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Impact of locational pricing on the roll out of heat pumps in the UK

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ABSTRACT

This paper investigates the impact of locational pricing on the roll out of heat pumps in the UK. Qualitative assessment of proposals set out for electricity market reform in the UK identified locational pricing as potentially having an impact on heat pump running costs. Energy system modelling was used to assess the economics of both individual heat pumps and system-wide heat pump roll out under both unified pricing and locational pricing for the UK for 2020 and 2035. PyPSA-GB, a future power system model, was employed to simulate unified and locational wholesale prices and the Octopus Agile tariff was used to calculate indicative retail tariffs applicable to domestic heat pumps. The research highlights that locational pricing can create market conditions which better reflect the true cost of generating and delivering electricity, however, it can also lead to higher heat pump operating costs in regions with projected high heat demand. Key findings reveal that locational pricing could result in significant geographical disparities in heat pump operating costs due to varying electricity prices across different zones. Further work is required to develop policy to alleviate high operating costs and to promote flexible operation of heat pumps.

1. Introduction

Locational pricing is a market structure with different prices for electricity based on where it is used within the grid network (Liu et al., 2009). It aims to reflect the true cost of generating and delivering electricity in different areas, taking into account factors such as transmission constraints, generation capacity, and demand patterns in specific regions. By incentivising generators to locate strategically and consumers to manage their demand more effectively, locational pricing can enhance overall system reliability while minimising congestion issues. However, implementing effective locational pricing mechanisms can be challenging due to various technical, regulatory, and market design considerations (Litvinov, 2010).

Locational pricing has the potential to significantly impact the adoption of heat pumps. Heat pumps operate by using electricity to facilitate efficient heating or cooling services, and are seen as a vital technology for decarbonising heat. Therefore, it is crucial to understand the economic feasibility of heat pumps under different electricity prices across various locations (Sauer and Howell, 1983). Locational pricing possesses considerable potential to significantly influence the level of roll out of heat pumps expected in a number of countries (Eicke and Schittekatte, 2022). This paper focuses on the UK, but provides insight applicable to countries with similar heat pump roll out plans.

The UK is in the early stages of decarbonising domestic heat. Currently around 90% of domestic heating in the UK is supplied by combustion of fossil fuels, either natural gas or oil (BEIS, 2021a), but continuing to heat dwellings in this way is incompatible with net-zero decarbonisation targets (BEIS, 2017). Heat pumps, powered by low-carbon electricity, are one of the main technologies proposed to replace fossil fuel boilers (Climate Change Committee, 2019; BEIS, 2021b), since they provide several times more heat output than basic electric resistance heaters. The widespread use of heat pumps in UK homes presents several significant challenges.

1. *Heat pump uptake to date has been low.* Despite the existence of various UK government schemes and incentives, around 35,000 heat pumps are installed per year (BEIS, 2017), compared to over 1.5 million gas boilers. The government has set a target of 600,000 heat pump installations per year by 2028. Barriers to heat pump uptake

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include financial concerns (capital costs or running costs), lack of familiarity with the technology, lack of trained installers, fears of heat output being inadequate and others (Frontier Economics and Element Energy, 2013).

2. *The use of heat pumps will substantially increase electricity demand* (Watson et al., 2023). This presents problems at a national level, in terms of electricity generation and transmission infrastructure (Eyre and Baruah, 2014; Baruah, 2014) and also at a local level, in terms of the electricity distribution network (Navarro-Espinosa and Mancarella, 2014).
3. *The parallel decarbonisation of heat and electricity.* Achieving full decarbonisation of domestic heating through heat pumps requires decarbonised electricity, largely generated by intermittent renewables. Times of heat pump electricity demand may not coincide with the availability of renewable electricity, for example during cold, still weather with low sunlight levels, such as was experienced in the UK in December 2022. However, there is potential to use heat pumps flexibly, utilising building thermal inertia (Verbeke and Audenaert, 2018) or explicit thermal storage (Navarro et al., 2016), in order to improve the match between heat pump electricity demand and renewable availability (Wang et al., 2022).
4. *The performance of heat pumps as installed.* Historically studies have indicated that the performance of heat pumps in field trials in UK homes has generally been lower than in comparable continental European trials (Gleeson and Lowe, 2013). However, more recent studies have shown that UK heat pump performance in homes has improved significantly over the past 15 years (Energy Systems Catapult, 2023). This may be due to improved standards of installation.
5. *The suitability of the existing UK housing stock for heat pumps.* Since heat pumps provide water at lower temperatures than fossil fuel boilers, dwelling fabric improvements and/or larger emitters might be required, which would add considerably to the cost of heat pump installation (Energy Systems Catapult, 2022). However, it is not clear whether high levels of fabric efficiency are really needed (Lowe and Oreszczyn, 2020; Palmer and Terry, 2021), and, where high flow temperatures are needed, high-temperature heat pumps have recently been found to have similar performance to standard heat pumps (Energy Systems Catapult, 2023).

A relatively unexplored challenge of heat pumps is the potential impact on operating cost due to reform of electricity markets, in particular locational pricing. A number of studies have assessed the impact of locational pricing in the UK, and it is one of the proposals in the recent Review of Electricity Market Arrangements (REMA) consultation set out by the UK Government (BEIS, 2022). National Grid's study on Net Zero Market Reform found that nodal pricing offers advantages in the areas of value for money, consumer fairness, adaptability and full chain flexibility, in comparison to a singled national price or zonal pricing (National Grid, 2022). An Energy Systems Catapult report asserted that transitioning the Great Britain (GB) power market to a nodal pricing design can enable an efficient transition to a net zero grid (Energy Systems Catapult, 2021). These reports assessed only the system-wide impact of locational pricing. Opposition to locational pricing in the UK can be seen in the responses to the REMA consultation (BEIS, 2022) where investors into renewable generation identified issues around risk to investment and reduction on returns.

Locational pricing has the potential to substantially reduce electricity prices for consumers in regions with high renewable shares. Green (2007) investigated nodal pricing by modelling the transmission network of England and Wales, and showed moving from uniform pricing to optimal nodal prices could enhance welfare, in addition to improving the accuracy of investment signals. A recent OFGEM (2023) assessment concluded that "locational pricing is likely to produce significant benefits for consumers compared to doing nothing to improve locational signals".

The aim of this paper is to investigate the potential implications that locational pricing could have on the roll out of heat pumps in the UK. The paper first qualitatively examines the proposals set out for electricity market reform in the UK, particularly in REMA, and the potential impacts of these proposals on heat pump economics and adoption. The paper then assesses the economics of an individual heat pump under locational pricing for the UK, by simulating locational prices using a future power system dispatch model, in addition to applying household and heat pump energy models. Finally, the paper analyses the system level impacts of different scenarios of heat pump roll out under locational pricing. The scope of this paper is limited to wholesale markets, and it does not attempt to assess the potential locational pricing benefits of reducing balancing costs or incentivising flexibility.

2. Electricity market reform impact on heat pump roll out

This section examines the proposals set out for electricity market reform in the UK, particularly in REMA, and potential impacts of these proposals on heat pump economics and adoption. It briefly explores the history of electricity markets in the UK, sets out current heat pump economics and links to electricity markets, and reviews the proposals for electricity market reform in REMA.

2.1. History and current state of electricity markets in the UK

The Great Britain (GB) electricity sector moved from state control to private sector ownership as a result of the 1989 Electricity Act (Electricity Supply, 1992), with transfer of ownership taking place in 1990, and competition in the generation and supply functions being adopted in stages up to 1998, allowing for new entrants to both sectors.

After around a decade of private ownership, concerns arose that the initial 'Pool' approach to electricity trading was failing to match price to costs, due to the market power of the key companies held over from the initial privatisation. Government acted to replace the Pool with 2001's New Electricity Trading Arrangements (NETA). This new approach replaced central dispatch of power with a self-dispatched energy-only market rooted in bilateral trading, again with the goal of maximising competition. A balancing mechanism was introduced to penalise failure to deliver contracted power, justified as addressing market manipulation.

The latter half of the 2000s downward pressure on electrical capacity margins arising from closure of coal and nuclear plants had raised concerns about GB's ability to maintain supply year round. The outcome of both these concerns was the 2013 Electricity Market Reform (EMR), an effort both to secure financing for a new generation of low carbon investments, and to deliver improved systemic and operational reliability, intended in the short term to stimulate growth in gas generation to build the capacity margin, and in the longer term to grow the share of renewable and nuclear power (Liu et al., 2022).

The UK's fourth round of market reform is via the Review of Electricity Market Arrangements (REMA). Billed by the UK Government as a response to high wholesale energy prices beginning in late 2021 but stoked by the Russian attack on Ukraine in early 2022 (BEIS, 2022), it contains the more wide-ranging statement "We do not consider that existing market arrangements are likely to deliver our ambition for a decarbonised and secure electricity system by 2035 at least possible cost to consumers". This acknowledges both the need for systemic change and that price was not the only underlying issue. REMA's proposals were opened to consultation in 2022, drawing a substantive volume of responses (BEIS, 2022); no response from the Government has been published at time of writing.

2.2. Discussion on heat pump economics

REMA sets out proposals for changes to current electricity market arrangements, but does not include reform of retail markets in its scope. Most heat pumps deployed in the UK will likely be domestic users who purchase electricity in retail markets. In the context of the retail market, electricity suppliers purchase electricity from the wholesale market and sell it to households and businesses. The costs of wholesale electricity, influenced by elements subject to REMA proposed reform such as locational pricing, energy supply and demand, transmission constraints, and generation capacity, greatly impact the prices in the retail market. Therefore, retail prices for consumers, including heat pump users, are not isolated from the dynamics of the wider electricity market.

As noted earlier, uptake of heat pumps to date has been low. The relatively higher total cost of heat pumps has been one of the main challenges in the deployment of the technology. The total cost consists of the capital and operational costs. The capital costs include the equipment price and installation cost, while the operational costs include the electricity and maintenance cost. Comprehensive costs of heat pumps and their comparison to other heating technologies has been carried out in other studies, e.g., see Energy Systems Catapult (2022), and this section focuses on discussion of the challenges.

In the UK, it has been shown that although the equipment price of heat pumps has a declining trend as the number of installation increases in the past decade, their capital costs have been relatively stagnant (Renaldi et al., 2021). This implies an increasing trend in the installation costs. Possible explanations to this trend include limited learning effects and knowledge spillovers due to the localised nature of heat pumps installers and lower competitions between installers.

In comparison with other low-carbon heating technologies, the price per kW of air-source heat pumps is lower than solar thermal and ground-source heat pumps and higher than biomass boilers (Renaldi et al., 2021). As the incumbent heating technology, gas boilers have the lowest price at approximately £30/kW (Renaldi et al., 2021).

Different policies have been established to reduce the total cost of heat pumps. For example, the Renewable Heat Incentive (RHI) was designed to help in reducing the operational costs by providing yearly payments for the heat produced (Lowes et al., 2019). Recently, the Boiler Upgrade Scheme (BUS) has been promoted to reduce the capital costs by providing lump sum grant to help end users in replacing their fossil fuel heating systems with a heat pump or biomass boiler (BEIS, 2021c).

In the past decade, the heat pump deployment in the UK has been significantly influenced by these policies. Annual installations were growing rapidly the first half of last decade (2010-2014) and significantly slowing down in the second half period (2015-2019) (MCS, 2023). In general, the installation rate of heat pumps in the UK is still relatively low (Rosenow et al., 2022). This could lead to minimal competition between installers, which could slow down the reduction in installation costs. The current balance of tax and regulatory costs through the fuel costs has also been shown to negatively impact heat pump deployment in the UK (Barnes and Bhagavathy, 2020).

2.3. High-level assessment of REMA proposals on heat pumps

This section aims to identify reforms in REMA which have the potential for highest impact on the roll-out of heat pumps in the context of UK government targets of 600,000 heat pump installations by 2028 (Department for Energy Security and Net Zero, 2023). Later in this paper, the identified reforms will be analysed using detailed spatial-temporal energy system models to quantify individual heat pump economics and system impacts.

The UK government is consulting on electricity market reform through REMA and the wide variety of options are currently under fierce debate between stakeholders. The aim of REMA is to establish the electricity market reform necessary for a fully decarbonised electricity system by 2035, which supports the transition to an economy-wide net zero energy system by 2050. The reforms are intended to form the final critical step towards supporting the net zero transition, as opposed to an interim step from which major reform is still required.

The main aims outlined in REMA are - reforming to a net zero suitable wholesale market; markets suited to the roll out of mass low-carbon power; incentivising investment in flexibility technologies such as by introducing locational pricing; ensuring capacity adequacy; and reforming ancillary services which enable operability. These approaches are discussed here as stand-alone measures, but it is likely a mixture of these approaches will form the next stage of market reform in the UK. The following subsections reflect the REMA document by using the same organising headings as those used in the REMA document: Chapter 6 "Mass low-carbon power", Chapter 7 "Flexibility", Chapter 8 "Capacity Adequacy", and Chapter 9 "Operability".

2.3.1. Wholesale market

The electricity market is subject to variable wholesale electricity prices, and changes in these prices can impact the cost of running a heat pump. Wholesale prices will be increasingly variable due to the differentials between low marginal cost of electricity from renewable sources such as wind and solar, and the high marginal cost of electricity from sources like hydrogen and carbon capture and storage (CCS) power production.

Retail markets are also crucial for heat pump users as this is the market where the majority of domestic consumers purchase electricity. The proposed changes in the REMA can impact the end-users significantly. For example, time-of-use tariffs linked to wholesale markets, such as Octopus Agile (Steele, 2019), and tariffs for EV users can affect the cost of electricity for heat pump users.

Wholesale market – location

Locational pricing (including zonal and nodal pricing) involves charging different prices for electricity based on the location of the user, and can have a significant impact on the adoption and roll-out of heat pumps in the UK. The cost of electricity varies across regions due to differences in transmission and distribution infrastructure, in addition to location of low/zero marginal cost electricity production from renewable energy sources. As a result, areas with weaker infrastructure or low renewable deployment may experience higher electricity prices. This can create challenges for the deployment of heat pumps in these regions, where the cost of electricity may be prohibitively high. This reform has the potential to have a significant impact on the roll out of heat pumps and is the subject of futher analysis in this paper.

Wholesale market - technology

Splitting the wholesale market by technology, which involves charging different prices for electricity based on the source of the electricity, can have both positive and negative impacts on the roll-out of heat pumps in the UK. This approach could help incentivise installation of wind and solar which could help increase the availability of low-cost electricity which could support the wider deployment of heat pumps. However, splitting the wholesale market could also result in higher costs for electricity generated from fossil fuels which could make heat pumps more expensive to operate.

2.3.2. *Mass low-carbon power*

The primary lever for delivering mass low-carbon power has been Contracts for Difference (CfDs). CfDs can have a significant impact on the roll-out of heat pumps in the UK by providing long-term price stability for renewable energy sources. By providing long-term price stability, CfDs can also help to reduce the cost of renewable energy, making it more competitive with other sources of energy, which could in turn support the wider deployment of heat pumps. Furthermore, CfDs could encourage the deployment of renewable energy sources in regions where they are less abundant, helping to make the deployment of heat pumps more cost-effective across the country.

2.3.3. *Flexibility and capacity adequacy*

In a capacity market, electricity suppliers bid to provide a certain amount of capacity to the grid, and the system operator awards contracts to suppliers based on their bids. Large-scale heat pumps and thermal storage can provide capacity by reducing electricity demand during peak periods. For example, if a large district heating system has heat pumps as the heat generation source buying electricity on tariff that charges during off-peak hours and discharges during peak hours, the system can operate to reduce the building's electricity demand during peak hours, which can reduce the need for additional capacity (Tan et al., 2022).

The participation of heat pumps and thermal storage in a capacity market would depend on the design of the market and the rules and regulations governing participation. For example, the rules may require that the resource must be available for a certain number of hours during peak periods, or that it must be capable of responding to a system operator signal within a certain timeframe. Additionally, the value of capacity payments may need to be sufficient to incentivize the participation of heat pumps and thermal storage in the market (Rinaldi et al., 2022). This would depend on the level of competition in the market, the cost of providing capacity, and the value of reliability to electricity consumers.

2.3.4. *Operability*

Heat pumps have the potential to participate in new operability or grid services markets, which are designed to provide flexibility to the electricity grid by allowing different types of resources to provide services that help manage grid stability and ensure reliable electricity supply. Heat pumps can provide demand response services by adjusting their electricity consumption in response to a signal from the system operator, or frequency response services by adjusting their electricity consumption in response to changes in the frequency of the electricity grid.

Local markets containing participating heat pumps can also be a potential option (Huynh et al., 2022) for enhancing grid operability. In this concept, heat pumps can participate in a local energy market that is co-located with the heat pump, to exchange energy and grid services (potentially limited to distribution grids) with the local community. For example, a group of households with heat pumps and solar panels can participate in a local market, buying and selling electricity and distribution-level grid services with each other (Testi et al., 2020). The heat pumps can be used to provide flexible demand response services to the local grid, allowing households to benefit from lower electricity prices during off-peak hours (Fischer and Madani, 2017).

2.4. Choice of locational pricing for further analysis

Locational pricing was chosen from the set of proposals in REMA due to several factors:

- *Impact on Running Costs*: Locational pricing has the potential to influence the running costs of heat pumps through changes to wholesale electricity prices which can be passed onto retail market. As these costs can be a determining factor in the uptake of heat pumps, an understanding of how locational pricing could influence these costs is crucial.
- *Promoting Efficient Use*: Locational pricing incentivises heat pump owners to use their systems more efficiently, by shifting their usage to times when electricity prices are low. This would require flexible heat demand or thermal storage, but would make heat pumps more attractive and affordable to potential users.
- *Geographical Influences*: Locational pricing takes into account the geographical location, which can inherently affect the viability of heat pump installations. Understanding the geographical price variations can provide a more nuanced understanding of heat pump adoption potential.
- *Flexible Demand Response*: Most heat pump systems have a degree of thermal storage and can be considered as 'flexible loads'. Locational pricing can incentivise shifting of this flexible load to times of lower price, aiding in grid balancing efforts.

- *Alignment with Decarbonisation*: Locational pricing, by reflecting a better representation of the cost of supply, can help incentivise renewable generation and thus align with the broader goal of decarbonisation, which is also a key reason for the push towards heat pumps.

3. Modelling Methods

This section describes the methods used in the analysis of the economics of individual and system-level heat pumps under locational pricing using quantitative modelling. It describes the methods used to quantify the varying heat pump operating costs in different locations using power system modelling and models for heat demand and heat pump performance. It sets out the models and equations used to quantify both unified pricing and locational pricing retail tariffs. It describes the models used for both (i) quantifying the heat pump performance and heat demand of a single detached household, and (ii) assessing system-level heat pump roll out.

The type of locational pricing assessed is zonal pricing (Bjørndal and Jørnsten, 2001), with the GB power market divided into 20 distinct zones. Analysis was undertaken for 2020 and 2035 to aid understanding of the impact on the heat pump stock currently and in a net zero power system. National Grid's Future Energy Scenarios (FES), specifically the Leading the Way scenario, was used as the basis for the data on the 2020 and 2035 national electrical power systems (National Grid ESO, 2021). The relevant models and datasets for this paper can be found in the referenced repository Lyden (2024).

3.1. Unified and locational pricing

Unified pricing and locational pricing retail tariffs were calculated by using the open-source power system modelling tool PyPSA-GB to calculate wholesale electricity prices, then using the methodology employed by Octopus Agile to translate the wholesale prices to a retail tariff. These models simulate the impacts of unified and locational pricing strategies on the economics of heat pump adoption in UK households.

PyPSA-GB is a Python model developed for analyzing the future power system in Great Britain based on National Grid's Future Energy Scenarios (FES) (Lyden et al., 2023). PyPSA-GB optimises power system dispatch allowing the evaluation of generator dispatch, network flows, and electricity prices. It aids decision-makers and stakeholders in making informed choices regarding the functioning of the power system, and in this case was used for simulating marginal prices for both unified pricing and locational pricing.

Octopus Agile is an innovative tariff which operates by translating real-time changes in the wholesale energy markets into dynamic prices for consumers. The tariff uses day-ahead prices for each half-hour of the following day retrieved directly from Nord Pool who provide wholesale market prices for retailers. These prices reflect the cost to Octopus of purchasing energy for its Agile customers and include the price for the energy itself, the cost of using the national grid (transmission), and regional distribution network costs. Added to these costs are additional charges such as 'Balancing Services Use of System' (BSUoS), which are costs incurred by the energy supplier in order to maintain adequate supply and demand balance in the electricity grid, as well as a profit margin and a VAT (value added tax) charge. The final price offered to customers for each half-hour changes daily, reflecting the variability in the wholesale energy market and allowing customers to adapt their usage according to the price signals sent by the Agile tariff. The equations used to represent the Octopus Agile tariff in this research can be found in Steele (2019).

The integration of the modelled wholesale electricity prices of PyPSA-GB and conversion to retail tariff using Octopus Agile equations results in retail prices applicable to domestic heat pump users. In summary, unified and locational pricing were modelled as follows:

- **Unified pricing** modelled in PyPSA-GB by assuming no network constraints and allowing generators, demands, storage, and flexibility technologies to interact regardless of location, as is the current GB market arrangement where the free market extends to any generator being able to sell electricity to any demand. The resulting unified wholesale price for the whole of the GB market was used in the Octopus agile tariff equation to output a unified retail price.

- **Locational pricing** modelled as zonal pricing in PyPSA-GB by including network constraints and splitting the market into 20 bidding zones (see Figure 1) which reflect potentially constrained areas of the network as set out by National Grid's ETYS (National Grid, 2013). This results in potentially different locational wholesale prices for each of the zones, dependent on local supply/demand and network availability. The locational prices for each zone was used in the Octopus agile tariff equation to output locational retail prices for each zone.

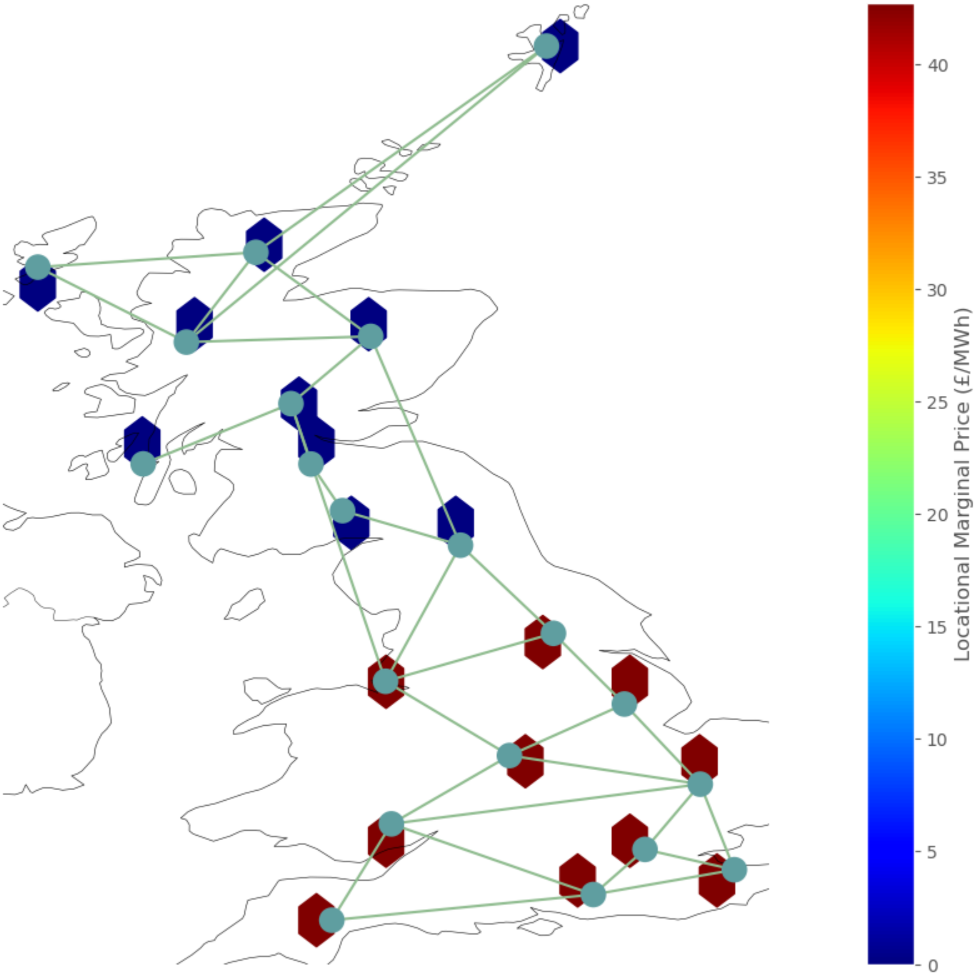


Figure 1: Locational wholesale pricing as modelled in PyPSA-GB across the 20 zones in 2020.

3.2. Single household heat pump and heat demand

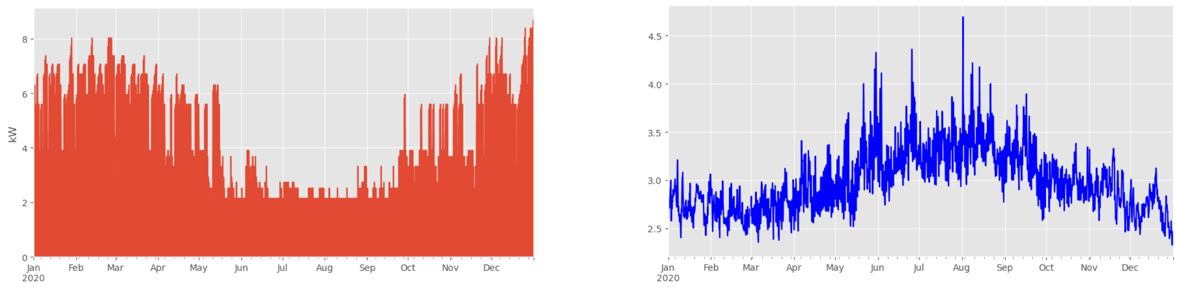
To assess the impact of locational pricing on a heat pump for a single household, models for air-source heat pump performance and heat demand were used to develop hourly profiles of heat pump Coefficient of Performance (COP) and combined space heating and hot water demand for a single detached house.

The method for generating hourly profile for the space heating and hot water demand utilised regression analysis of pre-simulated housing standard profiles, scaling based on floor area, and applying diversity using a normalised smoothing method, see Lyden and Tuohy (2019) for more details on this method, and Figure 2a for the output for the 2020 hourly heat demand of single detached house in Edinburgh.

To model an air-source heat pump a simplified model based on the Lorentz cycle was utilised to ascertain the theoretical COP. Heat pump manufacturer sheets were used to determine the manufacturer COP for a single operating condition (i.e., one set of outdoor temperature, flow and return temperatures). The actual COP was then attained by multiplying the theoretical COP with the heat pump efficiency, which was derived from the stated COP divided by the manufacturer COP. This process yields the actual COP for each timestep, accommodating for real-time temperature changes and fluctuations. See Figure 2b for COP in Edinburgh in 2020.

3.3. System-level heat pump roll out

System-level analysis was undertaken which looks at the whole GB heat pump stock for 2020 and 2035 and assesses the impact of locational pricing on heat pump operational cost at a national level. This analysis developed total heat



(a) Head demand of single detached house in Edinburgh.

(b) COP of air-source heat pump in Edinburgh.

Figure 2: Heat demand and COP of a single detached house with an air source heat pump in Edinburgh in 2020.

pump heat demand and COP profiles for each of the 20 zones described earlier. These were then combined to output a heat pump electrical demand hourly profile for each zone which could be used with the unified and locational retail electricity prices to calculate total heat pump operation cost in each zone. This cost only includes the cost of the heat pumps consuming electricity.

The analysis takes a holistic view, capturing the interactions between electricity and domestic heating by employing spatio-temporal models and future energy scenario data for supply and demand for GB. The analysis used aggregated domestic heat pump profiles in each of the representative zones based on the modelling of the total heating demand from data fro each clustered local authority area.

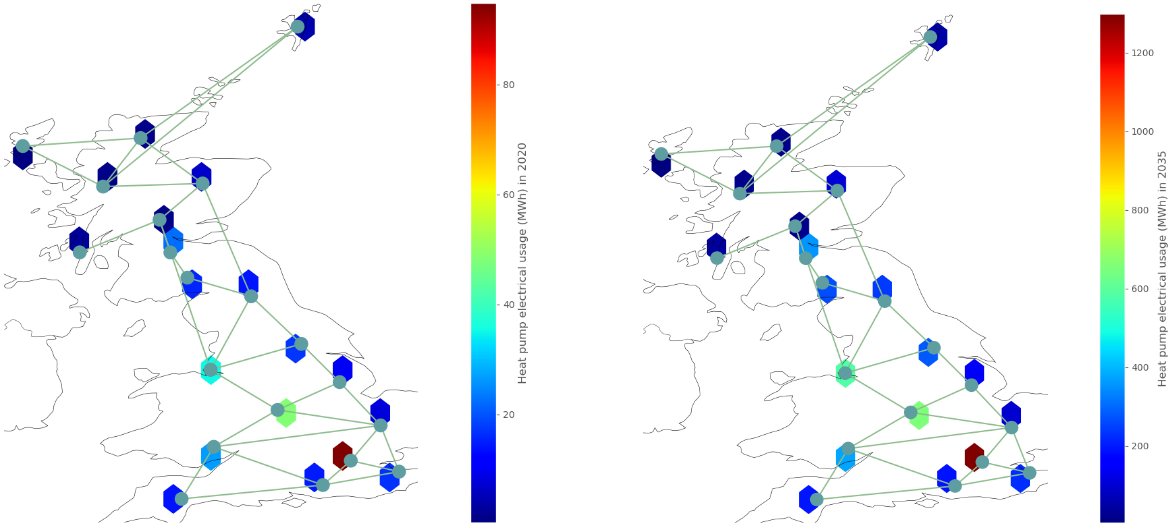
The data-driven heat demand modelling approach applied estimates of the aggregated total domestic heat demand profiles at the local authority level in GB. This is distinct from the approach for the method on individual heat pump analysis described in the previous section. The number of dwellings with heat pumps was sourced from National Grid's Future Energy Scenarios 2022 data considering the leading-the-way scenario (National Grid ESO, 2021). The total domestic dwellings with heat pumps were mapped to the nearest zone using a k-means clustering method. The calculation of the aggregate domestic heat demand for dwellings with heat pumps was made using the empirical model derived by Watson et al. (2021) from the renewable heat premium payment (RHPP) field trial dataset. Watson et al. (2021) found a strong linear relationship between the outdoor air temperature and heat demand, except at the breakpoint temperature using a broken-stick regression on the field trail data sampled for the year 2013/2014. The data-driven regression equations are:

$$HT_d(kWh) = \begin{cases} m_1 x T_d + c_1, & \text{for } T_d < T_{breakpoint} \\ m_2 x T_d + c_2, & \text{for } T_d > T_{breakpoint} \end{cases}$$

where HT_d is the total day heat demand, m_1, m_2, c_1 and c_2 are regression coefficients, T_d is the average outdoor air temperature, and $T_{breakpoint}$ is the breakpoint temperature which dictates which regression equation to be used.

The aggregated total domestic heat demand was obtained by multiplying the empirical heat demand with the number of dwellings in each zone, which gave the estimated total heat demand at representative zones considered in PyPSA-GB. Further information can be found from Watson et al. (2021) regarding the temperature-banded normalised profiles and scaling of the total heat demand using these normalised profiles to take into account the time of the day to decouple the temperature-only dependency of the heat demand. Similarly, the coefficient of performance (COP) for heat pumps is weather dependent in different seasons and, thus, the COP of heat pumps at each zone in the PyPSA-GB model was estimated as a function of the outdoor ambient temperature, see Watson et al. (2023) for details on regression coefficients.

Figures 3b and 3b show the projected, almost 10-fold, increase in heat pump electrical usage across GB from 2020 to 2035. This substantial rise, indicative of the accelerating adoption of heat pumps in the UK, underscores the significant transformation anticipated in the domestic heating landscape. No significant deviation for 2020 heat pump geographical distribution was found in the FES data for the roll out to 2035.



(a) Heat pump electrical demand in 2020.

(b) Heat pump electrical demand in 2035.

Figure 3: Total heat pump electrical usage in each zone in 2020 and 2035.

4. Results

4.1. Unified and locational pricing in 2020 and 2035

Figure 4 shows the wholesale prices under existing GB market rules with unified pricing for the year 2020. The depicted marginal prices, which are historically set by gas power generation, fluctuate throughout the year, reflecting the variables impacting supply and demand, renewable energy availability, along with other operational factors. There are also intermittent periods where the marginal cost reduces to zero. These instances highlight periods of excess renewable generation, which are most likely due to high wind energy production. The graph also includes a line representing the mean electricity price for that year which provides a consolidated view of the year's electricity pricing trends.

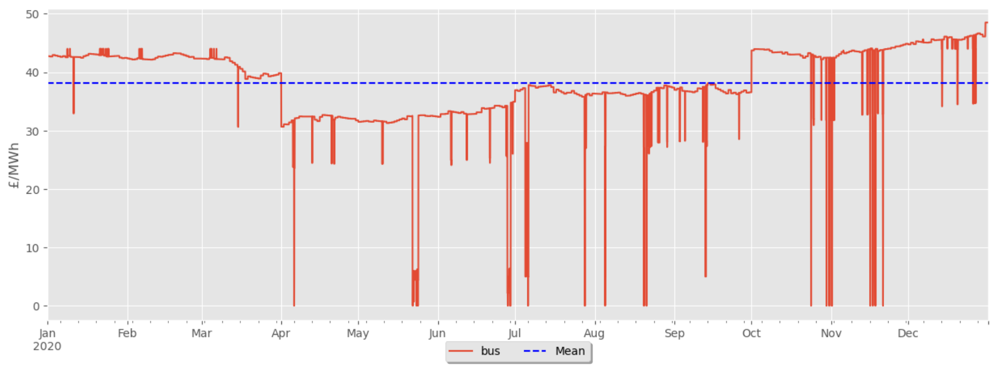


Figure 4: Unified pricing in 2020.

Figure 5 shows the modelled locational electricity pricing in each zone in the UK for 2020. There are increasing periods of zero marginal costs as the locational pricing scheme better reflects the real system impacts of the renewable energy generation which is limited by constraints in the network. These constraints are also reflected by a heightened level of variability compared to unified pricing. The network constraints arise from limits on the transmission network's ability to meet the electrical demand, resulting in locations with excess generation and others with deficits, leading to a more variable price environment.

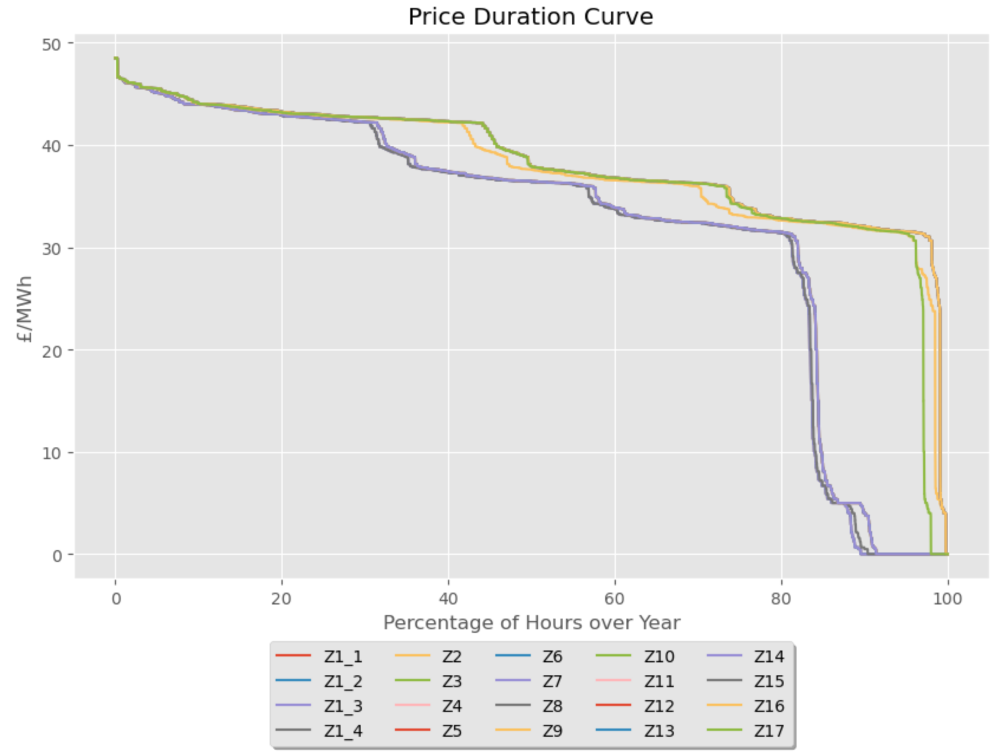


Figure 5: Price duration curve of locational pricing in 2020.

Figure 6 shows the modelled unified marginal electricity pricing in the UK for 2035. Most notably, the instances of zero marginal cost electricity have become more frequent, outnumbering occurrences of above-zero marginal cost. This trend signals an escalating influence of renewable energy sources, notably wind and solar, which, when supply outpaces demand, induce zero-cost prices.

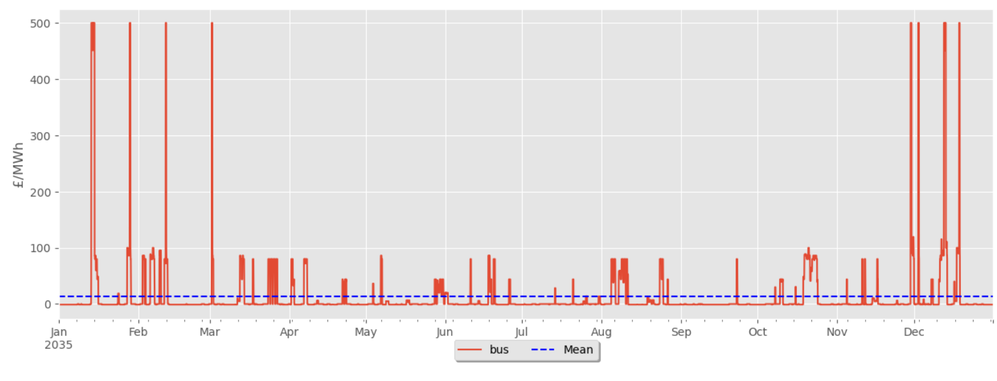
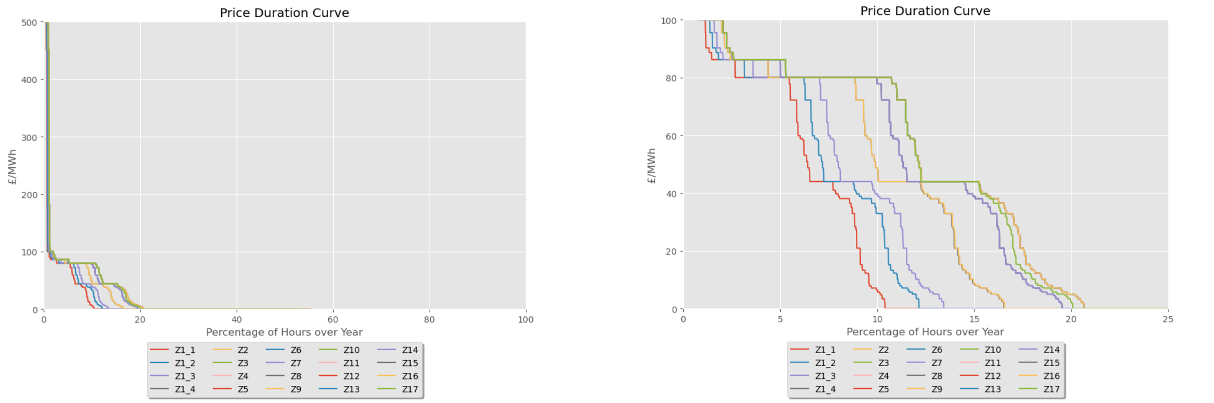


Figure 6: Unified pricing in 2035.

Figures 7a and 7b illustrates the modelled locational pricing for the UK in 2035. There is a growing prevalence of periods where electricity is priced at zero marginal cost, surpassing instances when there is a non-zero price. While the overall trends may resemble unified pricing, locational pricing entails distinct discrepancies in the prices of different zones. This is due to increasing network constraints between zones, and increasing differences between the highest and lowest priced electricity generators.



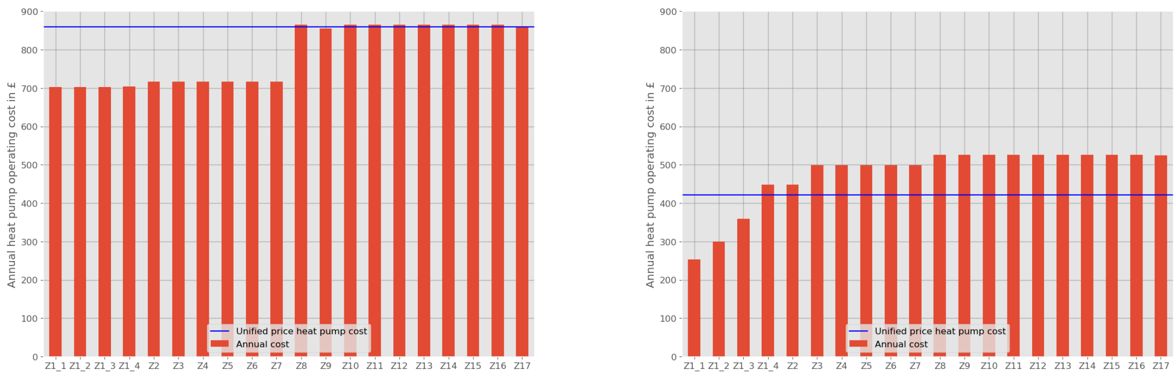
(a) Price duration curve of locational pricing in 2035.

(b) Price duration curve of locational pricing in 2035 - zoomed.

Figure 7: Locational pricing in 2035.

4.2. Individual heat pump operating cost in 2020 and 2035

Figures 8a and 8b illustrate the contrasting heat pump operating costs in 2020 and 2035, displaying a notable difference between zonal and unified pricing schemes. The figures show only the cost of electricity for the heat pumps for a single year (2020 and 2035), and do not include investment costs. The 2020 figure shows that zonal prices are either quite similar to the unified price or exhibit a lower trend in the north part of the network (zones Z1_1 to Z7). This downward adjustment could likely be attributed to the constraints associated with the B6 network boundary. By 2035 there is a more significant locational difference in the operating costs for zones. Heat pumps located south of the B6 boundary have significantly higher operating costs than under unified pricing, while the operating costs in areas above the B6 network boundary is even lower. 2035 electricity prices are also significantly lower than electricity prices in 2020 leading to lower annual heat pump operating costs. This is due to a higher proportion of zero marginal cost generation from renewable power sources, namely wind and solar.



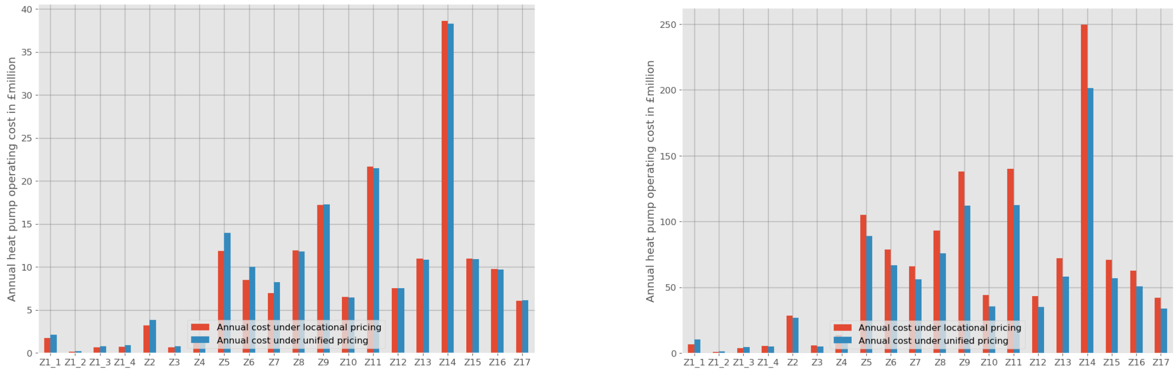
(a) Heat pump operating cost in 2020.

(b) Heat pump operating cost in 2035.

Figure 8: 2020 and 2035.

4.3. System-level impacts of locational pricing on heat pump operating costs

Figures 9a and 9b show the cost implications of unified and locational prices on the system-level heat pump roll out for 2020 and 2035 respectively. Both graphs showcase the total zone heat pump operational cost under unified and locational price schemes side by side. For unified pricing in both 2020 and 2035, the total operational costs of all heat pumps in each zone across Great Britain (GB) is different in each zone, but this is only dependent on the number of heat pumps installed, and therefore the total electrical demand of the heat pumps. These graphs highlight the importance of understanding the interdependence between the zones where the largest number of heat pumps will be installed and the zones where locational pricing will result in different prices compared with unified pricing.



(a) Heat pump cost in each zone in 2020.

(b) Heat pump cost in each zone in 2035.

Figure 9: System-level heat pump cost in each zone in 2020 and 2035 for locational pricing (red) and unified pricing (blue).

5. Discussion

Under locational pricing, heat pump operating costs in Figures 9a and 9b show different costs for each zone reflecting the varying local electricity market dynamics, with greater differences seen in 2035. Lower costs are seen in the north of the network while substantially higher costs are modelled in the south of the network, where there is higher heat pump demand. For 2035 the national annual heat pump operating costs are £1,046 million under unified pricing compared to £1,271 million under locational pricing. A limitation of this analysis is the sole focus on wholesale costs, which is projected to increase under locational pricing under most assessments. This study does not account for the benefits of reduced balancing costs and increased opportunities for flexibly operating heat pumps.

There is a significant increase in prices under unified pricing from 2020 during intervals when there are non-zero marginal costs. This can be ascribed to the projected transition from unabated gas power generation towards technologies such as Carbon Capture and Storage (CCS), hydrogen power plants, grid-scale energy storage systems, and demand-side flexibility. Implementing these methods results in higher operational expenditures which may occasionally lead to substantial increases in marginal costs when there is high demand or insufficient renewable generation. There is large uncertainty in the input data for the marginal cost of these future generators and flexibility technologies, particularly demand-side flexibility which may have lower costs than current forms of thermal power plant flexibility.

The findings from this study indicate potential implications for the rollout of heat pumps in the UK. The fluctuation in operating costs, as shown in figures presenting heat pump costs under unified and locational pricing, suggests that pricing strategy significantly impacts heat pump economics, and hence their viability and attractiveness to consumers. It is important to note that certain areas under locational pricing indicate high operation costs, which could deter heat pump adoption in these regions. On the other hand, regions with low operating costs could see a faster adoption rate. Therefore, it is critical to consider these economic impacts and carefully design policy interventions that can mitigate cost differentials, ensuring an equitable and sustainable transition towards heat pumps across all regions. Policymakers and energy agencies will need to factor in these nuanced effects in their strategies to expedite the heat pump rollout in alignment with the UK's wide-ranging decarbonisation objectives.

The results from the analysis provide substantial insights into the potential impacts of heat pump integration into the electricity system. The high variability in operating costs under locational pricing suggests that the financial feasibility of heat pump adoption could be subject to geographical disparities. Regions with higher operational costs due to net import of electricity might experience slower adoption rates as the economic attractiveness of heat pumps diminishes. Conversely, regions with lower operational costs, courtesy of net exporting conditions, could likely see a more rapid adoption.

Moreover, the results show that pricing fluctuations caused by the locational pricing could necessitate more dynamic operation of heat pumps. This implies that the integration of heat pumps into the electricity system needs to be strategically planned, taking into consideration the potential for locational price-induced usage patterns. For consumers, this could translate into adjusting usage times to periods with lower electricity prices, thereby optimising operating costs and potentially promoting energy efficiency. Future work could include flexibile operation of the heat pump along with thermal storage technologies in the modelling to realise the potential benefits locational pricing can unlock by rewarding flexible operation of heat pumps.

6. Conclusion and Policy Implications

The study has explored aspects of the potential impacts of locational marginal pricing on the adoption and operation of heat pumps in the UK. Key findings reveal that locational pricing could result in significant geographical disparities in operating costs due to varying electricity prices across different zones. Regions with high level of renewable generation often incur lower operational costs, suggesting faster heat pump adoption in these areas. Conversely, regions with net electricity imports may witness slower uptake due to potentially higher operational costs.

This study has set out a methodology capable of exploring the relationship between the wholesale and retail electricity market, locational pricing, and heat pump operations by employing state-of-the-art tools such as PyPSA-GB and innovative retail tariffs such as Octopus Agile. This intersection of energy economics, market design, and technology adoption presents ample potential for further exploration. Future research could delve deeper into customer response mechanisms to varying prices, the socio-economic aspects of the varying costs of heat pump operations, or the development of appropriate policy measures to mitigate negative impacts from high operational costs in certain regions.

The findings of this study carry significant implications for policymakers in the UK, particularly in light of the goal of the large-scale heat pump roll-out for residential heating. While policies encouraging the adoption of low-carbon heating technologies like heat pumps have previously been implemented, including the Renewable Heat Incentive (RHI), these findings suggest the need for more comprehensive approaches that consider the dynamics of the electricity market.

The locational disparities in operational costs due to locational pricing suggest that policymakers should look into geographical differentiation in their assistance programs. For instance, financial incentives or subsidies could be weighted in favour of regions where operational costs are significantly higher, thus ensuring a fair and widespread uptake of heat pumps across the country.

The findings present policy implications within the frame of the Review of Electricity Market Arrangements (REMA). Given the potential of locational pricing to shape consumer behavior and energy usage, measures could be taken to encourage retail electricity providers to adopt dynamic tariff structures like that of Octopus Agile, to better reflect wholesale market dynamics. This could incentivise more efficient and flexible energy usage among consumers in line with the REMA's aim of enhancing consumer engagement and competition in the retail electricity market. It is highly recommended that the next phase of electricity market reform in the UK takes these issues into account.

Furthermore, the results underscore the prospect of network constraints impacting the operational costs for heat pumps. As a response, strategic infrastructure investments could ensure the adequate capacity and resilience of the transmission and distribution networks, thereby curbing potential price volatility due to network constraints.

In conclusion, this paper explores the potential impacts of locational pricing on the roll out of heat pumps in the UK. It highlights that locational pricing has both positive and negative implications for heat pump economics and adoption. Locational pricing can create market conditions which better reflect the true cost of generating and delivering electricity and this can support the wider deployment of heat pumps, however, it can also lead to higher operating costs in certain regions and create uncertainty for heat pump users. This paper emphasises the need for careful consideration of the geographically-dependent economic impacts and consumer-facing challenges of locational pricing. It suggests incorporating strategies to alleviate high operating costs and promoting flexible operation of heat pumps.

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