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Universal Digital Twin – the impact of heat pumps on social inequality

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ABSTRACT

This paper investigates how using heat pumps for domestic heating would impact fuel poverty and social inequality. The analysis integrates a geospatial description of climate observations, gas and electricity infrastructure, energy consumption and fuel poverty from the base world of a Universal Digital Twin based on the World Avatar knowledge graph. Historic temperature data were used to estimate the temporal and geospatial variation of the performance of air source heat pumps in the UK. The corresponding change in gas and electricity consumption that could be achieved using heat pumps instead of gas for domestic heating was estimated. The geospatial impact of the heat pumps was assessed in terms of CO_2 savings, and their effect on fuel cost and fuel poverty. Whilst heat pumps would reduce emissions, it is predicted that they would increase fuel costs. It was shown that both local and regional areas of high fuel poverty would experience some of the largest increases in fuel cost. This illustrates the potential for the transition to sustainable heating to exacerbate social inequality. The analysis suggests that existing regional inequalities will increase, and that it comes down to a political choice between investments to support the most effective use of heat pumps, and delayed investments to counter social inequality. The ability of the World Avatar to integrate the models and data necessary to perform this type of holistic analysis provides a means to generate actionable information, for example, to enable local policy interventions to address the tension between social and environmental goals.

1. Introduction

Energy accounts for over 70% of global greenhouse gas emissions, with energy use in buildings contributing more than the entire transport sector [1]. The decarbonisation of energy is projected to require significant changes, ranging from large-scale electrical distribution [2,3] to the exploitation of distributed resources such as wind and solar [4] as well as the development of intelligent infrastructure [5,6] and modelling approaches [7,8]. The ramifications of these changes are interdisciplinary and require the holistic consideration of socio-economic, environmental, engineering [9,10] and political [11] factors over a range of geographic [12] and seasonal time scales [13].

The majority of emissions from the energy sector in the UK result from the combustion of fossil fuels either in power stations to generate electricity or in gas boilers to heat homes [14]. The gas used for heating is delivered via the national transmission system. The inherent flexibility of the transmission system, both in terms of pressurising it to smooth out daily fluctuations in demand, and in terms of decompressing liquefied natural gas and importing gas to smooth out seasonal changes, enables a consistent supply of cheap energy (compared to electricity) throughout the UK [15]. The potential loss of these advantages is an important consideration in the assessment of future energy scenarios.

Heat pumps are one option to reduce emissions from heating because they enable electrical energy to be converted to heat in an approximately 1:3 ratio [16]. The decarbonisation of heating may well involve the mass adoption of heat pumps that use renewable electricity working alongside boilers that use hydrogen instead of natural gas to meet peak demand [17]. Tassou et al. [18] examined the performance of heat pumps at three locations in the UK in 1986. They observed that local climatic conditions effected operating costs and concluded that performance would need to increase by about 50% for heat pumps to become a viable alternative to gas boilers. Not only has this increase in performance occurred during the intervening years, but there is now an urgent need to address the sustainability of heating. To fully assess the implications of such a transition, policy makers must consider not only environmental, but also economic and social implications of different

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Nomenclature

ΔC	Change in domestic fuel cost
ϕ_{FP}	Proportion of fuel poverty
η	Heat pump efficiency
Q	Heat raised
E	Electricity consumption
G	Gas consumption
C	Domestic fuel cost
P_1	1st percentile
P_{99}	99th percentile
C_{G}	Cost of gas
C_{E}	Cost of electricity
$\mathrm{CO}_{2,\mathrm{G}}$	Gas emissions
$\mathrm{CO}_{2,\mathrm{E}}$	Electricity emissions
ΔC_{G}	Change in cost of gas
ΔC_{E}	Change in cost of gas
$\Delta\mathrm{CO}_{2,\mathrm{G}}$	Change in gas emissions
$\Delta\mathrm{CO}_{2,\mathrm{E}}$	Change in electricity emissions
η_{boiler}	Boiler efficiency
ϕ_{heating}	Proportion of gas used for heating
T_H	Hot-side temperature
T_C	Cold-side temperature
COP	Coefficient of performance
LSOA	Lower super output areas
SCOP	Seasonal coefficient of performance
SEDBUK	Seasonal efficiency of a domestic boiler in the UK
SPARQL	SPARQL Protocol and RDF Query Language
UK	United Kingdom
ONS	Office for National Statistics
IE	Inequality index

scenarios [19], for example the impact on continuity of energy supply as well as the impact on affordability and social inequality. The ability to perform a holistic assessment requires the consideration of many different types of data, including both temporal and geospatial variations in climate and energy demand, and social factors such as the geospatial variation in the affordability of energy. The issue of how to integrate the data and ensure openness and transparency in such assessments remains a widespread problem [20].

The World Avatar project [21,22] offers a solution that enables the transparent integration of different types of models and data, improving interoperability between heterogeneous data formats and software [8]. The World Avatar uses a dynamic knowledge graph to model the physical world. Representations of real world infrastructure are stored and related items linked, and integrated with computational agents that describe the behaviour of real world systems, providing a natural design for a Universal Digital Twin [23]. The knowledge graph provides a uniform method both to query and host distributed data (*i.e*, data held on different computer systems and published by different entities). The data are semantically encoded using vocabularies defined by ontologies so that it is possible to understand the context of the data (*i.e*, ask what it is) and are stored as Linked Data [24,25] so that it is possible to find related data by traversing the graph. The computational agents are also able to be described in the knowledge graph, so that it is possible to search for agents and understand their functionality. These features support the realisation of interoperability, where the ability to discover and understand the contents of the knowledge graph supports the reuse of data and agents. The approach is readily extensible and can integrate data from different domains because ontologies can be used to describe any system, and have previously been created to represent the built environment [26], aspects of chemistry [27,28] and more [29,30]. The World Avatar contains the notion of a base world, which is updated in real-time by computational agents. Parallel worlds can be hypothesised from the base world, enabling cross-domain scenario analysis [21]. Current coverage of the Universal Digital Twin of the UK within the World Avatar includes a geospatial description of the gas transmission system [31], gas consumption statistics and climate information, electrical power systems [32] and land use [33].

The **purpose of this paper** is to investigate how the use of heat pumps for domestic heating would affect fuel poverty and social inequality, and analyse the regional differences in impact across the UK. The paper estimates the coefficient of performance of air source heat pumps, the corresponding CO_2 savings and the effect on fuel cost and fuel poverty. Understanding the geographical diversity of the impact of heat pumps enables the possibility of forecasting future areas of fuel poverty. Thus, the significance of the analysis extends beyond simply assessing technical aspects of heat pumps – it provides sensitive information to support the 'leveling-up' agenda of the current UK government to reduce social inequality. The data used by the analysis are queried from a dynamic knowledge graph, demonstrating the ability of the proposed design for a Universal Digital Twin to integrate the disparate social, technical and geospatial data necessary to support this type of holistic analysis.

The paper is structured as follows. Section 2 discusses inequalities and current policy with respect to the decarbonisation of heat in the UK, and explains the principles of air source heat pumps. Contextual information about the World Avatar and Universal Digital Twin used in this work is provided. Section 3 extends the coverage of the Universal Digital Twin to include statistics about fuel poverty, and explains the method used to disaggregate annual gas and electricity consumption data and to calculate the change in energy consumption due to the use of heat pumps. Section 4 uses data queried from the Universal Digital Twin to estimate the social and environmental impact of using air source heat pumps instead of gas for domestic heat provision in the UK, and highlights regions that may benefit from localised policy interventions to address the tension between social and environmental goals. Finally, Section 5 draws conclusions and discusses future work.

2. Background

2.1. Regional inequalities in the UK

The UK has significant socio-economic inequalities. These can be measured in various ways. Typical economic indicators are gross domestic product per worker and income per household. Other measures include societal indicators such as levels of skills and health indicators such as life expectancy. The inequality can be largely explained by a North-South divide. This was recently confirmed by the Centre for Cities [34] which established that The North lags behind The South across a range of indicators. In general, productivity, measured as annual income divided by hours worked, suggests that northern regions have, on average, jobs that generate less income. The North-South divide has been further exacerbated by the pandemic [34]. Inequality is often also measured in terms of individual prosperity and visible quality of life. This may encompass the existence of deprived neighbourhoods as well as quality of schools and the built environment. As noted in the Annual Fuel Poverty Statistics Report [35], different types of dwellings and household characteristics have significant impact on the risk of experiencing fuel poverty. The report indicates that rural areas in Norfolk and Wales, as well as northern areas have higher risk of fuel poverty than southern areas. This confirms Dorling and Tomlinson's [36] analysis of territorial differences in the affluence of British society. Understanding potential systematic changes that may provide new sources of societal inequality is essential, not least to counter fuel poverty and live up to the ambitions of the 'levelling-up' agenda of the UK government [37].

2.2. Current policy with respect to decarbonisation of heat

The current recommendation for the decarbonisation of heating is for a hybrid solution, with heat pumps and hydrogen both contributing towards the replacement of natural gas [17]. The production and combustion of hydrogen is less efficient than electrification. However, hydrogen can be used to store energy and is expected to play a key role in maintaining the resilience of the energy system [15]. Heat pumps are expected to be able to provide heat the majority of the time, with hydrogen boilers providing heat at peak loads [17]. The Committee for Climate Change estimates that 19 million heat pumps will need to be installed to reach net zero by 2050 [38]. In the run up to the COP26 climate conference [39], the UK government announced grants to support the installation of heat pumps [40], while during the conference, the Mayor of London indicated that new developments in London would struggle to gain approval without sustainable heating [41]. Near-term grants such as the Green Homes Grant scheme are expected to support the installation of fewer than 50,000 heat pumps per year, falling far short of meeting the target of 600,000 installations per year and ever further short of the Balanced Pathway proposed by the Committee for Climate Change [42]. While it is clear that there remains a policy gap to be filled, quantifying how the energy system will be effected by a transition on this scale is urgent and important. Speirs et al. [43] highlight this need, and the requirement to develop an understanding of

> *'... whole-system impacts into the decarbonisation of the gas network, including both spatial and temporal resolution... '*

The social impact of a transition to sustainable heating must also be included within such an investigation in order to address all three pillars of sustainability [44].

2.3. Key principles of heat pumps

Lord Kelvin, then William Thomson, first proposed a practical heat pump system in anticipation of the fact that

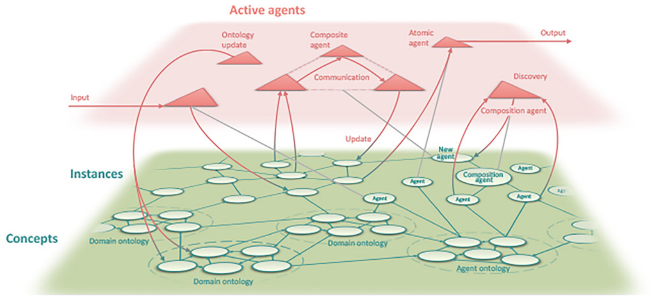
> *'... conventional energy reserves would not permit the continuing direct combustion of fuel in a furnace for heating.'* [45]

Heat pumps operate on the same principles as air conditioners and refrigerators, albeit with an obvious difference in their application. They compress a working fluid to increase its temperature and pressure. The hot fluid is passed through a heat exchanger to reject useful heat, for example to heat a building. The fluid is then expanded to reduce its temperature and pressure. The fluid is now colder than ambient and is passed through another heat exchanger that uses heat from the surroundings to warm it [46]. The energy extracted from the surroundings is typically 3–4 times larger than the electrical energy required by the heat pump. This ratio is known as the coefficient of performance (COP). The fact that the COP is greater than one, combined with the possibility that heat pumps can be powered using renewable electricity, underlie the interest in heat pumps for sustainable heating.

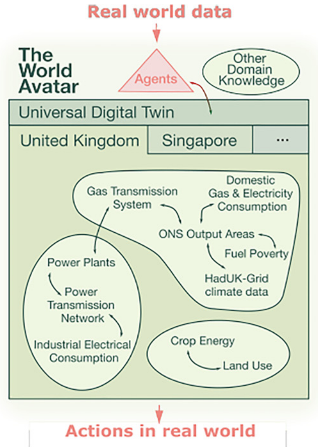
Modern heat pumps typically extract heat from either the ground or the air. Ground source heat pumps rely on the circulation of water through underground pipes to extract heat. The installation of these pipes presents a significant barrier to entry, particularly in urban areas where there are also concerns about whether heat could be removed from the ground faster than it can be replaced [47]. In contrast, air source heat pumps extract heat from the surrounding air. Whilst they have lower coefficients of performance than ground source heat pumps [46], the use of air presents a number of advantages. Air source heat pumps are smaller and cheaper, so present a lower barrier to entry. Additionally, there are no concerns regarding extracting heat faster than it can be replaced from air. In this work we therefore focus on the adoption of air source heat pumps.

2.4. The World Avatar

The World Avatar project aims to construct a holistic model of the world using a dynamic knowledge graph. The dynamic knowledge graph combines the ability to host semantic models (composed of concepts and instances) of domains of interest with computational agents that operate on the knowledge graph. The agents are semantically described in the knowledge graph and enable the automation of tasks including input of data, simulation and analysis, and output either in the form of data or by controlling actuators in the real world [23]. The semantic annotation of the knowledge graph enables the discovery and understanding of agents [48] and facilitates interoperability between models and data from different domains [49,50]. The idea is illustrated in Fig. 1.



(a) The design of the World Avatar dynamic knowledge graph [23]. Image reproduced under a CC BY 4.0 licence.



(b) Schematic showing the relationship between selected data from the base world of the World Avatar.

Fig. 1. Overview of the World Avatar.

In this paper we make use of information from a Universal Digital Twin of the UK in the World Avatar. Fig. 1(b) shows the relationships between the data sets in the digital twin. The data include descriptions of the power plants and industrial electrical consumption [32], crop energy and land use [33], the gas transmission system, domestic gas and electricity consumption, HadUK-Grid climate data [51,52] and the geospatial output areas [53] used to report data from the Office for National Statistics (ONS) [54]. The ontologies used to describe the gas transmission system, gas consumption, climate data and ONS output areas are described in detail in previous work [31]. The linking with the ONS output areas enables the straightforward integration of additional statistics about these areas with other data. Specific examples include domestic energy consumption and fuel poverty data, both of which were added as part of this work. Both required new ontologies. See the following section and appendix for details.

3. Methodology

3.1. Fuel poverty ontology development

An ontology was created to provide a vocabulary to represent fuel poverty statistics in the World Avatar. The ontology relates the existing

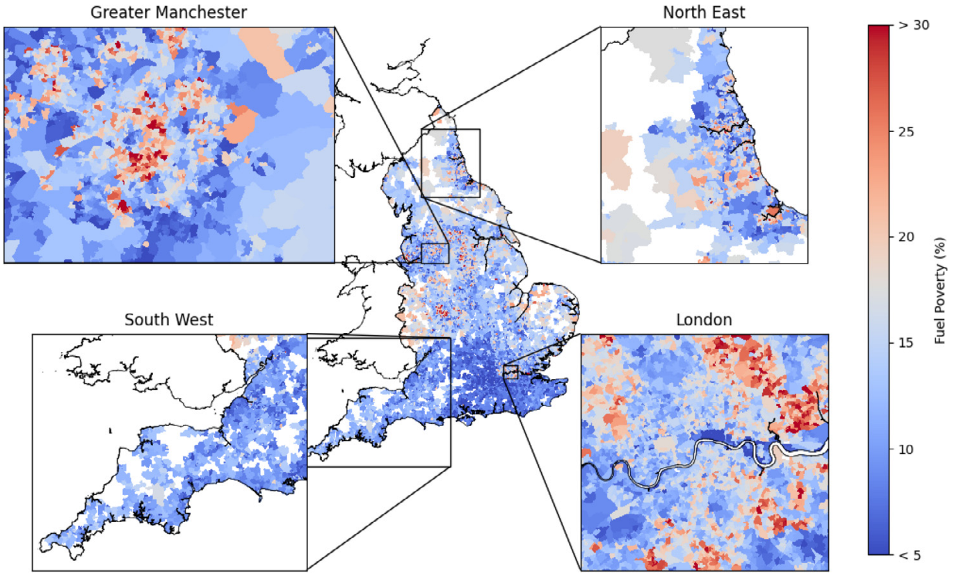


Fig. 2. Fuel poverty data queried from the base world of the World Avatar.

concept of `Statistical-Geography`, which represents ONS output areas throughout the UK, to new classes that represent data describing the number of households and number of fuel poor in an area. An input agent was created to populate the World Avatar with data from the UK Government describing fuel poverty in England [55]. (The data do not extend to other regions). The data provide an estimate of the number of households, an estimate of the number of fuel poor households and the corresponding proportion of fuel poor households in different geographic regions of the country. We adopt the same definition of fuel poverty as the UK Government, which defines fuel poor households as those that live in energy inefficient properties and that cannot afford the cost of the fuel required for their home [56].

Figure 2 shows data for the proportion of fuel poor households queried from the World Avatar. It can be seen that pockets of high fuel poverty exist in urban areas such as Greater Manchester and London, along with a general trend of increasing fuel poverty observed moving from south to north. Full details of the fuel poverty ontology and an example query can be found in Appendix A.

3.2. Disaggregation of gas and electricity consumption

Figure 3 shows the geospatial and temporal distribution of domestic gas and electricity consumption in Great Britain. The annual consumption data originate from the Department for Business, Energy & Industrial Strategy (United Kingdom) [57] and form part of the base world of the World Avatar [31].

In order to assess the performance of alternative technologies, in this case heat pumps, but also renewables such as solar and wind, it is important to account for seasonal variations in behaviour. It is therefore necessary to understand how energy consumption and climate vary throughout the year. Whilst the climate data in the World Avatar derived from the HadUK-Grid climate data set [52] are available on a monthly basis, the energy consumption data are only reported on an annual basis. The annual consumption was therefore disaggregated by proportioning it to match the month-by-month profile of national gas and electricity consumption [58]. The geospatial distribution of the monthly gas and electricity consumption is assumed to remain unchanged versus the annual data in Fig. 3(a). The disaggregated data are shown in Fig. 3(b), with the geospatial distribution represented in box and whisker form. The distribution is asymmetric and shows a number of regions with disproportionately high consumption. The significance of the energy demand for heating is implicit in the seasonal variation in Fig. 3(b).

3.3. Change in energy consumption due to heat pumps

The coefficient of performance of a heat pump used for heating is

$$\mathrm{COP}_{\mathrm{heating}} = \eta \frac{T_{\mathrm{H}}}{T_{\mathrm{H}} - T_{\mathrm{C}}}, \tag{1}$$

where η is the efficiency of the heat pump, and T_{H} and T_{C} are the absolute temperatures of the hot and cold side of the heat pump cycle. Air-source heat pumps typically have a COP in the range 2–4. The corresponding heat raised by the heat pump is

$$Q = \mathrm{COP}_{\mathrm{heating}}\, E, \tag{2}$$

where E is the electrical energy consumed by the heat pump.

In the case of gas heating, the heat raised is

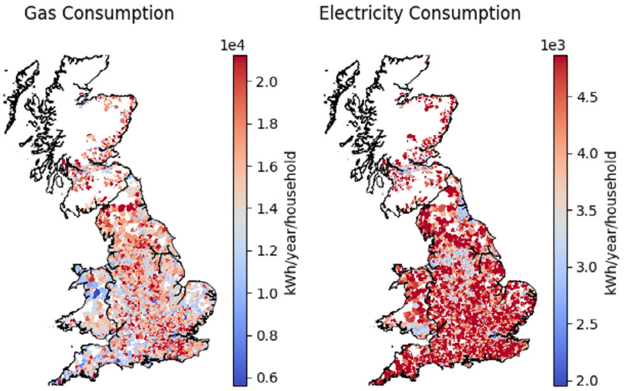
$$Q = \eta_{\mathrm{boiler}}\, \phi_{\mathrm{heating}}\, G, \tag{3}$$

where G is the gas consumption (expressed as an energy, so in kWh or equivalent), η_{boiler} is the efficiency of the boiler and ϕ_{heating} is the proportion of the G that is used for heating. If a heat pump is used to displace gas heating, then the change in electricity consumption ΔE can be estimated as a function of the change in gas consumption ΔG by eliminating Q from eqs. (2) and (3)

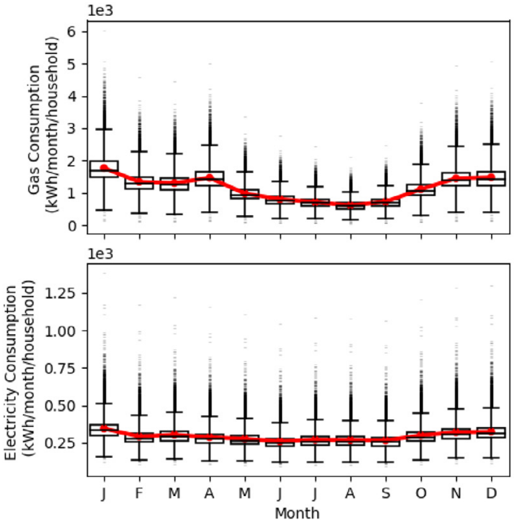
$$\Delta E = -\frac{\eta_{\mathrm{boiler}}\, \phi_{\mathrm{heating}}}{\mathrm{COP}_{\mathrm{heating}}} \Delta G. \tag{4}$$

The negative sign in eq. (4) is such that a reduction in gas consumption (*i.e*, a negative value of ΔG) due to the adoption of heat pumps results in an increase in electricity consumption (*i.e*, a positive value of ΔE).

It assumed that $\eta_{\mathrm{boiler}} = 0.8$ and $\phi_{\mathrm{heating}} = 0.9$. The value of η_{boiler} is estimated on the basis that modern boilers achieve around 80% efficiency in the field [59]. This is significantly less than indicated by the formal SEDBUK (Seasonal Efficiency of a Domestic Boiler in the UK) rating of modern boilers, which suggest efficiencies of up to approximately 90%. Older (pre 2005) boilers can have efficiencies as low at 60–70% [60], and clearly any such boilers that are still in use would reduce the average efficiency of the fleet. The value of ϕ_{heating} is estimated on the basis of typical household energy usage, where space heating, water heating and cooking account for 63.6%, 14.8% and 6.1% of total consumption respectively [61]. Assuming that these proportions are representative of gas usage in the UK, normalising these values suggests that of the order of 90% of gas is used for heating. Whilst gas produces higher grade heat (*i.e*, hotter water) than heat pumps, heat pumps are sufficient for space heating and some water heating (*i.e*, warming cold water before finishing with an immersion heater if needed). However, it is clear that there



(a) Annual gas and electricity consumption per household, where the number of households is taken as the number of consuming gas and electricity meters respectively. Data queried from the base world of the World Avatar.



(b) Disaggregated consumption. The distribution of consumption across output areas is shown in box and whisker form. Median consumption is shown in red.

Fig. 3. Domestic gas and electricity consumption.

exists uncertainty both in terms of exactly how much gas would be displaced by heat pumps and how much additional electricity would be required by immersion heaters. In order to address the uncertainty in η_{boiler} and ϕ_{heating}, the analyses presented in this paper were repeated for efficiencies in the range $0.7 \leq \eta_{\text{boiler}} \leq 0.9$ and $0.8 \leq \phi_{\text{heating}} \leq 1$. The results were found to be insensitive to the assumed values, except where explicitly stated. Full details of the sensitivity analysis are given in Appendix B.

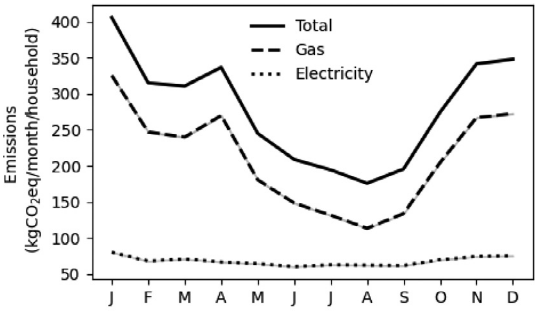
3.4. Change in emissions and fuel cost

The change in emissions ΔCO_2 and fuel cost ΔC arising from the displacement of gas heating by heat pumps is estimated as

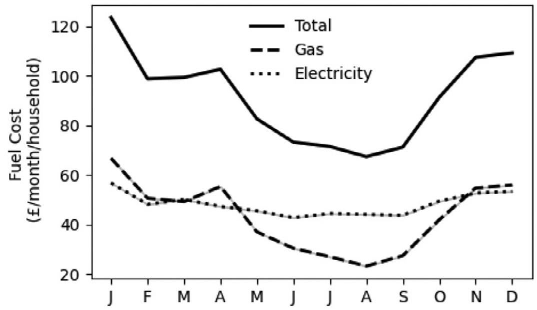
$$\Delta\text{CO}_2 = \Delta G \cdot \text{CO}_{2,\text{G}} + \Delta E \cdot \text{CO}_{2,\text{E}}, \tag{5}$$

$$\Delta C = \Delta G \cdot C_{\text{G}} + \Delta E \cdot C_{\text{E}}, \tag{6}$$

where ΔG and ΔE are the change in gas and electricity consumption, and $\text{CO}_{2,\text{G}}$ and $\text{CO}_{2,\text{E}}$, and C_{G} and C_{E} are carbon dioxide equivalent emission intensities and unit costs of gas and electricity respectively.



(a) Estimated carbon equivalent emissions.



(b) Estimated monthly fuel cost.

Fig. 4. Estimated fuel cost and carbon equivalent emissions due to domestic gas and electricity consumption in Great Britain (2019).

Although wholesale electricity prices may vary hourly, domestic energy tariffs in the UK typically charge a price per unit of energy that only varies on a time scale of months. In the analyses that follow, constant values of $\text{CO}_{2,\text{G}} = 0.184$ and $\text{CO}_{2,\text{E}} = 0.223$ kgCO$_2$eq/kWh, and $C_{\text{G}} = 0.038$ and $C_{\text{E}} = 0.165$ £/kWh are assumed based the average emissions intensity [62] and energy cost [63] in 2019. A few recent tariffs offer variable pricing that is tied to the instantaneous wholesale price, for example Agile Octopus [64]. These are marketed as offering cheaper energy than traditional tariffs because they avoid the cost of hedging against changes in wholesale prices. The approach in this paper would naturally extend to consider this sort of tariff if suitable data were available via the digital twin, for example instantaneous consumption data from smart meters and temperature data from weather sensors.

Whilst the capital cost of installing a heat pump is substantial, subsidies exist to assist with this expense [65]. Further, it is expected that capital costs will decrease, as demonstrated by solar and wind energy, where costs have fallen 40% and 82% respectively over the past 10 years [66]. We therefore restrict our current focus to the operating cost (*i.e*, fuel cost), which will be affected differently in different parts of the country by external factors such as the climate, both because of its affect on the demand for heating and on the performance of heat pumps [16,18].

Figure 4 shows the emissions and fuel cost per household estimated using eqs. 5 and 6 due to the median domestic energy consumption shown in Fig. 3, where the number of households is taken as the number of consuming gas and electricity meters respectively. It is clear that gas is responsible for the majority of emissions, but that electricity is responsible for approximately half of household fuel costs. The environmental case for moving away from gas heating looks compelling, but it is far from clear how the efficiency gains of heat pumps versus the change in electricity demand and higher cost of electricity will affect the social case. This question is considered in the next section.

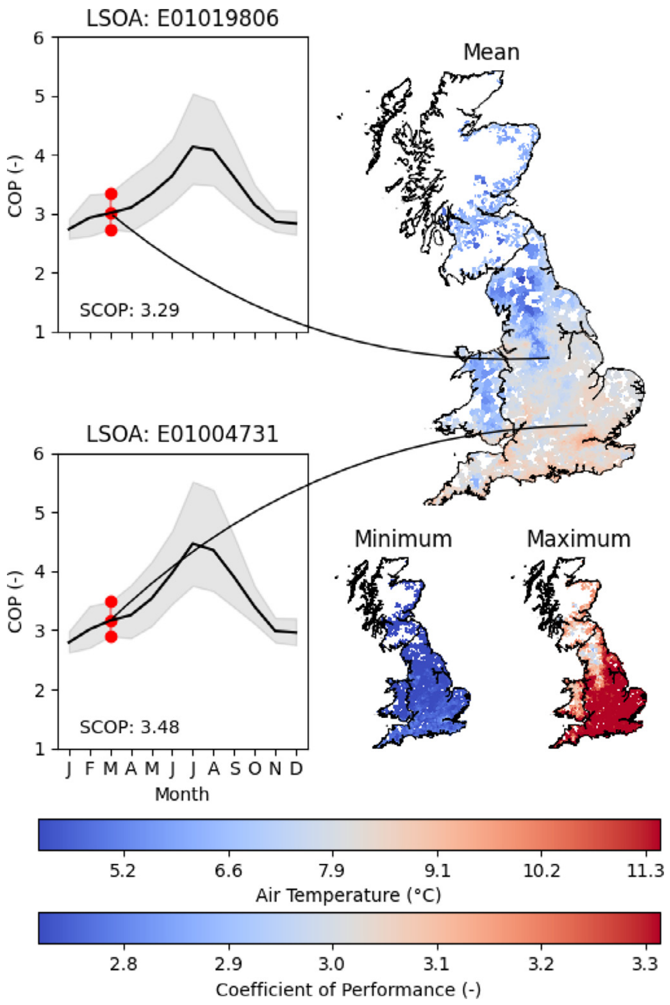
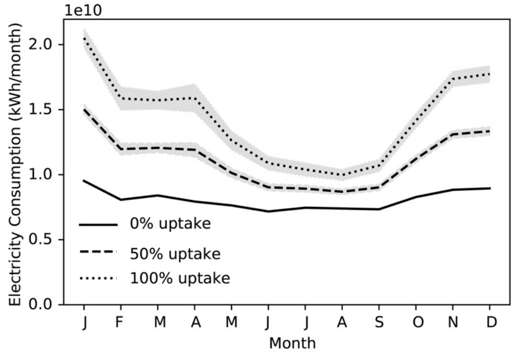
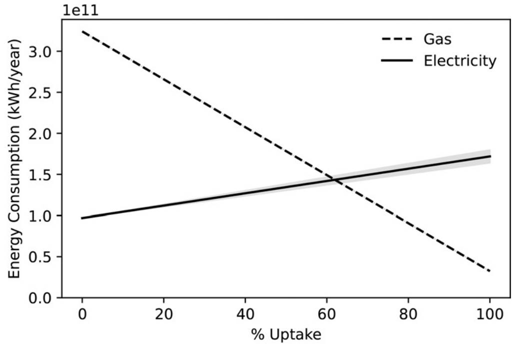


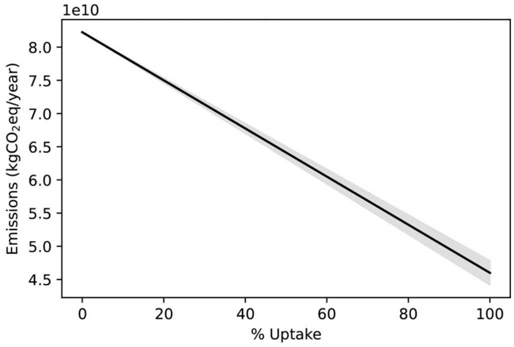
Fig. 5. Left: Coefficient of performance (COP) of air source heat pumps in LSOA output areas E0109806 (North East Derbyshire 001F) and E01004713 (Westminster 011A) in 2019. The solid line shows the COP for the mean air temperature. The shaded region shows the range of the COP corresponding to the minimum and maximum air temperatures. The points highlight the values for March 2019. Right: The mean, minimum and maximum COP and corresponding air temperature throughout Great Britain in March 2019.



(a) Monthly electricity consumption.



(b) Annual gas and electricity consumption.



(c) Total annual carbon equivalent emissions.

Fig. 6. Change in domestic gas and electricity consumption in Great Britain for different heat pump uptake scenarios. The lines show values calculated using mean air temperatures (2019). The shaded regions shows the range corresponding to the minimum and maximum air temperature (2019).

4. Use case – impact of heat pumps

4.1. Coefficient of performance

Figure 5 shows the estimated COP of heat pumps in Great Britain. The COP is calculated using eq. 1 with temperature data [52] queried for each ONS output area via the World Avatar. The calculation assumes a hot side temperature $T_H = 45°$ C as per standard industry practice [67] and an efficiency $\eta = 0.35$. The inset plots show how the COP at selected locations varies throughout the year. The map shows the full geospatial distribution of COP and air temperature in March 2019.

The estimated COP varies throughout the year as expected. The results are consistent with field trials of commercial heat pumps [46] and with manufacturers' data [68] that report COP ≈ 2.5 at 0 °C and Seasonal Coefficients of Performance, SCOP of 3–4. The direct relationship between the COP and air temperature is implicit in Fig. 5, where both are able to be plotted on the same map. It can be seen that geospatial differences in climate make a significant difference to the COP, where the data in Fig. 5 for the mean air temperature and corresponding COP show a strong gradient from north to south. The COP from September to April is probably most relevant to how a heat pump will perform in practice because people in Great Britain do not need much heating in the summer (although they do still need hot water). The shaded regions on the inset panels are wider than might be expected at first glance. However, it is important to remember that the corresponding temperature data are the monthly extrema, such that the shaded regions represent bounds on the instantaneous COP.

4.2. Change in national electricity and gas consumption

Figure 6 shows the impact of the uptake of heat pumps on national domestic gas and electricity consumption, where uptake is defined as the proportion of gas used for heating that is displaced by heat pumps.

Figure 6 (a) shows that the uptake of heat pumps leads to a significant increase in electricity consumption, with the largest increases

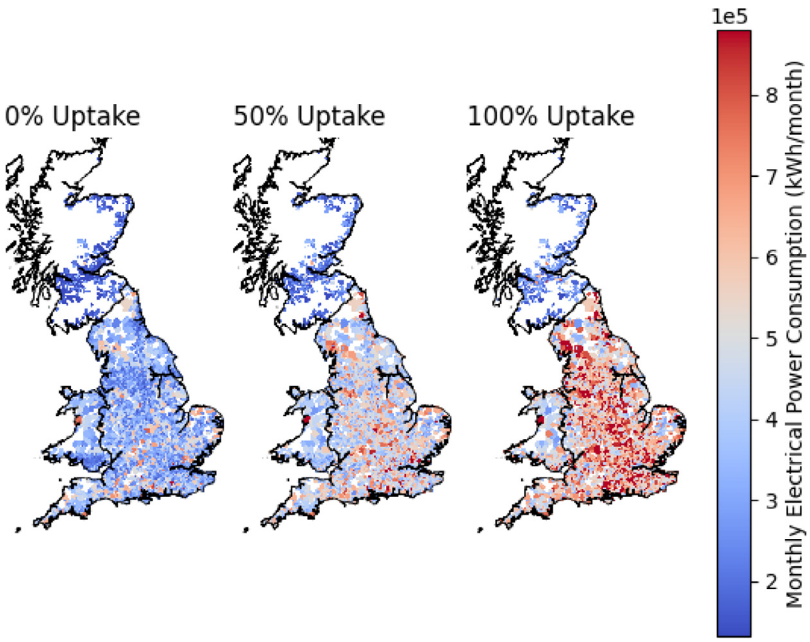


Fig. 7. Maximum monthly electrical power consumption for different heat pump uptake scenarios (2019).

falling between September and April when the demand for heating is highest. Fig. 6(b) shows the corresponding change in annual gas and electricity consumption. The gas consumption decreases linearly as a consequence of the definition of uptake. The annual electricity consumption is calculated by summing the monthly contributions from eq. (4), so accounts for the seasonal variation in COP. Fig. 6(c) shows the carbon equivalent emissions versus level of uptake. The uptake of heat pumps leads to a net decrease in emissions.

The shaded regions in Fig. 6 show that the uncertainty due to fluctuations in temperature is relatively small. The calculated electricity consumption and emissions also vary depending on the assumed values of the boiler efficiency (η_{boiler}) and the proportion of gas used for heating (ϕ_{heating}). Likewise, the residual gas use at 100% uptake follows as a consequence of the proportion of gas used for heating. However, the results in Fig. 6 were found to be insensitive to these parameters, varying less than ±10% across the parameter range considered (see Section 3.3), so comparable with but sometimes slightly larger than the shaded regions that show the effect of temperature. Full details of the sensitivity analysis are given in Appendix B.

Figure 7 shows the impact of the uptake of heat pumps on the geospatial distribution of the maximum monthly electrical power consumption. The maximum at each location occurs when the local heating demand combined with local minimum air temperature cause maximum consumption of electricity. It is clear that the uptake of heat pumps would cause different electrical demands in different regions, with the geospatial distribution of the demand broadly matching that of current gas consumption shown in Fig. . This is a first step towards understanding the impact that different heating scenarios might have on the geospatial distribution of peak power demand and will be important for the purpose of analysing future energy systems. Similar to Fig. 6, the data are relatively insensitive to the assumed values of the boiler efficiency (η_{boiler}) and proportion of gas used for heating (ϕ_{heating}).

However, it is important to note that the estimates in Fig. 7 are also limited by the time resolution of the consumption data published by the UK Government [57]. Fig. 7 assumes a constant power demand each month on the basis of the disaggregation described in Section 3.2. It is not possible to estimate the instantaneous maximum demand without making further assumptions about the disaggregation of the consumption data or without access to instantaneous consumption data, for example from smart meters. The possibility of making such data available via the digital twin is something that should be considered in the future.

4.3. *Effect on households and social inequality*

Figure 8 shows the impact of transitioning from gas to heat pumps for individual households. In this analysis, it is assumed that the number of households that could switch is equivalent to the number of consuming gas meters.

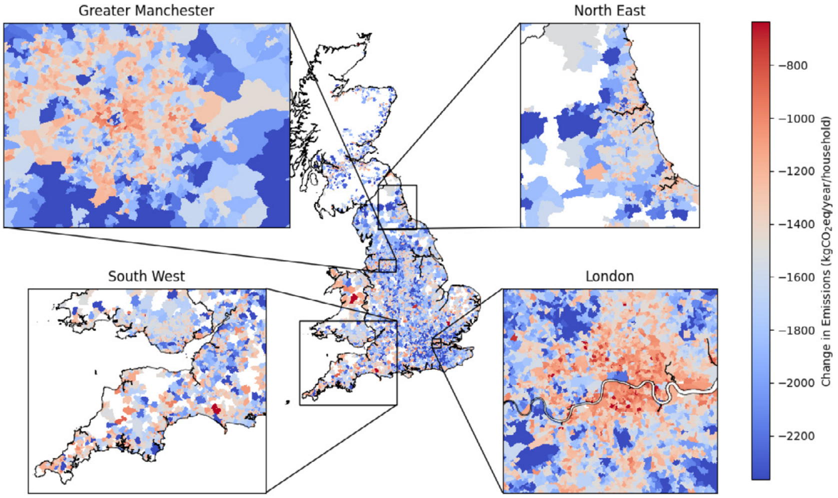
Figure 8 (a) shows that all households would reduce emissions, with savings being of the order 1000 $\text{kgCO}_2\text{eq/year/household}$. This is insensitive to the assumed values of the boiler efficiency (η_{boiler}) and proportion of gas used for heating (ϕ_{heating}), with the geospatial distribution showing no discernible change and the magnitude of the saving varying by approximately ±10% at the extremes of the parameter range considered (see Section 3.3).

Figure 8 (b) shows the change in energy cost per household. The magnitude of the change is sensitive to parameters assumed in eq. (3), with electrification becoming more expensive and regional effects more pronounced at higher values of the boiler efficiency (η_{boiler}) (because more heat is required to replace a given quantity of gas). At the extremes of the parameter range considered (see Section 3.3), the change in cost varied from an increase of approximately £200 per month in the north to a *saving* of approximately £30 per month in the south. Despite the sensitivity of the magnitude of the change, the geospatial distribution of the change is insensitive to the parameters, with the change in fuel cost increasing broadly from south to north. Full details of the sensitivity analysis are given in Appendix B.

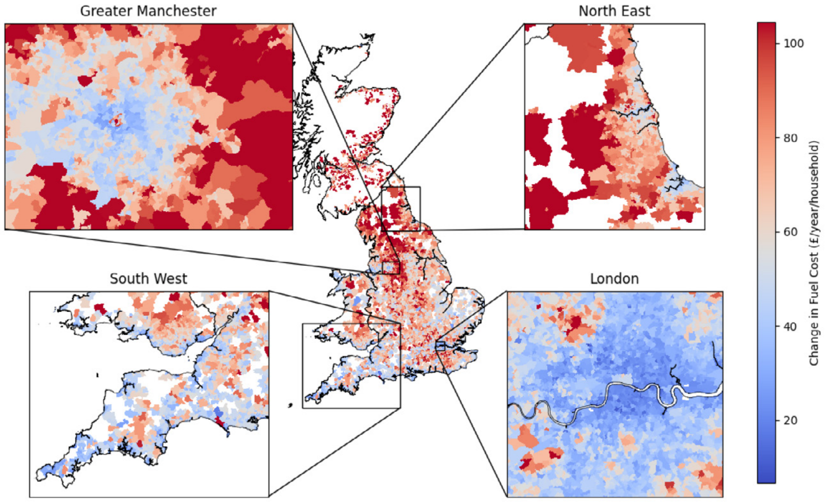
Figure 8 (b) shows that transitioning from gas to heat pumps would impose significant changes in fuel costs on households, both at a local and a national level. The magnitude of the (annual) change is significant compared to the (monthly) fuel costs shown in Fig. 4(b). Further, comparison with the fuel poverty data in Fig. 2 suggests that there may exist regions of high fuel poverty that experience large increases in fuel cost, exacerbating social inequality. This begs the question, can we identify such regions and how can we use this information to inform policy?

The social impact of the change in fuel cost is considered in terms of an inequality index

$$\text{IE} = \left(2\frac{\Delta C - \min_{\Delta C}}{\max_{\Delta C} - \min_{\Delta C}} - 1\right) \cdot \left(\frac{\phi_{\text{FP}} - \min_{\phi_{\text{FP}}}}{\max_{\phi_{\text{FP}}} - \min_{\phi_{\text{FP}}}}\right), \tag{7}$$



(a) Change in emissions.



(b) Change in fuel cost.

Fig. 8. Change in emissions and fuel cost of households adopting heat pumps (2019, mean air temperature).

where ΔC is the change in domestic fuel cost per household per year, and ϕ_{FP} is the proportion of fuel poverty. The purpose of the min and max terms is to normalise the index. In principle they could be true extrema. However, in the analysis that follows we choose the following parameterisation:

$$\min_{\Delta C} = P_1(\Delta C), \quad \max_{\Delta C} = P_{99}(\Delta C),$$
$$\min_{\phi_{\mathrm{FP}}} = 0, \quad \max_{\phi_{\mathrm{FP}}} = 0.2,$$

where $P_n(\cdot)$ denotes the n^{th} percentile of the distribution of the argument across all households. The reason for this choice is to exclude outliers, such that the inequality index for the majority of households is relatively evenly distributed in the interval $[-1, 1]$.

Figure 9 shows the inequality index defined in eq. (7) as a function of fuel poverty and change in fuel cost, overlaid by points showing the distribution of data for households in England. (The available data [55] do not extend to other regions). A negative value of the inequality index (blue) indicates a decrease in social inequality due to favourable changes in fuel cost in regions of high fuel poverty. A positive value of the inequality index (red) indicates an increase in social inequality due to unfavourable changes in fuel cost in regions of high fuel poverty. The distribution of data for households in England is insensitive to the assumed values of the parameters, except for the case of decreased boiler efficiency ($\eta_{\mathrm{boiler}} = 70\%$), where replacing inefficient boilers would of

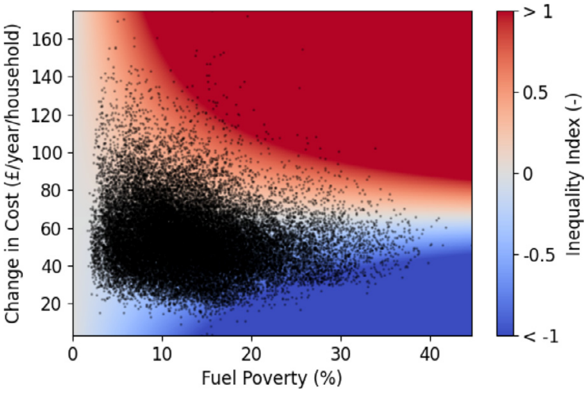


Fig. 9. Inequality metric as a function of fuel poverty and change in fuel cost for households adopting heat pumps (2019, mean air temperature), overlaid by points showing the distribution of data for households in England. A negative value of the inequality index (blue) indicates a *favourable* change in fuel cost in regions of high fuel poverty. A positive value of the inequality index (red) indicates an *unfavourable* changes in fuel cost in regions of high fuel poverty. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

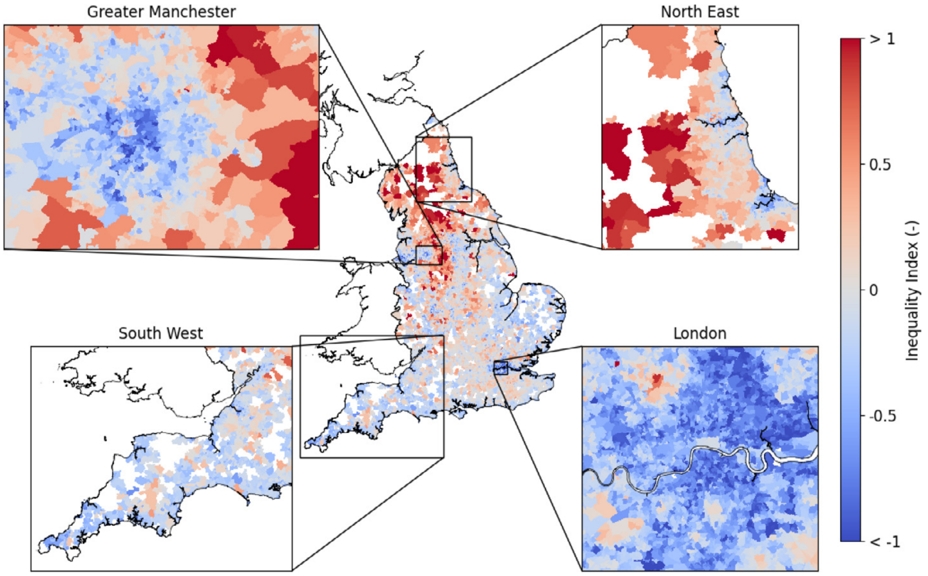


Fig. 10. Effect of households adopting heat pumps on inequality (2019, mean temperature). A negative value of the inequality index (blue) indicates a *favourable* change in fuel cost in regions of high fuel poverty, which we interpret as a decrease in social inequality. A positive value of the inequality index (red) indicates an *unfavourable* change in fuel cost in regions of high fuel poverty, which we interpret as a increase in social inequality. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

course result in more favourable changes in fuel cost. Full details of the sensitivity analysis are given in Appendix B.

Figure 10 shows the relative effect of transitioning to heat pumps on social inequality throughout England. The map shows a broad gradient of increasing social inequality running from south to north, reflecting the overall trend in the climate (see Fig. 5 for temperature data from March 2019). Over and above this trend, the data show discernible regions of increased local inequality, for example around Greater Manchester and in the North East. It is also notable that the interior of Manchester and London are less affected than the surrounding areas, conceivably due to the urban heat island effect [69,70]. However, this urban effect is not uniform and there still exist specific inner-city regions that warrant further scrutiny, although this would require more detailed local data. This geospatial picture is insensitive to the assumed values of the boiler efficiency (η_{boiler}) and proportion of gas used for heating (ϕ_{heating}), although the predicted effect is less extreme in the case of decreased boiler efficiency ($\eta_{\text{boiler}} = 70\%$). However, the average efficiency of boilers in the field is approximately 80% [59] so this is unlikely to be representative of the overall situation. Having identified regions of concern, the question is how to use this information to develop suitable territorial interventions and shine light on the subsequent political choices?

4.4. *Regional effects and policy dilemmas*

The analysis extends beyond simply assessing technical aspects of heat pumps to provide information to support the 'levelling-up' agenda of the UK government to reduce social inequality. The impacts of households adopting heat pumps differ due to the impact of local climate on the efficiency and running costs of heat pumps. Fig. 8 sheds light on these regional differences by highlighting the changes in emissions and fuel cost of households adopting heat pumps. Fig. 8(a) elucidates that households in urban regions see some of the lowest decrease in emissions, with parts of London or Manchester reducing emissions by 700–1200 kg CO2eq/year/household (displayed in red). At the same time, households in less dense areas have the potential for some of the largest reductions in emissions, with the outskirts of London showing a potential reduction of up to 2200 kg CO$_2$eq/year/household. This reduction in emissions closely aligns with the existing gas consumption patterns seen in Fig.. Importantly, while the potential for reducing emissions is higher in areas with lower urban density – thus supporting climate goals – the cost effect on households shows a different picture: Fig. illustrates that households in warmer urbanised areas experience the cheapest transition.

Aside from this urban-rural divide, the results show an increased north-south gradient in social inequality due to the difference in climate as one moves north in the UK. As a result, northern rural areas, which are often comparatively colder, experience a twofold disadvantage: 1) existing energy use is higher in colder climates, and 2) the efficiency of heat pumps is lower in colder climates. This effect is summarised by Fig. 10, which shows striking disparities in the relative effects of households adopting heat pumps on social inequality. Blue indicates decreased social inequality due to favourable changes in fuel costs in regions of high fuel poverty. Red indicates increased social inequality, exacerbating existing regional inequalities due to unfavourable changes in fuel cost. In summary, we identify two spatially trends: Heat pumps have the potential to exacerbate both north-south differences as well as a rural-urban divide due to comparatively higher fuel costs. Fig. 10 shows for example the centre of London and Manchester in blue, whereas large parts of northern England including the Lake District (Cumbria), North Yorkshire, West Yorkshire, County Durham and Northumberland appear in red.

This result is significant. The UK is experiencing a decade of political upheaval fuelled by regional inequalities. This led to the development of the 'levelling-up' agenda of the current government to address the long-standing problem of regional disparities [37]. The Brexit vote has been interpreted as the 'revenge of the places that do not matter' at the ballot box [71], indicating the socio-political importance of the 'levelling-up' agenda. The disparities in social, economic and cultural terms that have influenced how people voted have been discussed at length [72,73], including the regional implications of these votes [74], and the political sensitivity of 'left behind places' [71].

Interpreting the maps in Figs. 8 and 10 together illustrates the dilemma that politicians will face in the future, and the disparate regional impacts of these choices. On the one hand, we see an urgent need to protect the 'left behind places' from further poverty risks and to avoid adopting policies that favour regions with a higher average incomes. At the same time, many of the 'left behind places' are colder and so offer greater potential savings of emissions (per household), and yet heat pumps would be less efficient and therefore more expensive to run in these areas precisely because they are colder. Understanding the regional and geographical diversity of an increased use of heat pumps enables the forecasting of potential areas of future fuel poverty, and exemplifies the wider socio-economic implications of the fundamental changes that energy systems are undergoing under the guise of decarbonisation. The analysis provides sensitive information about areas at risk of an additional factor disadvantaging less affluent parts of society, laying bare the harsh choices for politicians. Local ‘place-based strategies’ that respect both geophysical as well as socio-economic conditions need to be considered, including communication strategies that allow less informed parts of society to gain information about the choices facing their households.

5. Conclusions

This paper has quantified the temporal and geospatial impact of the transition from the use of natural gas to air source heat pumps for domestic heating. The performance of heat pumps was quantified using historic climate data, and was used to estimate the change in household emissions and fuel cost that would be caused by switching from gas heating to heat pumps. By extending the analysis to consider the geospatial distribution of fuel poverty, it was possible to identify areas of high fuel poverty that would experience large increases in fuel costs, highlighting the tension between the environmental goals of the UK government and the aspirations of its ‘leveling-up’ agenda to reduce social inequality. The methodology would generalise to other types of heat pump, given suitable data to evaluate the coefficient of performance.

The coefficient of performance of air source heat pumps was observed to vary with location and time of year. The displacement of gas by heat pumps resulted in increased electrical demand with a more pronounced seasonal profile. It was shown that the use of heat pumps would reduce emissions throughout the UK, where the change was largely proportional to the reduction in gas use. The change in the fuel cost was shown to vary depending on the assumptions made about the efficiency of existing boilers and the proportion of current gas consumption used for heating. It was shown that heat pumps would most often cause an increase in fuel costs at current (2019) energy prices, and that the change would be significant compared to existing energy costs, with household fuel costs predicted to change between + £200 and - £30 per month, depending on the assumptions and location, with it being more favourable to replace inefficient boilers. However, the geospatial distribution of the change in cost was insensitive to the model assumptions. This is because electricity was significantly more expensive than gas (at 2019 prices), such that the increase in electricity use (which is more strongly coupled to the prevailing climate after the adoption of heat pumps) had a stronger impact than the reduction in gas use.

An inequality index was introduced to understand the effect of the changes in fuel cost on social inequality due to fuel poverty. The inequality index broadly showed an increase in social inequality moving northwards, reflecting the impact of the climate on the performance of heat pumps. The analysis enabled the identification of specific regions that would experience a disproportionate increase in social inequality, confirming existing inequality pictures of the UK. The analysis further elucidated the political dilemmas posed by the ambition to reduce social inequality and to reach net zero. Moving towards more sustainable energy use requires the consideration of the practical and socio-economic implications for UK citizens, and thus requires politicians to discuss accompanying policy interventions such as place-based strategies to counter fuel poverty.

The data used in this analysis were queried from a Universal Digital Twin of the UK based on the World Avatar dynamic knowledge graph. This paper extended the digital twin to include a new ontology to describe geospatial fuel poverty statistics and demonstrates the ability of a design based on a dynamic knowledge graph to integrate temporal, geospatial, technical, environmental and social data, to enable holistic analyses leading to actionable information to support policy making. It would be straightforward to extend the coverage of the digital twin to facilitate the same analysis for other countries. This is important because although the results would generalise at a superficial level (*i.e*, heat pumps become favourable when electricity is cheap and green), the detailed outcomes would clearly vary from depending on the characteristics of each region. The design of the digital twin is universal – it can and will be extended to include other types of data. This is predicted to become increasingly important to enable the open and transparent integration of data and models to support future decision-making and analysis of different energy scenarios.

Research data

Research data supporting this publication is available in the University of Cambridge data repository. See doi:10.17863/CAM.74476.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Thomas Savage: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jethro Akroyd:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sebastian Mosbach:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Michael Hillman:** Methodology, Software, Visualization. **Franziska Sielker:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Markus Kraft:** Conceptualization, Investigation, Supervision, Validation, Writing – review & editing.

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Appendix A. Ontologies

This paper uses data queried from the World Avatar knowledge graph covering fuel poverty statistics, domestic electricity and gas consumption, HadUK-grid climate data and the output areas used to report of Office for National Statistics (ONS). Full details of the ontologies and example queries for the domestic gas consumption, HadUK-grid climate data and ONS output areas have been published in the Open Access literature [31].

The ontologies used to represent domestic electricity consumption and fuel poverty are new. The ontology used to represent the electricity consumption is exactly analogous to that used to represent gas consumption [31]. The ontology used to represent fuel poverty data is detailed below. Both ontologies, including definition of all namespaces and references to other ontologies, are provided as part of the research data supporting this publication. See doi:10.17863/CAM.74476.

A1. Fuel poverty ontology

Figure A.1 illustrates the structure of the fuel poverty ontology.

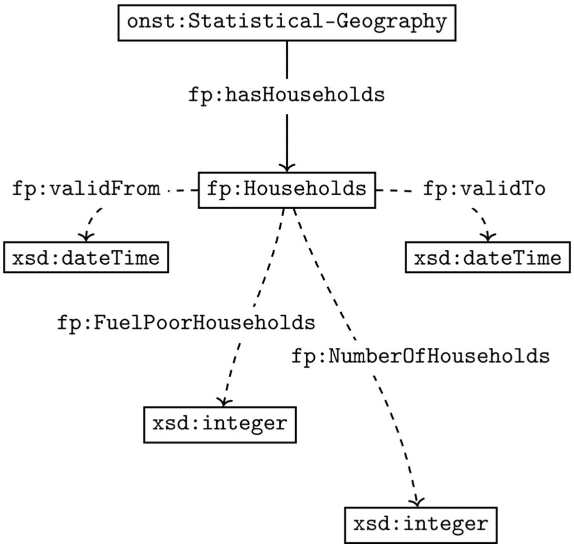


Fig. Appendix A.1. Ontology to describe fuel poverty statistics. Solid lines indicate object properties. Dashed lines indicate data properties.

A1.1. Description logic representation

Bold text denotes concepts that build on concepts from other ontologies. The full ontology is provided as part of the research data supporting this publication.

$$
\begin{aligned}
\textbf{Households} &\sqsubseteq \top \\
\exists\textbf{hasHouseholds}.\top &\sqsubseteq \text{Statistical-Geography} \\
\top &\sqsubseteq \forall\textbf{hasHouseholds}.\textbf{Households} \\
\exists\textbf{validFrom}.\top &\sqsubseteq \textbf{Households} \\
\top &\sqsubseteq \forall\textbf{validFrom}.\text{dateTime} \\
\exists\textbf{validTo}.\top &\sqsubseteq \textbf{Households} \\
\top &\sqsubseteq \forall\textbf{validTo}.\text{dateTime} \\
\exists\textbf{NumberOfHouseholds}.\top &\sqsubseteq \textbf{Households} \\
\top &\sqsubseteq \forall\textbf{NumberOfHouseholds}.\text{integer} \\
\exists\textbf{FuelPoorHouseholds}.\top &\sqsubseteq \textbf{Households} \\
\top &\sqsubseteq \forall\textbf{FuelPoorHouseholds}.\text{integer}
\end{aligned}
$$

A1.2. Example query

Appendix B. Sensitivity analysis

A sensitivity analysis was performed to check the impact of the assumed values of the boiler efficiency (η_{boiler}) and the proportion of gas used for heating (ϕ_{heating}). Table B.1 shows the cases considered in the sensitivity analysis. The rationale for the choice of the base case parameters is described in Section 3.3 of the main text.

The upper bound for the boiler efficiency (η_{boiler}) was chosen on the grounds that modern boilers have a formal SEDBUK (Seasonal Efficiency of a Domestic Boiler in the UK) rating of approximately 90% [59]. This is significantly higher than the average efficiency achieved in the field [59], such that 90% seems like a reasonable upper bound for the fleet. The lower bound was chosen on the grounds that whilst older (pre 2005) boilers can have efficiencies as low at 60–70% [60], such boilers are not representative of the entire fleet. 70% was chosen as a lower bound for the fleet.

The upper bound for the proportion of gas used for heating (ϕ_{heating}) in the sensitivity analysis was chosen on the simple grounds that the proportion cannot exceed 100%. The lower bound was chosen as 80% on the grounds that it was significantly more extreme than suggested by estimates of how much gas is used for things other than heating [61], and therefore provides a reasonable lower bound for assessing the sensitivity to this parameter.

B1. Change in national electricity and gas consumption

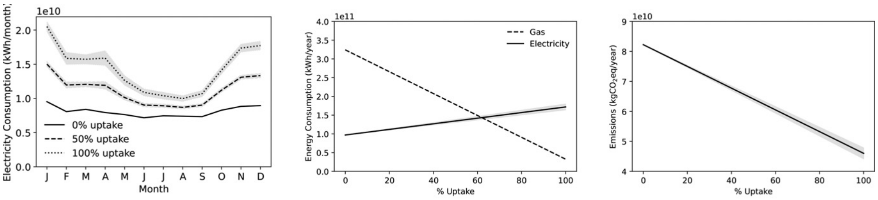
Figure B.1 shows the effect of the temperature and assumed parameters on the change in consumption of domestic gas and electricity in Great Britain. Analogous data for the base case is shown in Fig. 6 in the main text. As per the main text, uptake is defined as the proportion of gas used for heating that is displaced by heat pumps. The figure shows that the range of annual electricity consumption and emissions corresponding to the minimum and maximum air temperature is similar to the change in annual electricity consumption and emissions across the

Table Appendix B.1
Cases considered in the sensitivity analysis.

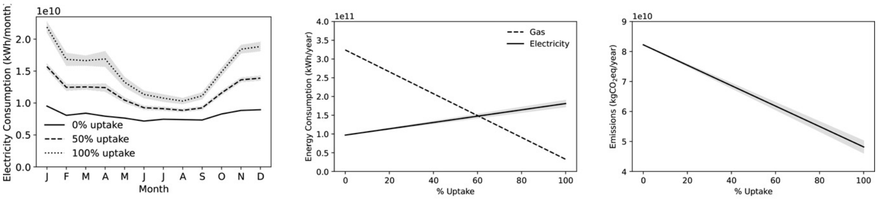
Case	Boiler efficiency η_{boiler}	Proportion of gas used for heating ϕ_{heating}
Base case	0.8	0.9
Increased boiler efficiency	0.9	0.9
Decreased boiler efficiency	0.7	0.9
Increased proportion of gas used for heating	0.8	1.0
Decreased proportion of gas used for heating	0.8	0.8

$$
\begin{aligned}
\textbf{Households} &\sqsubseteq \top \\
\exists\textbf{hasHouseholds}.\top &\sqsubseteq \text{Statistical-Geography} \\
\top &\sqsubseteq \forall\textbf{hasHouseholds}.\textbf{Households} \\
\exists\textbf{validFrom}.\top &\sqsubseteq \textbf{Households} \\
\top &\sqsubseteq \forall\textbf{validFrom}.\text{dateTime} \\
\exists\textbf{validTo}.\top &\sqsubseteq \textbf{Households} \\
\top &\sqsubseteq \forall\textbf{validTo}.\text{dateTime} \\
\exists\textbf{NumberOfHouseholds}.\top &\sqsubseteq \textbf{Households} \\
\top &\sqsubseteq \forall\textbf{NumberOfHouseholds}.\text{integer} \\
\exists\textbf{FuelPoorHouseholds}.\top &\sqsubseteq \textbf{Households} \\
\top &\sqsubseteq \forall\textbf{FuelPoorHouseholds}.\text{integer}
\end{aligned}
$$

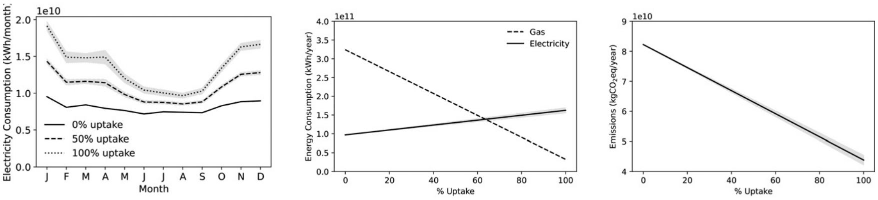
Fig. Appendix A.1. SPARQL query to obtain output areas and associated fuel poverty values as decimals.



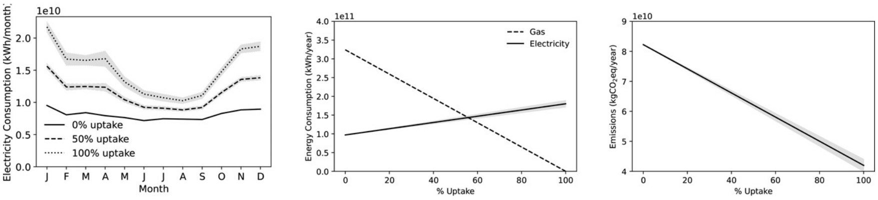
(a) Base case



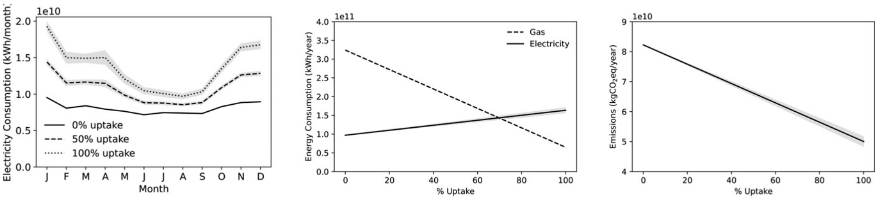
(b) Increased boiler efficiency.



(c) Decreased boiler efficiency.



(d) Increased proportion of gas used for heating.



(e) Decreased proportion of gas used for heating.

Fig. Appendix B.1. Sensitivity of change in domestic gas and electricity consumption in Great Britain for different heat pump uptake scenarios. The lines show values calculated using mean air temperatures (2019). The shaded regions shows the range corresponding to the minimum and maximum air temperature (2019). Left: Monthly electricity consumption. Middle: Annual gas and electricity consumption. Right: Total annual carbon equivalent emissions.

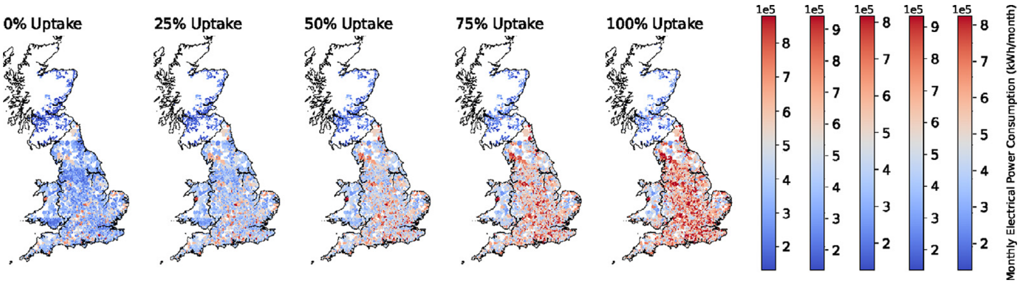
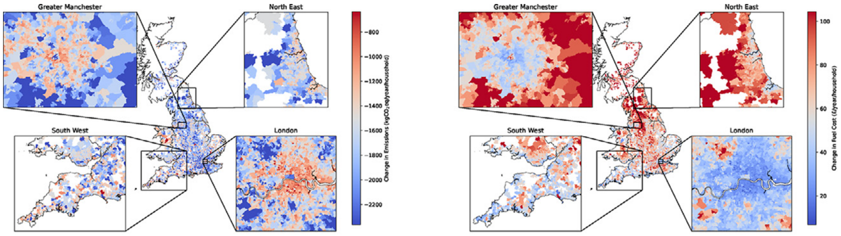
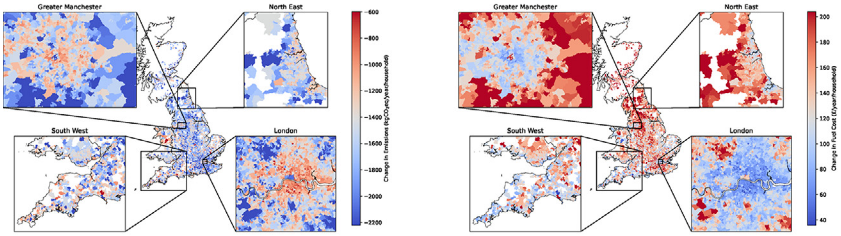


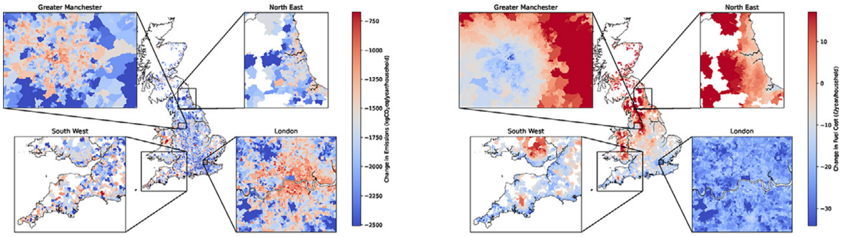
Fig. Appendix B.2. Sensitivity of maximum monthly electrical power consumption for different heat pump uptake scenarios (2019). Colour bars left to right: Base case. Increased boiler efficiency. Decreased boiler efficiency. Increased proportion of gas used for heating. Decreased proportion of gas used for heating.



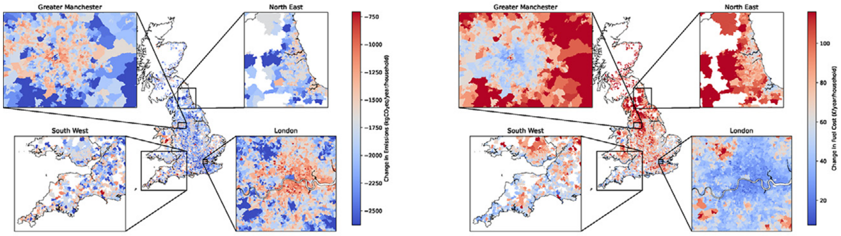
(a) Base case.



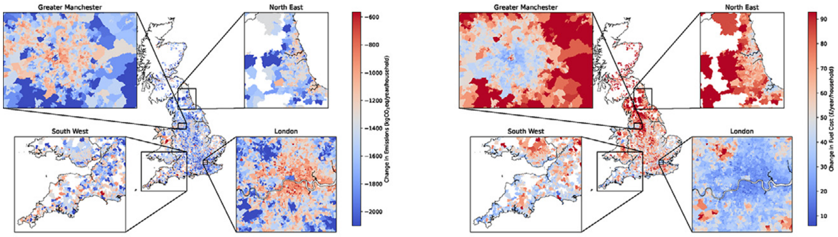
(b) Increased boiler efficiency.



(c) Decreased boiler efficiency.

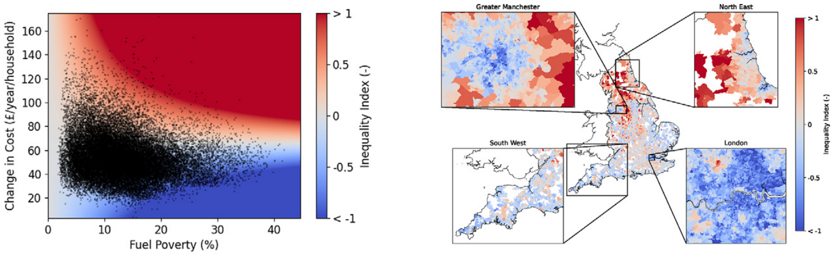


(d) Increased proportion of gas used for heating.

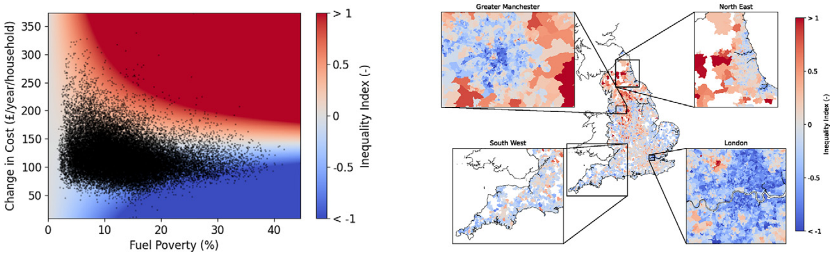


(e) Decreased proportion of gas used for heating.

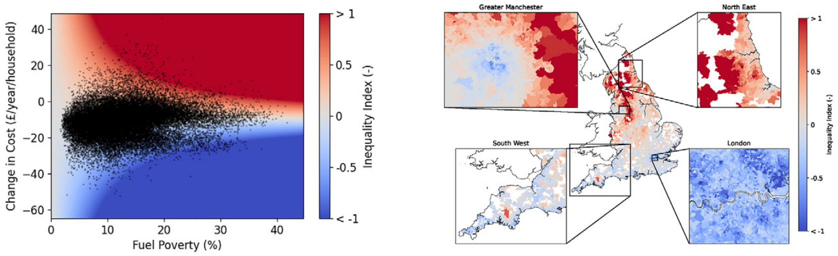
Fig. Appendix B.3. Sensitivity of change in emissions (left) and change in fuel cost (right) of households adopting heat pumps (2019, mean air temperature).



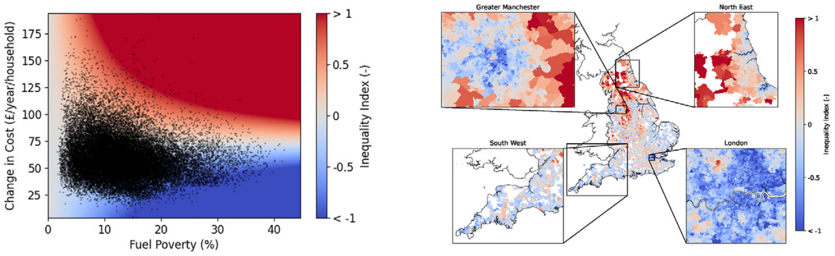
(a) Base case.



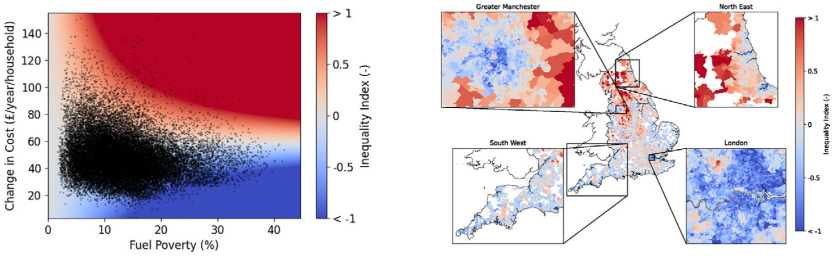
(b) Increased boiler efficiency.



(c) Decreased boiler efficiency.



(d) Increased proportion of gas used for heating.



(e) Decreased proportion of gas used for heating.

Fig. Appendix B.4. Sensitivity of effect of adopting heat pumps on social inequality (2019, mean air temperature). Left: Inequality metric overlaid by points showing the distribution of data for households in England. Right: Geospatial distribution of inequality metric.

Table Appendix B.2
Change in domestic electricity consumption and carbon emissions in Great Britain due to temperature and assumed parameter values at 100% uptake of heat pumps.

Case	Electricity consumption		Carbon emissions	
	%^{a}	%^{b}	%^{a}	%^{b}
Base case	9.1	–	7.9	–
Increased boiler efficiency	9.7	−5.4	8.5	−4.6
Decreased boiler efficiency	8.4	−5.5	7.3	−4.7
Increased proportion of gas used for heating	9.6	−4.8	9.6	−8.7
Decreased proportion of gas used for heating	8.5	−4.8	6.5	−8.8

^{a} Range corresponding to the minimum and maximum air temperature as a percentage of the value corresponding to the mean air temperature for each case. ^{b} Percentage difference from the base case calculated using the mean air temperature.

parameter range considered. Importantly, comparison of Fig. B.1 panels (b) and (c) versus (d) and (e) shows that unlike the assumed value of the boiler efficiency (η_{boiler}), the assumed value of the proportion of gas used for heating (ϕ_{heating}) affects the total gas displaced by the heat pumps (ΔG), with a notable corresponding effect on emissions. This is easiest to see by looking at the values at 100% uptake.

Table B.2 summarises corresponding numerical results at 100% uptake. Notwithstanding the difference in how the assumed values of the boiler efficiency (η_{boiler}) and proportion of gas used for heating (ϕ_{heating}) affect the total gas displaced by the heat pumps (ΔG), the results are relatively insensitive to the uncertainty in the temperature and to the assumed values of the parameters, varying less than ±10% across the parameter range considered.

Figure B.2 shows the effect of the assumed parameters on the geospatial distribution of the maximum monthly electrical power consumption. Analogous data for the base case is shown in Fig. 7 in the main text. As per the main text, the maximum at each location occurs when the local heating demand combined with local minimum air temperature cause maximum consumption of electricity. The data are relatively insensitive to the assumed values of the boiler efficiency (η_{boiler}) and the proportion of gas used for heating (ϕ_{heating}), with the magnitude of the change in any given location varying approximately ±10% across the parameter range considered, consistent with the data in Fig. B.1 and Table B.2.

B2. Effect on households and social inequality

Figure B.3 shows the effect of the assumed parameters on the impact of transitioning from gas to heat pumps for individual households. Analogous data for the base case is shown in Fig. 8 in the main text. As per the main text, it is assumed that the number of households that could switch is equivalent to the number of consuming gas meters.

The geospatial distribution of the change in emissions is insensitive to the assumed values of the boiler efficiency (η_{boiler}) and proportion of gas used for heating (ϕ_{heating}), with the magnitude of the change in any given location again varying approximately ±10% across the parameter range considered.

The geospatial distribution of the change in fuel cost is also insensitive to the assumed values of the parameters. However, the *magnitude* of the change in fuel cost is sensitive to the boiler efficiency (η_{boiler}). Electrification becomes less expensive and regional effects less pronounced at lower values of the boiler efficiency (η_{boiler}) because less heat is required to replace a given gas consumption, corresponding to a smaller change in electricity consumption (ΔE) for a given change in gas consumption (ΔG) in eqs. (4) and (6). The maximum change in fuel cost is observed to vary from an increase of £200 per month in the north to a saving of £30 per month in the south at the extremes of the parameter range for the boiler efficiency (η_{boiler}). The change in fuel cost is much less sensitive to the proportion of gas used for heating (ϕ_{heating}) because it affects both the change in gas consumption (ΔG) and the change in electricity consumption (ΔE), such that the changes in fuel cost due to the ΔG and ΔE terms in eq. (6) partly compensate for each other.

Figure B.4 shows the effect of the assumed parameters on the impact of adopting heat pumps on social inequality. Analogous data for the base case is shown in Figs. 9 and 10 in the main text. As per the main text, a negative value of the inequality index (blue) indicates a *favourable* change in fuel cost in regions of high fuel poverty, while a positive value of the inequality index (red) indicates an *unfavourable* change in fuel cost in regions of high fuel poverty. The geospatial trend and predicted effect on social equality is insensitive to the assumed values of the parameters, although the effects are less extreme in the case of the decreased boiler efficiency (η_{boiler}) in Fig. B.4(c). This is because of the sensitivity of the change in fuel cost to the boiler efficiency observed in Fig. B.3(c). In this case, the change in fuel cost due to adopting heat pumps is less significant, such that it is predicted that replacing an entire fleet of inefficient boilers would have a smaller effect on social inequality. However, there is already evidence that the average efficiency of the fleet is much closer to the base case [59], so whilst it is clear that replacing inefficient boilers with something more efficient would be advantageous, it is unlikely that this is representative of the whole fleet.

B3. High resolution figures

High resolution figures from the sensitivity analysis are available as part of the research data supporting this publication. See doi:10.17863/CAM.74476.

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