learning rate of 18 % (Jakob et al., 2019), with heat pump penetration in 2020 reaching approximately 14 % of households (Rosenow et al., 2022a).

We estimate the linear regression model specified in equation (1). Table 2 indicates that owner-occupied properties, and houses have been strongly associated with declining costs and increasing sizes of heat pumps (column 1 and 2). The opposite pattern can be observed for flats (apartments). Results are consistent when we introduce time dummies in column 2 to capture any unobserved fixed effects on cost dynamics over time. Coefficient in columns 1 and 2 are strongly statistically significant. Small differences in the values of the coefficients can be observed when we introduce time dummies in column 2.

Concerning size dynamics (columns 3 and 4), installed capacity has increased over time for all types of property and tenure, with flats the only exception. Similar to cost dynamics, results for size dynamics remain consistent when we introduce time dummies in column 4 to capture any unobserved fixed effects over time. Coefficients in columns 3 and 4 are strongly statistically significant. The constant parameter, that effectively captures the effect for all non-owner-occupied properties and bungalows is positive and statistically significant across all models. In columns 1 and 2, this indicates that any cost reduction in heat pump deployment over time is solely associated with owner-occupied houses. In columns 3 and 4, this indicates that non-owner-occupied properties including bungalows are associated with size increases (larger kW heat pumps). Conversely, flats are associated with size decreases.

In sum, we find that although the average total installed cost has increased over time, owner-occupied houses have kept cost increases at lower levels compared to the general trend. This aligns with our expectations in relation to property characteristics, as owner-occupied houses have fewer space restrictions and long-term interests in home improvement and energy bills. It also suggests that lower installation rate of heat pumps in non-owner-occupied properties could be partly attributed to relatively high total installed cost, among other factors.

Table 2
Linear regression models on the relationship between cost and size dynamics of heat pump installations, and property and tenure characteristics.

	Cost dynamics		Size dynamics	
	Log of total installed real cost (£)/installed capacity (kW)		Log of installed capacity (kW/unit)	
	[1]	[2]	[3]	[4]
House dummy	−0.0905***	−0.0961***	0.157***	0.160***
	(0.005)	(0.004)	(0.004)	(0.004)
Flat dummy	0.0634***	0.0316***	−0.133***	−0.118***
	(0.009)	(0.008)	(0.007)	(0.007)
Owner occupied dummy	−0.0991***	−0.143***	0.481***	0.498***
	(0.004)	(0.004)	(0.003)	(0.003)
Constant	7.131***	7.354***	1.806***	1.747***
	(0.004)	(0.009)	(0.003)	(0.008)
Year dummies	NO	YES	NO	YES
Observations	41,716	41,716	42,844	42,844
R-squared	0.035	0.117	0.406	0.417

Notes: Robust standard errors in parentheses. ***$p < 0.01$. Columns 1 and 2 use as dependent variable the log of the share of total installed cost (£) to installed capacity (kW), while columns 3 and 4 use as dependent variable the log of installed capacity (kW/unit). Monetary values are deflated using the Consumer Price Index with 2019 as base year. Fig. C2 (SI-C.2.) visually displays the coefficients for all year dummies specified in columns 2 and 4. All coefficients for year dummies in column 2 are statistically significant, while in column 4 the coefficients for year dummies from 2010 to 2017 are statistically significant. The constant parameter captures the effect for all non-owner-occupied properties and bungalows. For results including fixed effects for individual local authorities and year dummies see Table C1 (SI-C.2.).

5.3. *RQ3: What are the characteristics of local areas that are early adopters of heat pumps?*

We turn our focus to the spatial dimension and analyse the influence of local conditions on heat pump diffusion historically. To define our baseline model, we tested and compared results for various model specifications.[18] We excluded variables for social capital,[19] EPC ratings,[20] local businesses, and economic activity from the final baseline model as they were not statistically significant. Using Moran's I test we found evidence of spatial autocorrelation in the residuals of the OLS model and so used a spatial error model (SEM) rather than linear regression.

In Table 3, column 1 shows the results for the spatial error model (SEM) specified in equations (2) and (3). The spatially lagged error term is positive and statistically significant, further confirming our model's choice. The coefficient for the share of properties with no access to gas is positive and statistically significant. Considering local authority areas with reduced access to gas are also characterised by higher rates of properties using solid fuel and oil for central heating, we replace the variable controlling for reduced access to gas with two variables: one controlling for the share of properties using solid fuel (wood, coal) and the other for oil for central heating (column 1-Table D3 in SI-D.2.). We find that local authority areas with higher share of properties using solid fuel are almost three times more likely to install heat pumps, compared to those with higher share of properties using oil for heating. This supports the argument that one of the key functions of heat pumps, so far, has been to primarily replace expensive solid fuel and, to a lower extent, oil boilers. Local authority areas with higher share of limited access to

[18] See SI-D.1. For a detailed discussion on all tested linear regression models, and Table D1 for linear regression models results.
[19] We focus on energy community projects as it is a more relevant measure for capturing potential peer effects from the diffusion of low-carbon energy technologies.
[20] Considering the substantial number of properties with low energy efficiency in GB, it is reasonable to expect that reduced variation in EPC ratings cannot explain early heat pump adoption. Instead, we include home energy audits in the baseline model as it is a better proxy for energy-related home improvements.

Table 3
Model results testing local conditions associated with heat pump diffusion.

	Heat pumps (per 1000 households) - Ofgem data			
	[1] SEM	[2] SAR	[3] SLX	[4] SLX
			Direct effect	Indirect effect (spillover)
Property and household characteristics				
Limited access to gas %	10.67***	9.727***	10.34***	
	(1.546)	(1.532)	(1.518)	
New building stock %	−3.146	−2.235	−4.513**	4.934**
	(2.015)	(1.847)	(2.073)	(2.110)
Flats %	−5.721***	−4.703***	−3.909***	
	(1.299)	(1.224)	(1.290)	
Mean total installed real cost (£1000) per kW	0.743	0.804	0.777	
	(0.579)	(0.587)	(0.588)	
Mean gross disposable household income (£1000)	0.0221	0.0176	0.00874	
	(0.0164)	(0.0144)	(0.0161)	
Low-carbon energy capabilities and competences				
Total capacity of renewable energy (RE) projects - distributed (per 1000 households)	2.733***	2.036***	2.879***	0.194
	(0.702)	(0.690)	(0.761)	(1.421)
Home energy audits (per 1000 households)	15.03	12.49	22.63*	
	(13.45)	(12.82)	(12.71)	
Community energy projects (per 1000 households)	11.14***	11.98***	11.58***	−5.289
	(1.013)	(1.044)	(1.037)	(5.939)
Constant	−0.900	−1.280	−1.402	
	(1.184)	(1.110)	(1.120)	
Spatially lagged error - contiguity	0.404***			
	(0.144)			
Heat pumps spillover effect-contiguity		0.318***		
		(0.110)		
Pseudo R-squared	0.694	0.700	0.7158	
Observations	374	374	374	374

Notes: In column 1, we employ the spatial error model (SEM) that controls for spatial correlation between contiguous local authority areas in the disturbance term. In column 2, we use the spatial lag model (SAR) that accounts for endogenous spillover effects from the diffusion of heat pumps to contiguous local authority areas. In column 3 and 4, we control for exogenous spatial spillover effects (SLX) for specific independent variables that capture the transmission channels for spatial spillover effects. The direct effect (column 3) accounts for the relationship between explanatory variables and heat pump diffusion in the same local authority, while the indirect effect (column 4) for that of explanatory variables on the deployment of heat pump in contiguous local authority areas. Dependent variable is the cumulative number of heat pumps installed per 1000 households per local authority areas in Great Britain (380 in total) from 2010 to 2020. Standard errors in parentheses. The slightly smaller sample size (374) in the models reported in this table is because we do not have access to information on total installed cost for six local authority areas with very low numbers of heat pumps installed (e.g., Bolsover, East Dunbartonshire, etc.). This does not affect our results that remain virtually unchanged when we remove total installed cost variable - see column 1 and 2 of Table D1 in SI-D.1. Table D1 includes additional sensitivity analysis. For information criteria and test statistics refer to Table D4 in SI-D.2. ***p < 0.01, **p < 0.05, *p < 0.1.

gas are predominantly rural, and thus as a sensitivity test, we replace it with three variables controlling for the share of rural, suburban, and metropolitan LSOAs within each local authority (column 2-Table D3 in SI-D.2.). The coefficient for the share of rural areas is positive and statistically significant, while those for suburban and metropolitan areas are not, which further supports our results' robustness.

We find statistically significant evidence that local authority areas with a higher share of flats, predominantly metropolitan,[21] are associated with lower levels of heat pump deployment (column 1-Table 3). This confirms our expectation, as discussed at length above. We face difficulties in establishing statistically significant evidence for new building stock which may be attributed to the relatively low levels of new housing supply since 1980 in GB, with more than a quarter of it involving flats developed in England (Department for Communities and Local Government, 2017). Historically, stringent planning regulation and land use limitations have significantly restricted new housing supply in GB (Ball, 2011; White and Allmendinger, 2003). In addition, heat pumps only began to be commonly installed in newly built properties relatively recently, so housing stock from the 1990s is not necessarily better suited than older properties. Given mean total installed cost has been rising over time in GB, likely driven by on-site installation costs rather than equipment costs (see section 4.1), we interpret this to mean that households' decision to install heat pumps is not driven by cost competitiveness incentives but rather other factors, as discussed above. Motivated households are more likely to take technology risks and bear incremental costs. We regress an additional model specification incorporating a variable accounting for the average property price per local authority to test whether total installed cost is inflated in more expensive areas (column 3-Table D3 in SI-D.2.). We find no significant evidence in support of this argument.

Areas with more distributed renewable energy projects and community energy projects are significantly associated with more heat pump installations (column 1-Table 3), which we interpret as evidence of accumulated technical expertise and supply chains that are applicable to heat pumps as a different type of low-carbon electrification (section 3.2.2). As sensitivity analysis, we substitute the total number of distributed renewable energy projects for total capacity (MW).[22] Results remain highly consistent. We do not find statistically significant evidence for home energy audits in column 1- Table 3. We reason this is because the effect of accumulated technical expertise and supply chains on heat pump adoption is captured by the variables accounting for distributed energy and community energy projects, and thus leaving no variation for the home energy audits variable (column 6-Table D3 in SI-D.2.). Similar to Davis (2024) and Anderson and Kirkpatrick (2024) who find little correlation between heat pump adoption and income in the US context, we do not find significant evidence for mean disposable income. As a sensitivity check, we perform an additional panel regression analysis that further indicates the consistency of our results.[23]

We conclude that heat pumps to-date are more likely to have been installed in areas with clear needs for alternative heating (low access to piped gas) and enabling conditions in the form of low-carbon energy

[21] In column 2-Table D3 in SI-D.2., we replace the variable controlling for the share of flats with variables controlling for the share of rural, suburban, and metropolitan Lower Layer Super Output Areas. This adjustment is made to address multicollinearity issues in the model.

[22] We expect that both variables (count and capacity) capture the same effect. Results in column 4-Table D3 in SI-D.2. Confirm this.

[23] Due to data constraints discussed more extensively in section SI-D.3., we cannot strictly re-estimate our baseline model specified in column 1-Table 3 using a panel regression model. Where plausible, we replace variables with relevant proxies accounting for the same effects and show that our results remain largely consistent. We further re-estimate, as closely as possible, the models specified in columns 3, 5, 6, and 7 of Table D2, for which there is reasonable temporal variation in the independent variables, and results further support the robustness or our methodological approach.

capabilities and competences. Areas of early adoption are mainly rural, use solid fuel as previous central heating technology, have low shares of flats, and have more distributed renewable energy projects and community energy projects.

5.4. RQ4: what explains the spatial diffusion of heat pump installations over time?

To better understand the underlying nature of the observed spatial correlation, we use SAR (equation (4)), that accounts for endogenous spillover effects from the diffusion of heat pumps to contiguous areas. We re-estimate the model specification shown in column 1-Table 3, using the same dependent variable. We observe in column 2-Table 3 that the coefficients for limited access to piped gas, distributed renewable energy projects, and community energy projects remain statistically significant, and their coefficients retain largely comparable values between the two models, proving consistency of our results.

Focusing on the endogenous spillover effect, we find that heat pump deployment has a strong positive indirect effect on contiguous local authority areas. In terms of magnitude over the full 2010–2020 period, for every three heat pumps installed in a local authority area, it is likely that one heat pump would be installed in a neighbouring one.

We offer two distinct but related interpretations. The first is a peer or neighbourhood effect as a mechanism of social influence through which households can observe heat pump installation activity nearby and this strengthens perceived social acceptance and reduces perceived adoption risks (Wolske et al., 2020). As noted in the introduction, neighbourhood effects have been demonstrated for various low-carbon technologies, including rooftop solar PV (Graziano and Gillingham, 2015; Schaffer and Brun, 2015), electric vehicles (Pettifor et al., 2017), and smart home technologies (Vrain and Wilson, 2021). Social interaction is particularly relevant for adoption of heat pumps. Similar to solar panels (Bollinger et al., 2022), visibility of heat pumps installed in neighbouring households, accompanied by physical interaction, can lead to spatial spillover effects within close proximity (Min, 2025). Public awareness campaigns can further boost adoption dynamics as shown for ground source heat pumps (Karytsas, 2018; Karytsas and Theodoropoulou, 2014).

Our second interpretation of observed spatial spillover is related to supply chain materialisation, i.e., the accumulation and availability of heat pump installers whose service territories cover adjoining local authority areas. Comparable local dynamics have been reported for other types of renewable energy technologies (Corsatea, 2016; D'Agostino and Moreno, 2019). These two interpretations distinguish spatial spillovers in the demand and supply of heat pumps, respectively.

To test the validity of our interpretation, we estimate the regression model specified in equation (5). We capture the direct effect in column 3-Table 3, while the spatially lagged coefficients in column 4-Table 3 capture the exogenous interaction effects of three variables to neighbouring local authority areas: age of housing stock, distributed renewable energy projects, and community energy projects. We use the age of housing stock to identify supply-side spillovers effects, as a higher share of new building stock could indicate local supply chain materialisation. Community energy projects are bottom-up, citizen-led initiatives, and thus we use this variable to identify demand-side spillover effects that can explain peer effects. Finally, low carbon technologies, such as rooftop solar PVs, are commonly used in the literature to control for peer effects (Graziano and Gillingham, 2015; Schaffer and Brun, 2015), but may also signal the availability of skilled, specialised service providers for emerging technologies. Therefore, distributed renewable projects could indicate both supply- and demand-side spillover effects.

Column 3-Table 3 shows direct effects consistent with those in column 1 and 2 for the SEM and SAR models, with the exception that the coefficient for new building stock becomes statistically significant and doubles in terms of magnitude. Focusing on the indirect effect in column 4-Table 3, the interaction coefficient for new building stock is positive and larger in absolute value than the negative coefficient for the independent variable in column 3. This suggests that proximity to local authorities with higher share of new building stock increases the probability of heat pump installation.[24] We interpret this as evidence that local supply chains materialised around new construction activity could enable heat pump installers to extend their service territories and serve customers in neighbouring local authority areas. Our interpretation that spillover effects are primarily driven by installers availability is reinforced by sensitivity analysis substituting age of housing stock with employment in relevant to heat pumps 5-digit SIC sectors, which also yields similar and statistically significant results (SI D.2.,Table D5). Absence of significance for the interaction coefficient for community energy projects does not indicate *per se* absence of demand dynamics, but rather that peer effects cannot explain spatial heat pump diffusion at the early stages of deployment. This is reasonable as demand spillovers cannot effectively materialise when there is lack of sufficient local supply chains. This by extension can explain the increase in total installed costs (£/kW), given that reduced supply cannot meet existing demand, increasing on-site installation costs, as discussed earlier.

As an external validity test, we re-estimate the model specified in equation (5) using the same dependent variable but as reported in the BEIS dataset (see discussion in section 3.1). Results reported in Table D6 (SI-D.2.) are virtually identical to those for the Ofgem data, while the spillover effect is significant and almost twice as large in terms of magnitude compared to that in column 4-Table 3. To further test for the geographical extent of spillover effects, we use an inverse distance weighting matrix (the smaller the geographical distance, the larger the weight given) instead of a binary weighting matrix (with elements equal to 1 if two local authority areas share common borders, otherwise zero). This relaxes the restrictions in the model, as it allows us to capture the spillover effect not only in contiguous local authorities but also in proximal ones. Results in Table D7 (SI-D.2.) capturing the direct effect remain consistent, while we find no statistically significant indirect effects, indicating that spatial spillover effects weaken when distance increases.

6. Conclusions and policy implications

6.1. Conclusions

We empirically examine the local factors driving uptake of residential air source heat pumps employing a unique, highly disaggregated, spatial dataset for heat pump diffusion across GB at the local authority level, and longitudinally from 2010 to 2020. We use linear econometric methods to analyse the historical relationship between tenure and property characteristics, and cost and size dynamics in the diffusion of heat pumps. We find average total installed cost from 2010 to 2020 of 1075 £/kW and a learning rate of −3.3 %. Heat pumps are predominantly installed in owner occupied houses, which have managed to keep cost increases at comparatively lower levels than in other housing types.

We use spatial econometric methods that account for spatial autocorrelation and examine the drivers of the observed spatial spillovers. We find robust evidence that early adopting areas are more likely to be rural, off the gas grid, use solid fuel (or oil) for previous heating technology, and have more renewable energy and community energy projects. These local conditions associated with heat pump deployment to-date in GB are a combination of: enabling property and household characteristics (e.g. accessible outdoor space, available investment capital); low-carbon energy-related interest, capacity, and skills among households and communities; and local suppliers and installer availability and experience. In this heterogeneous spatial landscape for heat pump installations, early adopting areas benefitting from this

[24] Adding up the direct and interaction coefficients for the share of new building stock, the combined effect is positive indicating positive spillover effect on neighbouring local authority areas.

combination of conditions have served as test beds for deployment, in turn indirectly stimulating deployment of heat pumps in contiguous areas with less immediately advantageous local conditions (see Fig. 1 and timelapse animation Online Resource 1). This follows the classical spatial diffusion dynamic, characterised by an outwards spread from the early adopting cores to the later adopting rim and peripheries (Grübler, 1996). Empirical evidence suggests that spatial spillover effects are driven predominantly by the availability of local supply chains as manifested by higher construction activity in neighbouring local authorities, while limited availability of supply dynamics could explain increasing total installed costs.

6.2. Policy implications

Achieving net-zero targets for residential heating means overcoming three key challenges outlined below that currently constrain heat pump deployment. Current policy frameworks and incentives for overcoming these challenges and sustaining progress towards net-zero are insufficient (Rosenow et al., 2023), and thus insights from our analysis can help inform policies and strategies for accelerating future heat pump deployment.

First, stimulating heat pump adoption in pioneering regions can help drive beneficial spillover adoption in neighbouring regions. However, this requires trade offs between maximising effectiveness and widening equality of access.

Policy effectiveness means directing incentives at early adopting areas with enabling conditions to stimulate self-reinforcing learning and scaling dynamics. Equality of access means targeting incentives at areas with weaker enabling conditions and lower historical deployment rates (Morton et al., 2018). Stimulating heat pump deployment in areas with demonstrable potentials can more rapidly materialise supply chains, accumulate experience, and drive down costs. Spatial spillover effects can then diffuse these benefits to other areas and household types. However, in the short-term, such a strategy may be perceived as inequitable if financial incentives are disproportionately captured by wealthier households and areas.

A wider and more sustained heat pump rollout will require targeted government support and specific incentives to ‘cross the chasm’ from core to periphery (e.g., rural and peri-urban areas to urban centres). As Barnes et al. (2024) argue, this should be part of a “coherent, long-term policy framework” centred around increasing affordability, improving installer capacity, and more compelling propositions for households. Upskilling the existing workforce of thermal system installers is key to this effort. Early governmental responses to this challenge include roadmaps for sector transformation in the UK (House of Commons, 2024) and the US.[25] Recommendations involve utilising existing industry bodies as conduits for retraining the current workforce. For example, the UK Gas Safe Register, which certifies installers of gas-based thermal systems, could be leveraged to organise training workshops for heat pump installation. The transition to low-carbon domestic heating should also be aligned with broader policies aimed at mitigating regional inequalities, such as the EU’s cohesion policies. Calvillo et al. (2025) argue that the spatial diffusion of high-skilled technical jobs on heat pump installation in domestic settings can help mitigate observed regional economic disparities.

Second, installation costs need to come down to parity with gas boilers, so heat pumps are affordable and competitive at the point of purchase. This requires policy action across regions to tackle skills shortages and supply chain fragmentation that drive up installation costs.

As new technologies mature, ‘learning-by-doing’ initiates a virtuous cycle of experience stimulating cost and performance improvement which further stimulates uptake (Wilson et al., 2020). In spatial terms, global technological learning interacts synergistically with the social learning implicit within the spatial spillover dynamic. The build up of supply chains, in conjunction with increasing installer experience, can reduce installation cost and thus stimulate adoption across all regions (Edelenbosch et al., 2018). However, unlike other small-scale, distributed low-carbon technologies like solar photovoltaics or electric vehicle batteries, we find hardly any evidence of sustained cost reduction in the £/kW of heat pump installations. Why?

In the UK (Renaldi et al., 2021) similarly find a small negative learning rate on heat pump installation costs, but a small positive learning rate on heat pump equipment costs. This suggests upward pressure on costs is coming from ‘balance-of-system’ installations. The UK housing stock is older, less efficient, and more heterogeneous than in other European countries implying less standardisation in heat pump installations. The heat pump supply chain is also relatively fragmented and geographically dispersed across localised markets (Hanna et al., 2018). Energy retrofitters and renewable installers have long faced a stop-start policy environment in the UK which has undermined maturation and consolidation (Barnes and Bhagavathy, 2020). Together, these effects reduce availability of the repetitive learning-by-doing opportunities for installers that typically explain cost reductions as a function of experience with household-scale technologies in other markets (Nemet et al., 2020). Escalating on-site installation costs may be further exacerbated by skills shortages. Jakob et al. (2019) attribute slower than expected cost declines for heat pumps in Europe more widely to increased system integration (metering, sensors, controls), innovations to reduce noise, and quality improvements in planning and installation, including remote and self-auditing controls.

The UK’s Heat and Building Strategy targets cost reductions through more competition, scale economies (larger installers), and new financing models (BEIS, 2021a). Effectively stimulating cost reduction through virtuous learning cycles in which incentives and policies induce innovation (Grubb et al., 2021) also means addressing observed mismatches in the labour market. Advanced economies are actively trying to tackle skill shortages through policy initiatives such as the ‘EU strategy to boost industrial competitiveness, trade and quality jobs’ introduced by the European Commission in 2023. In the UK, the skills dimension to the Industrial Strategy (DfT, 2024) is set to extend commitments in the 2021 Net Zero Strategy to support low-carbon job creation including through reform of the skills system (BEIS, 2021b). However, greater effort is needed in this area.

Limited political feasibility of proposed policy actions is often interlinked with the discussed economic constraints. The increasing fiscal limitations in governmental budgets restricts the availability of point-of-purchase incentives. In countries such as the UK, dependence on imported heat pumps exposes deployment to exchange rate volatility and global supply chain disruptions, raising both costs and uncertainty. Public resistance to phasing out gas boilers further complicates implementation, as seen in the backlash against Germany’s proposed boiler bans in 2023, the so called ‘heat-hammer’. Additionally, distortions in energy market design undermine heat pump economics. For example, UK electricity prices are set by the marginal cost of gas-fired power generation, resulting in electricity prices that are often three times higher than gas, thereby discouraging consumer adoption (Barnes and Bhagavathy, 2020; Renaldi et al., 2021).

Third, stimulating adoption in hard-to-reach properties, like urban flats or apartments that lack outdoor space, is a challenge common to both pioneering and later adopting regions. This requires strategic complementary policy action across regions to support heat networks as alternative sources of heat decarbonisation.

The UN projects that 68 % of the world population will live in urban areas by 2050, up from 55 % in 2018 (United Nations, 2019). The strong emphasis in our results on properties with enabling characteristics for heat pump installations – owner-occupied houses particularly in rural areas off the gas grid – reflects the complexities of siting heat pumps in more space-constrained urban settings or in rental properties with split

[25] The US Department of Energy launched in May 2024 the Energy Skilled Recognition programme that aims in training workers for in-demand job opportunities that align with national clean energy transition goals.

incentives between landlords and tenants. Higher installation costs and limited numbers of installations in urban areas, in flats, and in the rental sector highlights one of the key challenges for stimulating wider heat pump uptake: deploying heat pumps in harder to reach segments of the housing stock in cities. As countries globally become more urbanised, this challenge will grow increasingly relevant. Shifting the policy focus from the lower unit-cost option (air source heat pumps per household) to larger installations connected to heat networks servicing multiple properties reduces risk that heat decarbonisation progress stalls once the high-potential areas with household and property characteristics enabling heat pump adoption are saturated (Lake et al., 2017). Trials of large scale district heating networks have been launched in various cities worldwide in recent years,[26] including through use of ground source heat pumps, heat pump arrays, or large sources of waste heat such as underground transport networks or sewer networks.[27] Social influence can further strengthen awareness and encourage the adoption of residential heat pump systems in urban areas (Karytsas, 2018).

6.3. Limitations

A limitation of our study is that although we find robust statistical evidence of spatial spillovers effects, we can only infer the importance of behavioural drivers, local supply chain capacities, and skills using the available quantitative data. There are non-quantifiable elements that are beyond the scope of our study (e.g., perceived technology risks, heating behaviours) that could help explain heat pump deployment. We could not directly assess the effect of administrative capacity on heat pump diffusion, and thus future research could explore this potential diffusion channel in greater depth. Future quantitative studies should focus more on spatially disaggregated microeconomic data on local entrepreneurship and firm activity specific to heat pump markets. Qualitative studies should focus on understanding the effect of social interaction and behavioural factors. From a technological perspective, it would be interesting to test whether there is mismatch between the capacity of installed heat pumps and specific property characteristics (e.g., space area, number of rooms, etc.), as this could be responsible, among other factor, for driving costs upwards. Finally, from a policy perspective, it would be helpful to pinpoint the costs of retrofitting older, energy-inefficient properties, while controlling for individual property and geographical characteristics. Improving energy efficiency was a requirement for installing heat pumps under the RHI scheme, so it is important to understand if and how energy retrofitting drives costs upwards.

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CRediT authorship contribution statement

Theodoros Arvanitopoulos: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Charlie Wilson:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Craig Morton:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

We have nothing to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2025.114787.

Data availability

Data and syntax used in this article can be accessed online in the OSF repository at https://osf.io/tpg2n/?view_only = df8b540f54974a6a820aa140a61a9c67.

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[26] Examples include Stockholm's district heating network that provides heating to 800,000 homes, while trials for new large-scale district heating systems are underway in Lund (Sweden) and Lemgo (Germany).

[27] An example is the Bunhill Heat and Power Network (BHPN) project in Central London, that will use waste from the London Underground network to heat homes and public-use building.

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