Energy Strategy Reviews 55 (2024) 101518

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

The importance of heat pump cost reduction and domestic supply chain development in the presence of persisting energy price shocks

Antonios Katris [*], Karen Turner, Christian F. Calvillo, Long Zhou

Centre for Energy Policy, School of Government and Public Policy, University of Strathclyde, McCance Building, 16 Richmond Street, Glasgow, G1 1XQ, UK

ARTICLE INFO

Handling editor: Mark Howells

JEL classification:
C68
L68
Q41
Q43
Q48

Keywords:
Domestic supply chains
Electrification of heat
Energy price shock
Heat pump installation cost
Low carbon heat

ABSTRACT

In this paper we conduct economy-wide scenario simulations to investigate whether and how the wider economic stimulus associated with deploying heat pumps in the UK may help mitigate the macroeconomic and distributional impacts of persistently high electricity and gas prices. Our results show that expansionary processes triggered by producing and installing heat pumps can help offset contractionary pressures associated with higher energy prices. However, outcomes depend on the extent of domestic supply chain content in manufacturing heat pumps, on installation costs to households, on how and where government revenues accrue. Moreover, the relative importance of drivers varies over time. For example, higher purchase and installation costs may support a greater initial stimulus via producer and domestic supply chain gains, despite the greater cost burden on households. However, over time, cost reductions are required to deliver the most favourable economy-wide outcomes.

1. Introduction

The UK Heat and Buildings Strategy [1] lays out the clear ambition of the UK Government to achieve the decarbonisation of residential heating, aligning with the broader efforts to reach the UK Net Zero targets by 2050. The broader objective of heating decarbonisation is to transition residential properties, one of the largest emitters in the UK, away from reliance on fossil fuel-based heating systems, with the plan being to phase out the installation of new gas boilers from 2035. Focus shifts to adopting low or zero carbon solutions, with a strong emphasis on electrifying residential heating via heat pumps, with the ambition of reaching 600,000 heat pump installations per year by 2028 [1].

In addition to its direct effect on reducing residential heating emissions, the heating decarbonisation process is viewed by the UK Government as an opportunity for economic growth [2]. Heat pump adoption is expected to reduce consumer bills via physical energy efficiency gains in electrification,[1] despite the fact that electricity is a high cost energy vector for households, certainly relative to incumbent gas [3]. In the near-to medium-term the heat pump rollout is also expected to stimulate job creation, provide essential support for transitioning existing employment traditionally associated with higher carbon activities, and to foster the advancement of new products, markets, and supply chains within the UK [1].

However, the deployment of low-carbon heating is taking place against a backdrop of high energy prices, particularly for natural gas and electricity, with the price of the latter partly driven by the former due to how gas-powered generation is used to balance supply and demand and determine wholesale prices [4]. Crucially, natural gas is currently the most commonly used heating fuel in the UK (used by 78 % of UK households in 2021 [5]), with electric heating systems expected to replace gas-fired systems in coming decades. The UK Government's 'Green Book'[2] reflects the significant increase in gas and electricity

* Corresponding author. McCance Building, 16 Richmond Street, Glasgow, G1 1XQ, UK.
E-mail address: antonios.katris@strath.ac.uk (A. Katris).

[1] The greater efficiency of heat pumps and the expectation of energy bills savings is echoed across different outputs of the UK Government. For instance, there are relevant points raised in a BEIS news story in relation to the Boiler Upgrade Scheme: https://www.gov.uk/government/news/five-reasons-to-get-a-heat-pump.

[2] The HM Treasury's Green Book is the main guidance tool used by civil servants working at the Treasury to conduct analyses regarding the UK economy. Among key parameters, such as the discount rates, the Green Book includes energy price estimates that civil servants are strongly advised to use in conducting analyses. The Green Book estimates can be found here: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal.

https://doi.org/10.1016/j.esr.2024.101518
Received 14 November 2023; Received in revised form 10 July 2024; Accepted 28 August 2024

prices over the past decade, and the expectation that prices will remain higher than pre-COVID pandemic levels for some time before decreasing again relative to the peaks of 2022 and early 2023 levels. Nonetheless, the price of electricity is likely to remain high relative to gas, with the challenge being the extent to which the gap between the two needs to close for the physical energy efficiency gains associated with heat pump use to offset the monetary difference. Meanwhile, the cost of installing heat pumps, including equipment and labour, is significantly higher than that of gas boilers. Here, the government's goal is to reduce heat pump purchase and installation costs by 25–50 % by 2025 and achieve parity with gas boilers by 2030.

Given the complexity and magnitude of the residential heating electrification, and how both the deployment and use of different heating systems will affect activity levels, income generation and prices across the economy, it is crucial for all parties involved to develop a comprehensive understanding of the broader economic consequences driven by the heat pump rollout. The deployment and adoption of heat pumps is likely to have a variety of intricate and interrelated spending, investment, and price impacts, occurring over different timeframes and involving a combination of infrastructure requirements, as well as the purchase, installation, adoption, and use implications. It is thus essential to consider the potential for broader economic impacts of electrifying residential heating, particularly in the presence of persisting higher energy prices. Crucially, it is key for policy audiences to identify how and where benefits may arise, hopefully to mitigate and not exacerbate the economy-wide impacts of persistent price pressures.

The main objective of this study is to investigate the economy-wide impacts of a widespread electrification of residential heating in the UK, via heat pumps, in the presence of higher electricity and gas prices for a prolonged period. We aim to understand how the heat pump rollout interacts with the persisting higher energy prices in affecting the wider UK economy and whether any benefits emerging from the activity associated with the broader adoption of heat pumps can act to mitigate the negative impacts of persisting higher energy prices. Moreover, we investigate the importance of achieving the UK Government's cost reduction objective and domestic supply chain development ambitions, in determining the potential economy-wide outcomes.

We address these main research questions.

1. How do the persistent electricity and gas price shocks impact the wider economy in different timeframes?
2. Whether, to what extent and how, do the economic activities associated with the heat pump rollout (i.e., required UK electricity network upgrades, alongside the purchase, installation and use of heat pumps) mitigate the adverse impacts of the higher energy prices?
3. What is the role of the projected cost reduction of the heat pumps and of a potentially higher domestic content of heat pump manufacturing, in determining the extent to which the heat pump rollout may mitigate the energy price shock?

The methodology we employ for our analyses is scenario simulation using a computable general equilibrium (CGE) model of the UK economy, informed by energy system analyses (methods detailed in section 3).

In addressing the aforementioned questions, we contribute to existing literature by tackling a pressing policy gap and advancing understanding on how the roll out of heat pumps has the potential to deliver a range of wider economic benefits that could help mitigate the negative impacts of higher energy prices. Ultimately, if households bear the cost of heat pumps, most likely through loan finance, and even if this involves low or no interest, the key implication is an erosion of the benefits emerging from the heat pump rollout. Indeed, the impact on household budgets can entirely offset gains associated with deployment activity in some timeframes; particularly if the cost reductions anticipated by the UK Government do not materialise. Increasing domestic content to feed more value into the UK economy via heat pump and ancillary equipment manufacturing and installation supply chains, can improve the broader economic outcomes in most years, but ultimately the realisation of purchase and installation cost reductions are what drive the best outcomes. However, achieving cost reductions could be challenging in practice, as learning-by-doing gains are mostly effective in the labour cost side of the installations, whereas the equipment cost may require policy interventions to be reduced at the desired levels and may only be achieved if a strong domestic supply chain has been established.

The remainder of the paper is structured as follows. Section 2 considers the foundations and gaps on understanding wider economy impacts of energy price shocks and decarbonising residential heat through shifts to heat pumps. Our integrated scenario simulation modelling approach and underlying data is then outlined in Section 3. Results and key findings are presented and explained in Section 4. Section 5 offers conclusions, policy insights and directions for future work.

2. The existing literature on the energy price shock challenges and economics of electrifying heat

As part of the broader efforts to achieve the UK net zero targets, it is critical to decarbonise residential heating by phasing out new gas boilers and adopting low or zero carbon solutions. The current UK policy focus is on electrifying residential heating via heat pumps. However, the success of this transition is affected by persistently high energy prices, particularly in natural gas and electricity which are at the frontstage of residential heating decarbonisation in the UK.

The literature has extensively explored the relationship between energy price shocks and economic dynamics in various aspects. For instance, He et al. [6] conduct an economic analysis of coal price-electricity price adjustment in China using a CGE model, providing insights into the broader implications for economic performance in the country's various sectors. Zhang et al. [7] investigate the effects of technology and price shocks of mixed energies on China's Energy-Environment-Economy system, offering a comprehensive analysis of the interconnectedness of these factors. Orlov [8] assesses the implications of domestic gas pricing and its interaction with other energy sources for economic outcomes in Russia. Dagoumas et al. [9] explore the link between energy prices, including but not limited to electricity, and growth in the EU. Yagi and Managi [10] examine the spillover effect of the energy price rise spreading across sectors and countries using a monthly input–output model. Kilian and Zhou [11] develop a vector autoregressive model to quantify the impact of various energy price shocks on headline and core CPI inflation, and assess how these shocks contribute to overall inflationary pressures.

Many other studies in this strand focus specifically on exploring the macroeconomic implications of oil price shocks. Baumeister and Hamilton [12] use traditional structural vector autoregressions by incorporating Bayesian inference to study the historical oil price movements, and find that oil supply shock is the main factor affecting energy price and subsequently leading to global activity reduction. Doroodian and Boyd [13] examine the linkage between oil price shocks, economic growth, and inflation in the presence of technological advancements, highlighting the importance of understanding the impact of energy prices on economic variables. Bergmann [14] explores the amplification of causal effects between oil price shocks and GDP growth, focusing on energy shares and their influence on economic outcomes. While Aydin and Acar [15] analyse the long-term economic impact of oil price shocks, Schwark [16] evidences the effects on medium-frequency (8–50 years) business cycles. Dong et al. [17] examines the impacts of oil price shocks due to exchange rate volatility from a multi-regional perspective.

Moreover, some studies investigate the wider economy and environment impact of energy price shocks due to various forms of environmental taxes (e.g., carbon tax) imposed. For example, Ismail et al. [18] develop a hybrid framework using the TIMES/CGE model to simulate a low-carbon pathway where the energy prices impact through the carbon tax. Mardones and Ortega [19] assess the individual and combined impact of environmental taxes on various emission sources as a result of the higher energy use cost in Chile, while Turner et al. [20] explore the implications to the UK economy of implementing a carbon tax on fossil fuels and depending on the labour market conditions and the options employed to recycle the revenue of a carbon tax.

Furthermore, the literature also includes several studies that explore the impacts of wider decarbonisation activities in association with energy price changes. Mu et al. [21] focus on the employment impacts of renewable energy development and electricity price changes in China using a CGE modelling framework, providing insights into the labour market implications of transitioning to renewable energy sources. Esmaeili et al. [22] examine the long-term interaction between the natural gas market, electricity market, and high penetration of renewable energy resources using System Dynamic Approach and Net Present Value method. They also investigate the effect of gas market shock on the behaviour of the whole system and the role of renewable resources in mitigating these adverse effects.

In terms of heat pump rollout linked with energy prices, there is a growing body of literature exploring the potential of heat pumps as a key electrification solution to accelerate and ultimately sustain decarbonisation of residential heating (see reviews [23,24]). Commonly, these studies include techno-economic analyses considering the uptake of heat pumps, with energy prices considered as factors determining the operational performance and economic attractiveness of heat pumps to households. For example, Barnes and Bhagavathy [25] highlight the weakening effect on economics of heat pumps from taxes and levies, which significantly contribute to the electricity price. Deetjen et al. [26] consider the technological advancements of heat pumps, among other factors, to study the costs and benefits of heat pump adoption by US households. Such benefits are commonly attributed to the combined and distinct characteristics of high coefficient of performance (COP), low primary energy consumption and increased overall efficiency of heat pumps [27]. Reflecting the importance of these characteristics, many studies explore the energy consumption and carbon emission reduction by using heat pumps, compared to other competing and incumbent options (e.g., gas boilers) in residential buildings [28–30]. Li et al. [31] investigate the combined effects of macro-economic drivers, climate temperature rise, digitalisation, and system optimisation considering integration of heat pumps, on the end-use demand and final energy consumption in industry, residence, mobility, and service sectors in Switzerland. Also, the heat pump equipment cost and the potential for supply development and cost reduction has attracted policy and industry attention [1] as a way to incentivise uptake and reduce the impact of high energy prices. However, recent evidence suggests that the cost reduction potential in the UK may be limited [32].

In summary, the existing literature provides valuable insights into the economic implications of energy price shocks and heat pump adoption for households. However, the studies in the cross-section of these areas of the literature primarily focus on the role of energy prices in determining the economic feasibility for households considering heat pump adoption as a clean heating alternative. There is therefore a gap in the literature in relation to examining of how energy price levels interact with the rollout activities and the use of heat pumps to determine the broader impacts to the economy driven by the rollout of heat pumps. By addressing this gap, the present study aims to contribute to the broader understanding of the economic implications of large-scale heat pump rollout in the context of price shock of electricity and natural gas, thereby providing valuable insights for policymakers and stakeholders involved in residential heating decarbonisation efforts.

3. Methodology

We use the UKENVI computable general equilibrium (CGE) model of the UK economy (e.g., Refs. [33,34]). CGE models are ideally placed in capturing the economy-wide impacts driven by relative price changes within an economic system. Our work places significant focus on the interaction between a persistent shock on the prices of electricity and gas and the rollout of heat pumps in residential properties, which also triggers economy-wide price responses. Therefore, a CGE model is an appropriate methodological tool to capture the interaction of the emerging price impacts and how they affect the wider UK economy.

We also draw information on the network upgrade requirements and physical energy consumption changes due to the use of heat pumps from Ref. [35] work using the UK TIMES energy system model. The aforementioned analysis captures the changes in energy consumption behaviour as a result of the decarbonisation of residential heating, allowing us to estimate and model the relative changes in household energy bills due to the use of low or zero carbon heating methods and for the relative electricity and gas prices considered here.

3.1. The UKENVI CGE model

The UKENVI model encompasses all sectors and economic activities in the UK, with the UK producers being aggregated into 34 production sectors responsible for producing 34 commodities. Our model is calibrated using a UK social accounting matrix (SAM), incorporating the most recently available UK input-output (IO) tables, for2018[3] [36], which we take as a baseline (year zero) for our scenario simulations, representing the structure of the UK economy with no other changes, including any endogenous technological advancements. This allows us to effectively isolate the impact of heat pump deployment, uptake and associated fuel switching against just one key factor in the economic landscape: the evolution of electricity and natural prices between 2018 and 2030. See Section 3.2 for more details on our scenario simulation approach.

3.1.1. Investment

We assume an endogenous dynamic investment behaviour, with the depreciation and interest rates being exogenously determined and with quadratic adjustment costs. All producers are forward-looking and we assume they have perfect foresight, including full knowledge of all price and demand levels across all time periods. The key implication is that each sector determines the optimal investment pattern to maximise the value of firms, following Hayashi's treatment [37], as the actual capital stock of each sector gradually adjusts to the desired level. When a long-run equilibrium is reached, the actual capital stock matches the desired capital stock, meaning that gross investment only covers the capital depreciation.

3.1.2. Labour market

For this work, we impose a fixed national labour supply, reflecting the existing labour market constraints and the limitations in migration currently in place. The labour supply consists of employed and unemployed workers in the base year (2018), with the initial (full-time equivalent, FTE) unemployment rate being the 4.1 % given by the UK Office for National Statistics.[4] We do not model specific skills and worker competencies, translating to an assumption of perfect mobility of workers between sectors. The real wage is determined by a bargaining function where the real wage rate is inversely related to the unemployment rate [38]:

$$ln[w_R] = \omega - \varepsilon \, ln(u_t) \quad (1)$$

In (1), w_R is the real wage rate, u_t is the unemployment rate in period t, while ε is the elasticity with which wages adjust to changes in the unemployment rate, set at 0.113 [39]. Note that our model does not

[3] Our data statement provides a link to the SAM we use in this study.

[4] The information are extracted by the seasonally adjusted unemployment [43].

require full employment as part of the long-run conditions so that there can be net employment gains or losses in the new equilibrium.

3.1.3. Household consumption

We identify five household quintiles, based on their gross income. The initial income composition and consumption structure is different for each quintile, determined by the data informing our SAM. Contrary to producers, we assume that households are myopic making their consumption decisions based on their disposable income (i.e., after taxes and savings have been deducted from gross household incomes) available each year. We consider this a more representative specification of how households make consumption decisions compared to the alternative where households also have perfect foresight (as we assume for producers) and their consumption behaviour is determined by the future discounted utility of consumption [33].

Across all scenarios considered here, we focus on a likely central case where households cover the cost of heat pumps using their own funds but spreading the cost over time via 10-year interest-free loans.[5] A key assumption is that any loan repayments precede any other consumption, directly restricting the disposable income of households (see Section 3.2 for the specific scenarios considered).

Household spending includes, among other things, the consumption of energy within residences, which mainly consists of electricity and gas and a very limited consumption of coal (less than 0.01 % of total residential energy consumption across all household income quintiles). The household consumption $C_{h,t}$ of each household income quintile is determined via the following equation:

$$C_{h,t} = \left[\delta_h{}^E\left(\gamma_h Ec_{h,t}\right)^{\rho e} + \left(1 - \delta_h{}^E\right) NEc_{h,t}^{\rho e}\right]^{\frac{1}{\rho e}} \quad (2)$$

In equation (2), ε is the elasticity of substitution between the residential energy goods, *EC*, and the remaining goods and services, *TNEC*, consumed by UK households, while δ is a share parameter of the consumption of residential energy goods. Regarding ε, we utilise the elasticity 0.61 utilised by Lecca et al. [31] in their own application of the UKENVI CGE model. For the purpose of our work, the efficiency parameter of energy consumption, γ, is the parameter we shock to simulate the impacts of the use of heat pumps on household energy bills.[6]

3.1.4. Government and trade

Real government spending is exogenously determined and fixed, with nominal spending adjusting with the changes in the government price index and the broader CPI. We do not impose a balanced government budget requirement, so that we can identify how the higher energy prices and the broader heat pump rollout affect the government budget balance position in different timeframes.

The UK trades with a single, rest of the world (ROW), external region. Exports and imports are sensitive to changes in the relative domestic and foreign prices, noting though that foreign prices remain fixed across all timeframes. Thus, export demand is inversely related to domestic prices, where we assume a default export price elasticity of 0.1 in the constant elasticity of transformation (CET) function that we use to model exports. This low elasticity value was selected to represent the fact that industries across the world, and especially in the trade partners of the UK, are likely to face similar energy-driven price pressures,[7] meaning that there may be smaller export impacts driven by the energy price shock.

Regarding imports, UK producers and consumers use a combination of domestic and foreign goods and services, which are considered as imperfect substitutes [40]. Our default Armington elasticity is 2.0. We note that as we treat the ROW region as external, we do not model the production of imported goods and services. This is particularly relevant for our scenarios as we only model the spending on imported heat pump equipment and not its manufacturing in the external region.

3.1.5. Closure block

In summarising the points previously made in relation to the closures used in our model, when the economy reaches its new long-run equilibrium the actual capital stock matches the desired capital stock for all sectors. There is no net investment in any sector and the gross investment is only sufficient to cover the capital depreciation. There is no need for full employment so the, fixed, labour supply is composed of employed and unemployed labour, allowing for net employment losses or gains. The wage rates are determined by the wage bargaining process described by equation (1). The government budget is not required to be balanced so there can be government budget savings or deficit. Finally, we do not impose a trade balance with the external region.

3.2. Simulation strategy

3.2.1. Setting the baseline

The starting point for our analyses is to explore the impacts of higher electricity and gas prices on the UK economy; that is to adjust our baseline to incorporate this likely important factor. For this purpose, we use the historical prices and the future price estimates included in a supplementary document to the HM Treasury's Green Book.[8] The data include different ranges of electricity and gas prices, but we have opted to focus on the highest estimates for both electricity and gas to avoid overestimation of the potential (partial) offsetting impacts of the heat pump deployment. Our model includes a single output price for each domestically produced good and service, including electricity and gas, which is applicable to every consumer. Similarly, there is a single price for each imported commodity, and therefore for electricity and gas. Hence, we calculate the weighted average of the different user prices reported in the Green Book.[9] Table 1 summarises the resulting evolution of electricity and gas prices used in our scenario simulations to identify how the evolution of electricity and gas prices affects the wider UK economy.

It is important to reiterate that we do not attempt to forecast what the

[5] UK Government and devolved nations offer both grants and/or interest free loans as the main policy support mechanism to promote heat pump uptake (see for example: https://www.mygov.scot/energy-saving-grants). However, the current budget allocated for grants is limited and may not be enough to support a widespread heat pump uptake. Consequently, we have considered interest free loans as the main repayment method for our analysis.

[6] Note here that within the residential energy consumption nest, we have set the elasticity of substitution away from coal as a residential fuel at the lowest level possible, 0.11, meaning that any efficiency changes almost exclusively affect the use of electricity and gas.

[7] Gas is a globally traded commodity so it is expected that consumers across the world will face similar prices. In terms of the electricity price, the source we use to inform our scenarios takes into consideration both the domestic electricity production cost and the cost of electricity imports to determine the electricity price in different timeframes. Therefore, it is necessary to assume that electricity prices, at least in the close trade partners of the UK will be comparable, but not necessarily identical, to the prices faced by UK electricity users, at least at basic prices.

[8] Specifically, we used data provided in the Green Book 'Supplementary Guidance: Valuation of Energy Use and Greenhouse Gas Emissions for Appraisal'. The document is developed by the UK Department for Energy Security and Net Zero, and as we understand, the price projections consider recent price hikes as a result from the war in Ukraine and other geopolitical factors. These projections can be found at: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal.

[9] This involves using the 'Energy Consumption in the UK: Final Energy Consumption' tables in the statistical output found at: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2022 to assign a weight to each of the prices. Because the energy consumption is reported in kilo tonnes oil equivalent, we use a conversion factor of 11.63 to convert to kWh.

Table 1
Summary of electricity and gas prices used to simulate higher energy price period.

		2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Electricity price (p/kWh)	**Domestic**	19.33	20.68	19.71	21.32	30.73	41.70	73.16	69.15	25.15	22.59	22.00	21.97	21.86
	Commercial	13.24	13.52	13.34	14.38	52.35	69.87	52.09	16.85	14.32	14.02	13.67	13.79	13.73
	Industrial	10.87	11.63	11.50	13.10	49.88	67.19	49.55	14.91	12.98	12.82	12.52	12.70	12.65
	Average	14.65	15.48	15.28	16.70	43.51	58.52	59.17	35.78	17.95	16.85	16.42	16.51	16.43
	% change to base year		5.66 %	4.29 %	14.01 %	196.95 %	299.40 %	303.87 %	144.24 %	22.51 %	15.00 %	12.10 %	12.68 %	12.15 %
Gas price (p/kWh)	**Domestic**	4.75	4.82	4.18	4.14	7.36	11.30	19.90	18.66	8.19	8.17	8.10	8.07	8.04
	Commercial	3.00	2.80	2.53	3.26	16.16	24.05	16.31	6.23	6.23	6.22	6.21	6.21	6.20
	Industrial	2.08	1.86	1.61	2.69	15.65	23.66	15.74	5.45	5.45	5.45	5.45	5.46	5.45
	Average	3.87	3.80	3.35	3.68	10.69	16.21	18.38	13.63	7.26	7.24	7.21	7.18	7.16
	% change to base year		−1.83 %	−13.41 %	−4.93 %	176.04 %	318.30 %	374.30 %	251.84 %	87.44 %	86.99 %	85.99 %	85.41 %	84.85 %
Electricity: Gas ratio	**Domestic price**	4.1	4.3	4.7	5.2	4.2	3.7	3.7	3.7	3.1	2.8	2.7	2.7	2.7

evolution of the UK economy may be in the years until 2030 as this would make isolating the causal effects of our hypothesised key interacting drivers of energy prices and the heat pump rollout overly complicated to compute and interpret. Instead, we aim to create a baseline, informed by government assumptions regarding electricity and gas prices, against which we can compare the heat pump roll out scenarios described below, with the aim of exploring the extent to which the heat pump rollout can help mitigate the negative pressures of longer-lasting higher energy prices in different timeframes.

In Table 1 we also report the evolution of the ratio between the domestic prices for electricity and gas. This has key implications for the energy bills of households switching to heat pumps. We have determined that, under our default assumptions regarding the physical energy efficiency of heat pumps, a price ratio of 3.59:1 is the point at which heat pumps have the same operating cost as gas boilers (i.e., the breakeven point), with smaller ratios leading to energy bills savings and vice versa (see Appendix B for a detailed description of how we model the use of heat pumps).

3.2.2. Scenario description: simulating the heat pump rollout

We consider what may be referred to as the enabling and realising stages [41] of the heat pump rollout. In terms of the former, we model the necessary network upgrade and the UK manufacturing and installation of heat pumps. The latter focusses on the use of heat pumps by UK households. For simplicity, in this analysis we do not extend to consider how the network upgrade costs may be recovered. This abstraction is motivated by the recent RIIO-ED2 final determinations[10] by Ofgem [42], Great Britain's energy market regulator, specifying a priority on delivering efficiency improvements through the upgrade of the electricity network, thereby enabling, where possible, the investment on the infrastructure to be implemented without increase in the network charges in bills. This being the case, any cost recovery analysis may not be relevant; alternatively, focussed refinements to our scenario simulations would be required.

Appendix B details how the heat pump rollout is layered in our simulations and details the assumptions included in each layer. Here, we discuss the main assumptions and variations thereof so that the reader can follow the presentation and discussion of the findings of our work.

Our central assumption is that the cost of heat pumps is covered directly by UK households via interest-free loans that allow them to spread the cost over 10 years. The latter means that the loan repayment period concludes after the end of the heat pump rollout.

As part of our central scenario (Scenario 1) we also assume that the average cost of purchasing and installing a heat pump starts at £11,810, with the installations performed by UK companies. However, Scenario 1 assumes that only 25 % of the heat pumps and 50 % of the ancillary equipment is manufactured by UK industries, meaning that just 58 % of the total spend is directed to the UK economy. From 2028 onwards, the cost is reduced to £7,351, reflecting the UK Government's ambitions to reduce the cost of heat pumps. The cost reduction is derived by a 30 % reduction in the cost of heat pumps and ancillary equipment and a 50 % reduction in the installation cost. The implication is that, after the cost reduction, 54 % of the total spend is now directed to the UK economy. Table 2 summarises the different assumptions in each scenario.

The scope of our analysis here is to explore how varying different assumptions regarding the heat pump cost and supply chains can influence the economy-wide impacts associated with the heat pump rollout, and, thus, the associated potential to mitigate the negative pressures of other economy-wide shocks, such as the higher energy prices we focus on here.

In Scenario 2, we focus on the assumption that the cost of heat pumps will be reduced over time. We assume that the ambition to bring down the cost is not achieved, meaning that the cost of purchasing and installing a heat pump remains fixed across the duration of our simulation. This has implications on the spending directed to UK sectors but also on the size of loan repayments over time.

In Scenario 3, we assume that instead of heavily relying on imported equipment (heat pumps and ancillary equipment), a strong domestic supply chain emerges that can support most of the demand by UK households. However, this is achieved at the expense of consistently higher heat pumps costs. We do explore an alternative though, in Scenario 4, where a strong domestic supply chain emerges, and a heat pump cost reduction is achieved.

In all scenarios, the only parameters changing are the ones discussed above, meaning that the evolution of electricity and gas prices, the network upgrade requirements, as well as the impact of heat pump use on households' energy bills remain the same across all scenarios. This is motivated by the need to isolate the implications of the changes implemented in each scenario and to identify the drivers of the economy-wide results affected by each change.

4. Results

4.1. The impacts of higher electricity and gas prices

As a starting point for our analyses, we explore the impacts on the UK economy of higher electricity and gas prices. As seen in Table 1, since 2018 (the base year of our model) the electricity price has been continuously increasing and is expected to remain above the 2018 levels at least until 2030, when the projected higher energy price period ends. Similarly, despite a small price reduction before 2022, the price of natural gas is, and is expected to remain, considerably higher compared

[10] RIIO stands for 'Revenues using Incentives to deliver Innovation and Outputs' and it is Ofgem's electricity distribution (ED) price control mechanism, to regulate distribution networks revenues and covers 5 year periods. The provisions mentioned are highlighted in pages 12 and 13.

Table 2
Summary of scenarios considered in the paper.

	Starting costs (% share to UK sectors)	Scenario 1: Central case (% share to UK sectors)	Scenario 2: Unchanging prices (% share to UK sectors)	Scenario 3: High domestic content - high price (% share to UK sectors)	Scenario 4: High domestic content - low price (% share to UK sectors)
Heat pumps	£3760 (25 %)	£2632 (25 %)	£3760 (25 %)	£3760 (75 %)	£2632 (75 %)
Ancillary equipment	£4370 (50 %)	£3059 (50 %)	£4370 (50 %)	£4370 (70 %)	£3059 (75 %)
Installation cost (labour)	£3680 (100 %)	£1840 (100 %)	£3680 (100 %)	£3680 (100 %)	£1840 (100 %)
Total Upfront Heat Pump Cost	£11,810 (58 %)	£7531 (54 %)	£11,810 (58 %)	£11,810 (83 %)	£7531 (81 %)

to 2018. Both electricity and gas prices are expected to peak in 2024, with a gradual de-escalation beyond that point.

The main implication of increasing electricity and gas prices is that they are, especially electricity, key inputs of all production sectors within the UK economy. Hence, increased electricity and gas prices introduce upward pressures on the prices of all goods and services produced by UK sectors. For instance, in 2024 (year 6 of our simulations) where the largest price impacts are observed, the UK CPI is increasing by approximately 10.6 % compared to the 2018 levels, reflecting to some extent the widespread increase in output prices across most UK sectors. This increase in production costs has negative implications for the competitiveness of UK sectors both in domestic markets, where there is an increased drive to use cheaper imported alternatives where possible, and in international markets which are evident in the approximate 0.3 % drop in total UK exports in 2024 (i.e. domestic products are less competitive internationally, therefore, there is less demand from UK products and services from the rest of the world).

Besides their effect on the prices of other UK sectors, electricity and gas are also among the goods and services that UK households, especially those on lower incomes, spend a considerable share of their disposable income. Therefore, the increased electricity and gas prices effectively limit the real disposable income of households. This combines with a contraction in export demand for UK outputs to trigger an economy-wide reduction in the demand for the output of UK sectors, leading to broader negative economy-wide outcomes. Fig. 1 demonstrates the evolution of the UK economy, influenced by the higher energy prices.

It is clear from Fig. 1 that the sustained, particularly in the case of electricity, increase in energy prices drives a wider reduction in the UK GDP that broadly follows the evolution of the energy prices. Even as the price increases start de-escalating and the high price period ends after 2030, it takes over 20 years before the economy returns to its original (here 2018) levels. Although we report GDP impacts in Fig. 1, the same pattern can be seen for other key macroeconomic variables such as employment, household consumption and exports. This raises the question then, to what extent is it possible for the heat pump rollout to ease some of the negative pressures driven by the higher energy prices?

4.2. Heat pump rollout in the presence of higher energy prices

The increased electricity and gas prices have a clear negative impact on the UK economy, reflected in temporary GDP losses of up to −3.9 % in 2024, driven by the lower household spending power and competitiveness losses of UK industries, both domestically and internationally (less exports, more imports of goods and services). For a single net zero action to be able to completely offset these negative pressures, it would be necessary to address the root cause of the negative pressures, i.e., the higher electricity and gas prices. Alternatively, generating sufficient activity in the UK economy to offset the GDP losses could also aid in significantly mitigating some of the associated economy-wide impacts such as losses in employment and household consumption. Reducing the market prices of electricity (or gas) is not among the aims of the heat pump rollout. Rather the investment activity in deploying heat pumps and energy efficiency gains in use can affect activity levels and affordability, which can help mitigate some of the effects of the persisting energy price shock. In terms of the former (enabling) activity, despite the total value of activity of up to approximately £120 billion, this is spread over 28 years with only a small part spent over the first years of the heat pump rollout (around £16 billion by 2030).

Enabling the rollout of heat pumps, requires not only the manufacturing and installation of the equipment but also the upgrade of the electricity network so that it copes with the increased electricity demand. Alabi et al. [34] have demonstrated that upgrading the UK electricity network can provide a stimulus to the economy, even when a significant part of the spending is directed abroad (and even in the context of the extreme of full cost recovery through energy bills that we do not consider here).

Fig. 2 demonstrates that the rollout of heat pumps can help improve the picture compared to our baseline. In the case of heat pump manufacturing and installation, the construction activity associated with installing the new residential heating systems accounts for the largest share of the spending directed to UK sectors, though there is also some manufacturing of the necessary equipment delivered by UK industries. In that context then, it is to be expected that the activities required to switch residential heating from gas boilers to heat pumps has the potential to provide a stimulus to the UK economy.

As expected from Fig. 1, the effect of the heat pump rollout is limited; the negative GDP impacts of the higher energy prices are eased by 0.037 % in 2024 and as the higher energy prices subside the improvement compared to the baseline increases to 0.044 % in 2030.

The potential mitigation of the energy price driven negative impacts could have been bigger in the absence of different factors that affect the household consumption of non-heat pump goods and services. The main one of these is the requirement for households to repay the loans used to cover the heat pump installation cost. As more heat pumps are installed more households start repaying their loan, restricting the amount of income they have available to spend on goods and services other than heat pumps. Set in the context of a significant share of the spending on heat pumps being directed abroad, the impact of the loan repayment is sufficient to drive an overall reduction of household consumption with negative implications for activity and employment across the economy.

Compared to the baseline adjusted for higher energy prices (see Fig. 2), the losses in household consumption are further aggravated by the higher economy-wide price levels that emerge as increased activity associated with the heat pump rollout takes place in the context of the national labour supply constraint and associated wage bargaining. The use of the more efficient heat pumps helps deliver average household energy bills savings of up to 9 % by 2050 and beyond. However, these only start manifesting from 2026 onwards, and at a very small scale (of 0.02 %). This is because before 2026 the electricity:gas price ratio is such that makes heat pumps more expensive to run compared gas boilers, further eroding household consumption in that timeframe. Ultimately, though, the heat pump rollout is sufficient to improve the position of the UK economy compared to our baseline, even during the 2035–2046 period when household consumption drops compared to our, energy price adjusted, baseline (see Fig. 2).

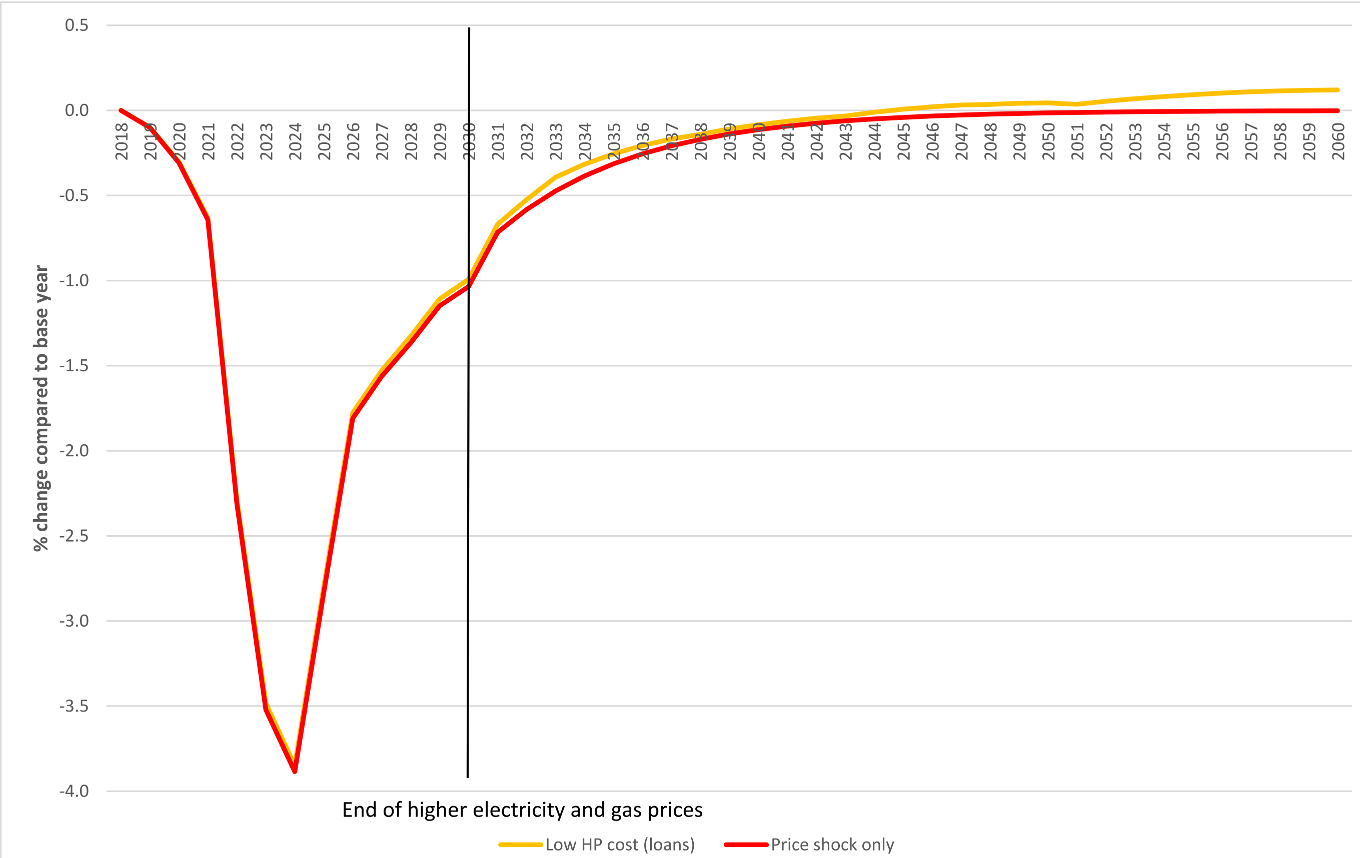

Fig. 1. Impact on UK GDP due to long-lasting higher prices of electricity and gas prices until 2030.

4.3. What if the cost reduction does not materialise?

A fundamental assumption of our central scenario (Scenario 1) is that from 2028, when a total of over 613,000 heat pumps has been installed, there is a significant cost decrease in all the components of the heat pump installation. Specifically, the total installation cost is reduced by over 36 %, well within the ambitions highlighted in the UK Heat and Buildings Strategy [1]. However, the strategy does not specify how these cost reductions will be achieved. Moreover, as most of the necessary equipment is imported, controlling the price levels is largely beyond the government's control. Thus, it is reasonable to consider a case where the government's cost reduction ambitions are not achieved, with the heat pump cost remaining fixed across the entire rollout period (Scenario 2).

Our analysis indicates that in some timeframes, including the period of higher energy prices, a consistently higher heat pump cost may be beneficial to the UK economy (see Fig. 3). There are two factors leading to this somewhat counterintuitive finding. First, higher cost means higher overall value of activity associated with the heat pump manufacturing and installation and therefore higher value-added generation. Second, the higher price is also associated with higher share of activity directed to the UK economy (please refer to Table 1), driving greater job creation and by extension activity in sectors not directly involved in the manufacturing and installation of heat pumps.

Still, any favourable outcomes observed under higher heat pump costs are temporary. As loan repayments start accumulating, the higher heat pump price means that households face larger instalments, and therefore higher restrictions in their disposable income, compared to the case where the cost of heat pumps eventually falls. Effectively, from 2034 onwards, the level of household consumption plays a more significant role in determining the economy-wide outcomes of the heat pump rollout. With a larger drop in household consumption under a consistently high cost of heat pumps, this is sufficient to overshadow and completely erode any gains emerging due to the additional activity that said higher heat pump cost coincides with. It is clear from Fig. 3 then that delivering on the cost reduction ambition can be beneficial across most timeframes, even if this means missing out on some potential benefits during the initial stages of the heat pump rollout.

4.4. The implications of establishing a strong domestic heat pump supply chain

A pattern emerging from our analyses is that, eventually, the restrictions introduced to the household consumption by the need to repay loans lead to varying degrees of erosion of the potential economy-wide gains from the heat pump rollout. A common denominator is the fact that a significant share of the heat pump manufacturing activity is taking place outside the UK, meaning that essentially covering the cost of heat pumps leads to an overall reduction of the household consumption, instead of only restricting the substitution possibilities. This raises the question: how would the potential outcomes be different if there was a stronger domestic supply chain?

Currently, approximately 75 % of gas boilers are manufactured by UK industries.[11] We consider an alternative case where the industries manufacturing heat pumps and ancillary equipment, have the capacity to meet the same share of UK demand as the gas boiler manufacturers. However, this introduces an uncertainty over what the price of the heat

[11] This is according to a 2020 Eunomia report for the Department for Business, Energy and Industrial Strategy (BEIS), taking into consideration the different manufacturing locations of UK firms. At the same time though, there are certain areas that remain off the gas grid. The report is available at: https://www.gov.uk/government/publications/heat-pump-manufacturing-supply-chain-research-project.

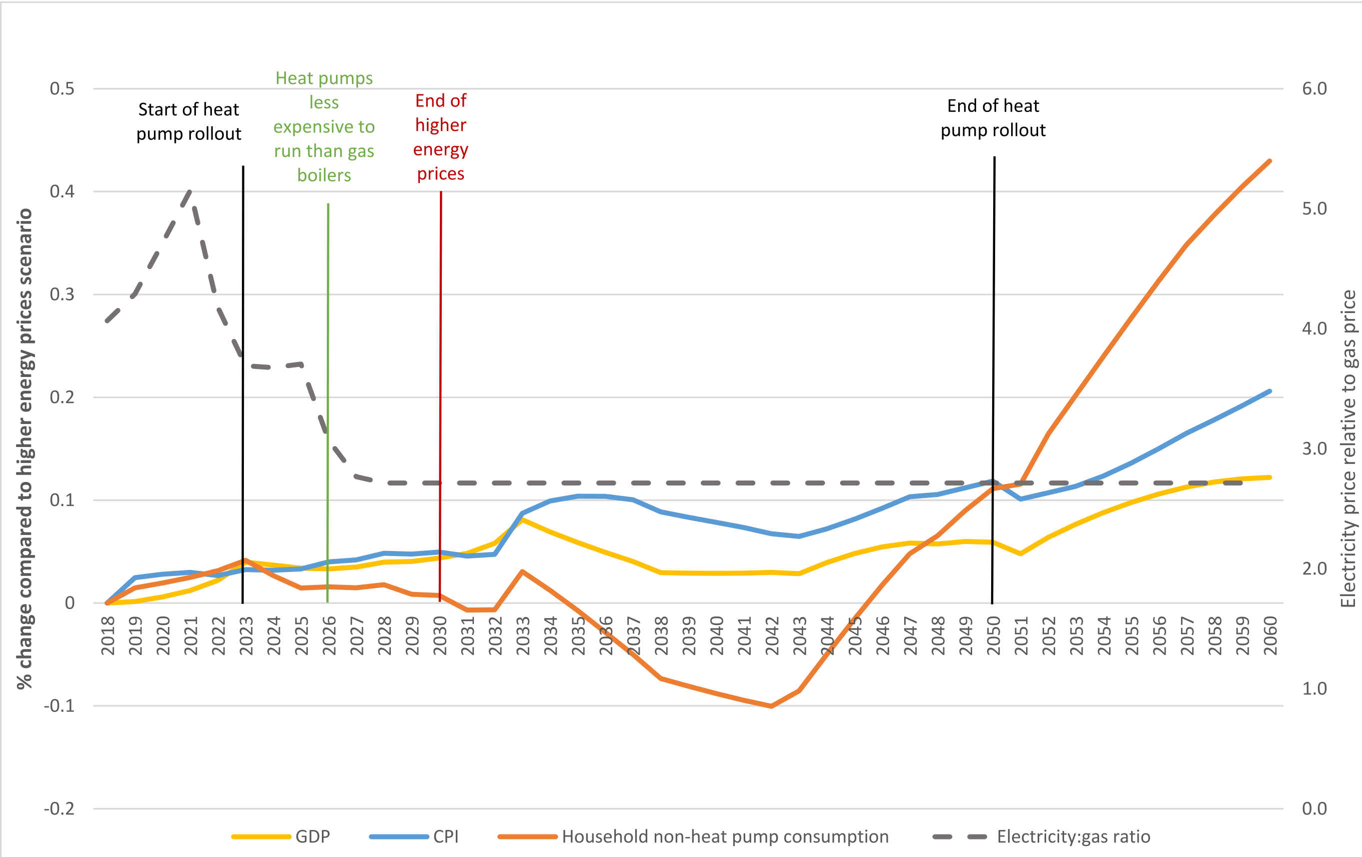

Fig. 2. Impact on key macroeconomic indicators due to rollout of heat pumps paid for via interest-free loans (central case).

pump installations may be. In the first instance we assume that the greater domestic content in heat pump installations is achieved at the expense of consistently high heat pump cost (Scenario 3).

Fig. 4 demonstrates the evolution of the UK GDP under different assumptions regarding the domestic content and the cost of heat pump installations. We can see in Fig. 4 that the high volume of domestic content and the comparably higher value of manufacturing and installation activity enable the best economy-wide outcomes in some timeframes, including the period of high energy prices (until 2030). High domestic content, even with consistently high installation cost, could ease the negative GDP pressures of the higher energy prices by 0.077 % in 2024 (instead of 0.037 % in our central case) and the mitigation increases to 0.12 % by the end of the high price period in 2030. This increase in economy-wide gains is driven by the additional manufacturing activity that in turn creates employment opportunities and allows the overall retention of more jobs and household wage income generation in the wider UK economy.

For instance, the latter, under our high domestic content assumption, is increased by over £0.84 billion compared to the baseline in 2024 and by over £1.2 billion in 2030, when in our central scenario we observe household consumption increases of £0.31 billion in 2024 and £0.09 billion in 2030 compared to the baseline.

The challenge is that despite the increased manufacturing activity, the compounding loan repayments start eroding the gains that the manufacturing and installation activity drive, to the point that beyond 2036 we observe reduced household consumption compared to the baseline. This loss in domestic consumption explains the steady decline of the economy-wide gains, which is further compounded by the gradual decline of heat pump installations from 2038 onwards. Eventually, the high domestic content case delivers less favourable economy-wide outcomes if the installation cost remains high, compared to the case where there is a lower cost but a greater reliance on imports. This radical switch in the economy-wide impacts is further escalated by the fact that beyond the end of rollout period there is a larger sum of loan instalments to be repaid if the installation costs remain high, compared to the case where the installation cost is reduced.

These findings reinforce the importance of reducing the installation cost of heat pumps. They imply that, in an ideal scenario, there would be a strong domestic supply chain for heat pumps and ancillary equipment, while reducing the installation cost from 2028 onwards. This is what we now explore in Scenario 4.

Examining the results in Fig. 4 we can see that over the entire heat pump rollout period (until 2050) a high domestic content with a low price after 2028 delivers better economy-wide outcomes compared to the central case of Scenario 1. This is to be anticipated as the restrictions on household income are identical, but with the presence of a strong domestic supply chain means that the level of activity directed to the UK economy is significantly higher. On the other hand, where we eventually have a smaller installation cost in Scenario 4, we observe smaller gains in the first half of the rollout period compared to Scenario 3 where the installation cost remains fixed throughout the simulations. This is a factor of our assumption of perfect foresight across UK producers (see Section 3.1). In Scenario 3 this means resources are allocated in such a way that that UK producers take advantage of the increased manufacturing activity and household consumption in the early years of the heat pump rollout period, before they start declining after 2036. On the other hand, in Scenario 4 producers anticipate the reduced value of manufacturing and installation activity but also the less steep decline in household consumption, leading them to spread resources more evenly across the entire rollout period.

Effectively Scenario 4 highlights the benefits of developing a strong domestic supply chain while also achieving cost reductions. It is a

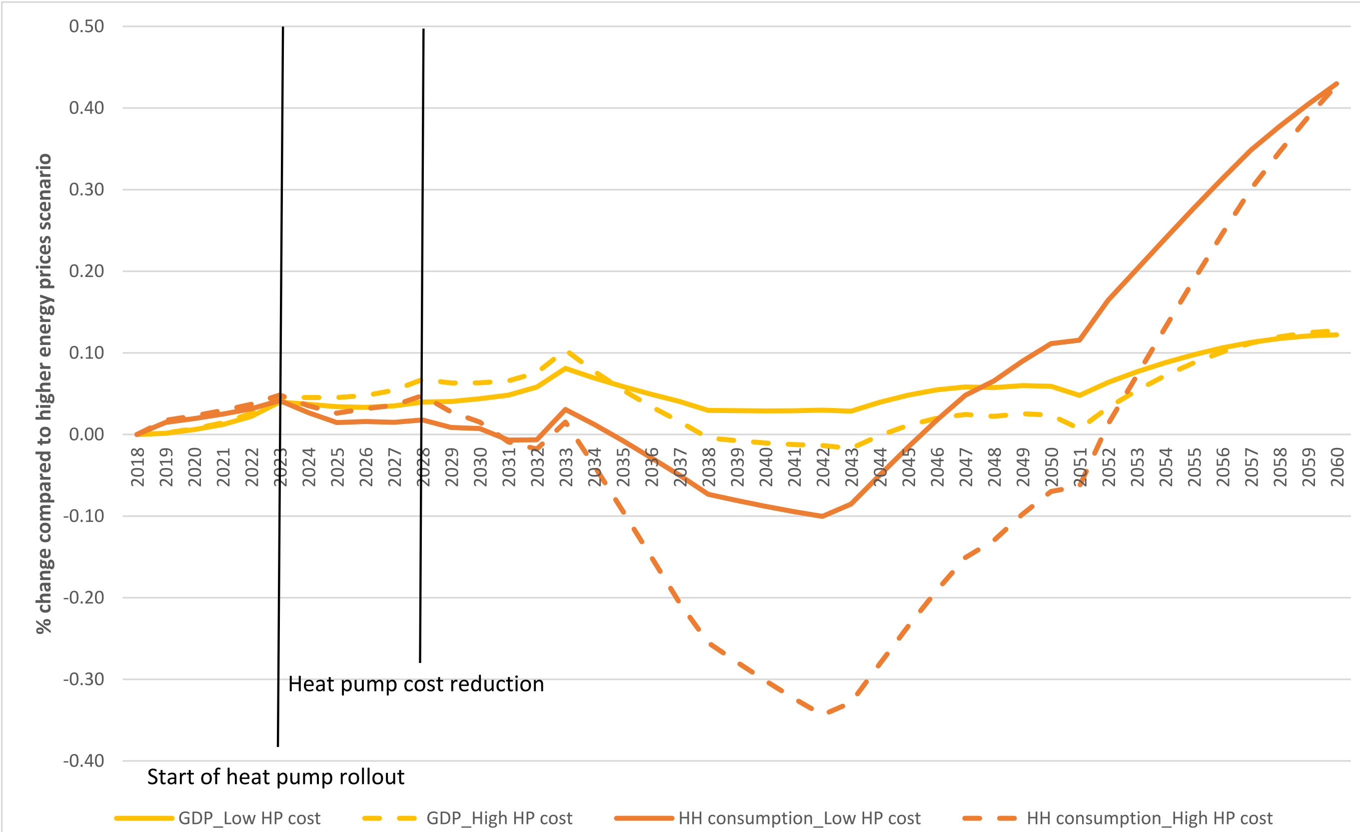

Fig. 3. Impact on UK GDP and household non-heat pump consumption due to switch from gas boilers to heat pumps for residential heating services - different installation costs.

favourable scenario if a desirable outcome is to achieve favourable economy-wide impacts across all timeframes, even if that means that there may be some missed opportunities for greater gains in some time periods. However, achieving the expected cost reduction may constitute a significant challenge. The cost of labour element of the heat pump installations - focusing here on the Construction sector activity required to install a heat pump system -could be reduced through some kind of learning-by-doing process. As more installations take place, qualified installers become more proficient so that, in principle, it is possible to reduce the time and number of workers required to complete an installation, thereby reducing labour costs. If a similar learning-by-doing process was to be applied to the manufacturing of heat pumps and ancillary equipment, it would require that the sectors involved more than double both their labour and capital efficiency simultaneously. This could introduce significant challenges in bringing the equipment costs down to the desired levels, so in practice it may be necessary for the government to introduce different cost reduction measures such as tax breaks.

5. Conclusions

We started by exploring how the persistently higher electricity and, in most years, gas prices affect the UK economy, and find that the outcome is the introduction of negative pressures across the economy. This is due to rises in household energy bills and, more widely, to extensive increases in the price of output all sectors, which reduces competitiveness in both domestic and international markets. Introducing a widespread rollout of heat pumps for residential heating purposes has the potential to ease some of the negative pressures to the UK economy, even where households have to finance heat pump purchase and installation costs, here, via interest-free loans.

A key parameter determining the extent in which the heat pump rollout will mitigate the negative effects of higher energy prices is the evolution of the heat pump installation cost. We find that a consistently high installation cost can deliver some temporary larger scale economy-wide gains, especially during the high energy price period, as it leads to greater value of manufacturing and installation activity and, crucially, greater retention of said activity by UK sectors. Eventually though, reducing the installation cost leads to better outcomes in the later parts of the rollout period and beyond. This is because it limits restrictions on household disposable incomes and, thus, household consumption expenditure. Ultimately, maximising the economy-wide gains associated with the heat pump rollout requires establishing a strong domestic supply chain. Still the timing and magnitude of the economy-wide gains depends on the evolution of the installation cost, with consistently high cost driving higher gains upfront and over time reduced installation cost leading to a more even distribution of the economy-wide gains. Still, we find that achieving reductions in installation costs via learning-by-doing gains alone may be challenging, particularly in relation to reducing the cost of the necessary equipment. This being the case, targeted policy interventions may be necessary to support the desired cost reduction.

This work should be regarded is an early level analysis of the heat pump rollout under persistent higher electricity and gas prices, where we make some simplifying assumptions to facilitate identifying the drivers of the emerging insights. For instance, we assume a single approach in covering the installation cost, applied to all households. In practice, it is likely that a combination of different instruments will be used to support the rollout of heat pumps, perhaps including the provision of grants to those least able to afford the installation cost. Each funding approach will have its own implications and it is worth exploring how the emerging results are affected by the funding mechanism. We also highlight how, in order to achieve the desired cost reductions, targeted government intervention may be necessary. However, depending on the type of intervention there will also be

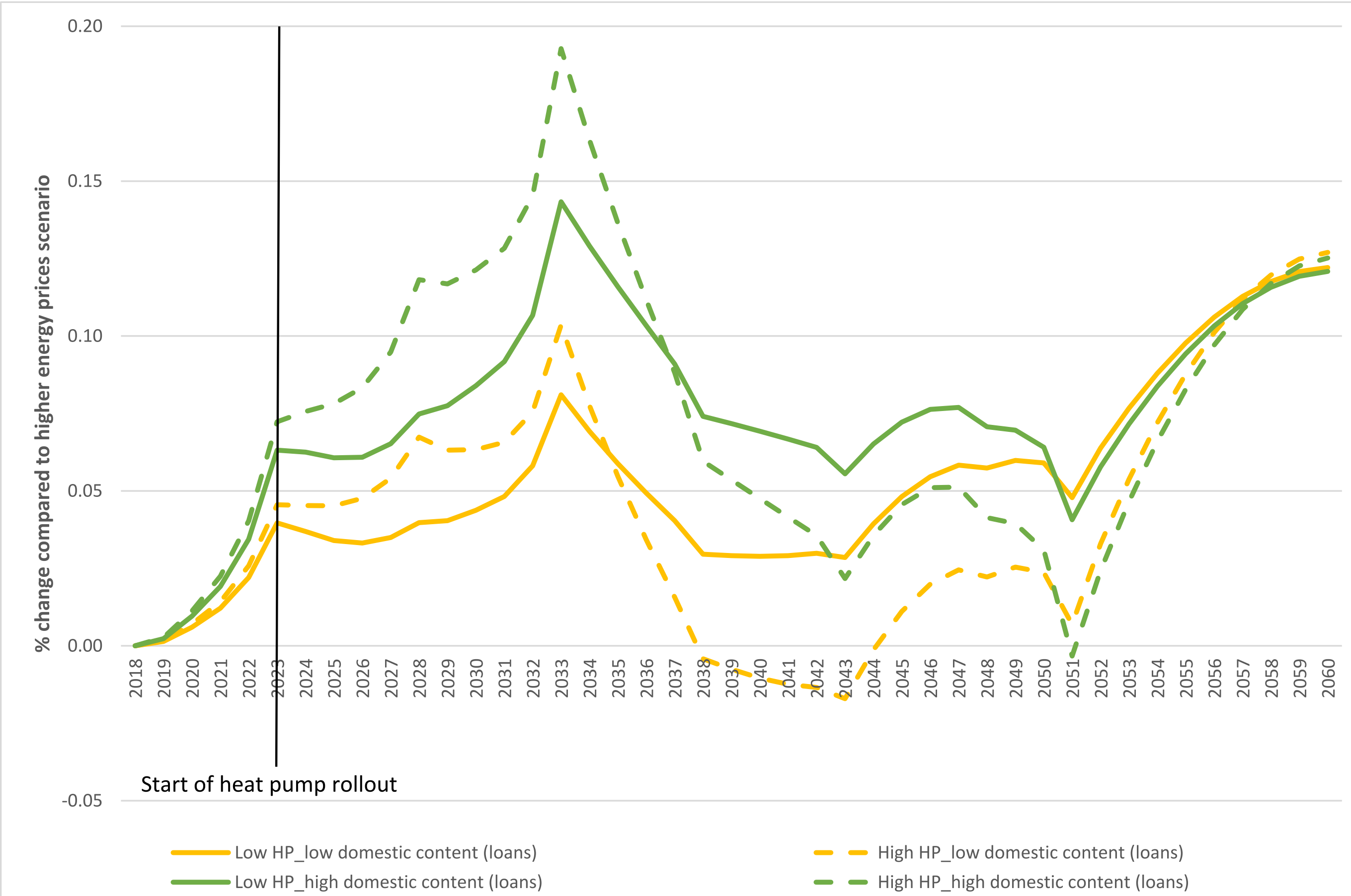

Fig. 4. Impact on UK GDP due to switch from gas boilers to heat pumps - different heat pump cost and domestic content scenarios.

implications for the wider economy that are worth exploring. Furthermore, we use a specific aggregation structure that does not take into consideration how the characteristics of the sectors manufacturing heating equipment may change if their production switches towards heat pumps and ancillary equipment. This consideration could be beneficial for future analyses. Finally, here we assume full participation in the decarbonisation of residential heating, while in practice some level of inertia and/or pushback from homeowners who do not wish to make such a radical change on how they heat their properties should be expected. Identifying the factors governing homeowners' attitudes and behaviour towards heat pumps and how each of these factors may affect the expected economy-wide outcomes of decarbonising residential heating is another key area for future research.

Funding

This research was undertaken as part of the UK Energy Research Centre research programme. Funded by the UK Research and Innovation Energy Programme under grant number EP/S029575/1. For the purpose of Open Access, the authors have applied a CC licence to any Author Accepted Manuscript (AAM) version arising from this submission.

Data statement

The model used in this study is calibrated using a 2018 UK Social Accounting Matrix (SAM), publicly available at: https://doi.org/10.15129/884b5286-bdb3-4eb9-bc47-08c77caf5f9e.

CRediT authorship contribution statement

Antonios Katris: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Karen Turner:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Christian F. Calvillo:** Conceptualization, Methodology, Investigation, Writing – review & editing, Visualization. **Long Zhou:** Conceptualization, Investigation, Data curation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Karen Turner reports financial support was provided by UK Energy Research Centre.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank colleagues at the Clean Heat Analysis team at the Department for Energy Security and Net Zero (DESNZ), and particularly Andrew Culling, for their contribution to the research reported here. Their contributions, particularly in terms of data provision and reviewing our modelling assumption has been instrumental for the completion of this work. We would also like to thank the colleagues working at the heat theme at the UK Energy Research Centre for helping us expand our understanding of the implications of heating decarbonisation and for providing comments and feedback on our work.

Appendix A. The sectors in our CGE model

Table A.1
Sectoral aggregation in CGE model and link to SIC2007 codes

Sector Number	Sector Name	SIC code
S1	Agriculture, Forestry and Fishing	01–03
S2	Coal and Lignite	05
S3	Crude Oil and Gas	06–07
S4	Other Mining and Mining Support	08–09
S5	Food, Drinks and Tobacco	10–12
S6	Textile, Leather and Wood	13–16
S7	Paper and Printing	17–18
S8	Coke and Refined Petroleum Products	19
S9	Chemicals	20
S10	Pharmaceuticals	21
S11	Rubber and Plastic	22
S12	Cement, Lime and Glass	23
S13	Iron, Steel and Metal	24&25.4
S14	Manufacture of Fabricated Metal Products, excluding weapons & ammunition	25.1–3&25.5–9
S15	Electrical Manufacturing	26–28
S16	Manufacture of Motor Vehicles, Trailers and Semi-Trailers	29
S17	Transport Equipment and Other Manufacturing (incl. Repair)	30–33
S18	Electricity	35.1
S19	Gas Distribution	35.2–3
S20	Natural Water Treatment and Supply Services	36
S21	Waste Management and Remediation	37–39
S22	Construction - Buildings	41–43
S23	Wholesale and Retail Trade	45–47
S24	Land Transport	49
S25	Other Transport	50–51
S26	Transport Support	52–53
S27	Accommodation and Food Service Activities	55–56
S28	Communication	58–63
S29	Financial and Insurance Services	64–66
S30	Architectural Services	71
S31	Services	68-70 & 72-82
S32	Public Administration, Education and Defence	84–85
S33	Health and Social work	86–88
S34	Recreational and Other Private Services	86–94

Appendix B. Detailed description of the different layers in our simulation

Layer 1: The necessary network upgrade

To develop Layer 1 we use network investment information from an analysis conducted using the UK TIMES model (see Calvillo et al., 2023 for the detailed analysis). There, modelling the switch from gas boilers to heat pumps as the main provider of residential heat services reveals that a total spending of £21.1 billion by 2050 will be necessary to upgrade and reinforce the electricity network. We assume that the network upgrade is conducted in 6 blocks of 5-years each (apart from the last one) to broadly match the 5-year price control periods implemented by the Great Britain energy market regulator, Ofgem. The upgrade is split evenly over each block and ramps up with each block, as suggested by the information provided by TIMES. We also ensure that enough network upgrade has been completed by 2037 so that the 50 % of the heat pump rollout can be serviced by the network. Finally, following Alabi et al. (2022) we assume that one-third of the total activity is implemented by the UK 'Construction' sector, while the remaining two-thirds involved imported inputs. However, as we use a national model we do not simulate the activity associated with the required imports. We also do not consider any cost repayments at this stage.

Layer 2: Installing and paying for heat pumps

Here, we consider the impacts of manufacturing, purchasing and installing heat pumps, along with different funding approaches on how the purchasing and installation costs could be met. Via UK TIMES model we calculate that a total capacity of 81.83 GW of heat pumps is necessary. By consulting with policy stakeholders, we assume that on average 8 kW air-to-water heat pumps will be installed, implying 10.23 million heat pumps in total are required by 2050 (the ending year of rollout).

To cover the total cost of deploying heat pumps, we assume that households pay out of their own funds, using interest-free loans with a 10-year repayment period to spread the cost over an extended period of time. We assume that covering the loan instalments takes precedence over any other consumption need and, therefore, reduces the households' disposable income. Moreover, because the loan repayments begin once the heat pump has been installed, the full repayment of the loans ends 9 years after the end of the heat pump rollout.

Based on these assumptions, we further diversify the layer into 2 sub-layers in terms of whether the heat pump cost reduction materialises and domestic content share in heat pump manufacturing supply chain in the UK, regardless of the funding options listed above.

Layer 2a: heat pump cost

Based on the consultation of policy stakeholders, the average upfront cost is estimated as £11,810 (incl. VAT) per heat pump purchase and installation, covering equipment, fittings, and installation (labour). The cost is broken down as follows.

- Heat pump: £3760
- Ancillary equipment (fittings, buffer, cylinder and controls): £4370
- Installation: £3680

Considering the number of heat pumps required to deploy from 2023 until 2050, the total cost of heat pumps is simply calculated as £120,796million, with the unit price £11,810 remaining unchanged during the heat pump rollout.

Alternative to this layer we also consider the heat pump cost across all components starting to reduce from 2028. The average unit cost of heat pump equipment and ancillaries are both expected to reduce by 30 %, and the installation cost is to reduce by 50 %, causing the average upfront cost falling to £7531 (incl. VAT) per heat pump. Based on this reduced cost of heat pumps, the total cost of heat pumps required is then as £79,655million by 2050.

Layer 2b: domestic content share of heat pump manufacturing

We first assume that 25 % of heat pump equipment, 50 % of all remaining ancillary components required and 100 % of installation cost will be sourced from UK sectors. The remaining 75 % of heat pump equipment is imported but we do not model its manufacturing, only the costs associated for purchasing this equipment. In total, £9,615million is directed to the UK 'Transport equipment/other mfr' sector that manufactures heat pumps, £22,349million to 'Electrical/electronic' sector for fittings and other necessary equipment and finally £37,640million to 'Construction', reflecting the installation cost. If considering cost reduction from 2028, the component cost would be £6,903million, £16,046million, and £19,949million respectively.

Alternatively, we consider the assumption that 75 % of both heat pump equipment and remaining ancillary components (and still 100 % of installation cost) will be sourced from UK sectors, implying £28,844million is directed to the heat pump manufacture, £33,523million to the ancillary manufacture and still £37,640million to construction. If considering cost reduction from 2028, the component cost would then be £20,710million, £24,070million, and £19,949million respectively.

Layer 3: Using the heat pumps

The 'realising' stage of the heat pump rollout is the focus of Layer 3. Here we aim to capture the economy-wide effects induced from energy bill savings when switching from gas boilers to heat pumps for residential heating. Information from UK TIMES analyses (Calvillo et al., 2023) suggest that the switch to heat pumps will lower the (physical) energy requirements of households by 39.45 %, assuming a coefficient of performance (COP) of 2.52, compared to a base scenario where residential heating is mainly delivered via gas boilers.

For example, if the gas and electricity have the same price, the households receive energy bills savings matching the physical energy savings, which is modelled as a 39.45 % permanent efficiency improvement for all UK households. However, considering this switch currently involves a switch from a relatively cheap fuel, natural gas, to a more expensive one (electricity), some of the physical energy savings could be eroded by relative price differentials between the two fuels.

References

[1] Business, Energy and Industrial Strategy (Department for) (BEIS), Heat and buildings strategy. https://www.gov.uk/government/publications/heat-and-buildings-strategy, 2021.

[2] HM Government, The ten point plan for a green industrial revolution. https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution, 2020.

[3] Energy Security and Net Zero (Department for) (DESNZ), Quarterly energy prices: june 2023. https://www.gov.uk/government/statistics/quarterly-energy-prices-june-2023, 2023.

[4] Zakeri, et al., The role of natural gas in setting electricity prices in Europe, Energy Rep. 10 (2023) 2778–2792, 2023.

[5] Business, Energy and Industrial Strategy (Department for) (BEIS), Public attitudes tracker: heat and energy in the home, Autumn 2022, UK, https://www.gov.uk/government/statistics/beis-public-attitudes-tracker-autumn-2022, 2022.

[6] Y.X. He, S.L. Zhang, L.Y. Yang, Y.J. Wang, J. Wang, Economic analysis of coal price-electricity price adjustment in China based on the CGE model, Energy Pol. 38 (11) (2010) 6629–6637.

[7] S. Zhang, T. Hu, J. Li, C. Cheng, M. Song, B. Xu, T. Baležentis, The effects of energy price, technology, and disaster shocks on China's Energy-Environment-Economy system, J. Clean. Prod. 207 (2019) 204–213.

[8] A. Orlov, An assessment of optimal gas pricing in Russia: a CGE approach, Energy Econ. 49 (2015) 492–506.

[9] A.S. Dagoumas, M.L. Polemis, S.E. Soursou, Revisiting the impact of energy prices on economic growth: lessons learned from the European Union, Econ. Anal. Pol. 66 (2020) 85–95.

[10] M. Yagi, S. Managi, The spillover effects of rising energy prices following 2022 Russian invasion of Ukraine, Econ. Anal. Pol. 77 (2023) (2023) 680–695.

[11] L. Kilian, X. Zhou, A broader perspective on the inflationary effects of energy price shocks, Energy Econ. 125 (2023) 196893.

[12] C. Baumeister, J.D. Hamilton, Structural interpretation of vector autoregressions with incomplete identification: revisiting the role of oil supply and demand shocks, Am. Econ. Rev. 109 (5) (2019) 1873–1910.

[13] K. Doroodian, R. Boyd, The linkage between oil price shocks and economic growth with inflation in the presence of technological advances: a CGE model, Energy Pol. 31 (2003) 989–1006.

[14] P. Bergmann, Oil price shocks and GDP growth: do energy shares amplify causal effects? Energy Econ. 80 (2019) 1010–1040.

[15] L. Aydin, M. Acar, Economic impact of oil price shocks on the Turkish economy in the coming decades: a dynamic CGE analysis, Energy Pol. 39 (3) (2011) 1722–1731.

[16] F. Schwark, Energy price shocks and medium-term business cycles, J. Monetary Econ. 64 (2014) 112–121.

[17] B. Dong, X. Ma, N. Wang, W. Wei, Impacts of exchange rate volatility and international oil price shock on China's regional economy: a dynamic CGE analysis, Energy Econ. 86 (2020) 103762.

[18] K. Ismail, M. Lubwama, J.B. Kirabira, A. Sebbit, Development of a sustainable low-carbon footprint for the Greater Kampala Metropolitan Area: the efficacy of a TIMES/CGE hybrid framework, Energy Rep. 9 (2023) 19–36.

[19] C. Mardones, J. Ortega, The individual and combined impact of environmental taxes in Chile – A flexible computable general equilibrium analysis, J. Environ. Manag. 325 (2023) 116508.
[20] K. Turner, O. Alabi, A. Katris, J.K. Swales, The importance of labour market responses, competitiveness impacts, and revenue recycling in determining the political economy costs of broad carbon taxation in the UK, Energy Econ. 166 (2022) 106393.
[21] Y. Mu, W. Cai, S. Evans, C. Wang, D. Roland-Holst, Employment impacts of renewable energy policies in China: a decomposition analysis based on a CGE modeling framework, Appl. Energy 210 (2018) 256–267.
[22] M. Esmaeili, M. Shafie-Khah, J.P.S. Catalão, A system dynamics approach to study the long-term interaction of the natural gas market and electricity market comprising high penetration of renewable energy resources, Electrical Power and Energy Systems 139 (2022) 108021.
[23] A.S. Gaur, D.Z. Fitiwi, J. Curtis, Heat pumps and our low-carbon future: a comprehensive review, Energy Res. Social Sci. 71 (2021) 101764.
[24] Y. Wang, J. Wang, W. He, Development of efficient, flexible and affordable heat pumps for supporting heat and power decarbonisation in the UK and beyond: review and perspectives, Renew. Sustain. Energy Rev. 154 (2022) 111747.
[25] J. Barnes, S.M. Bhagavathy, The economics of heat pumps and the (un)intended consequences of government policy, Energy Pol. 138 (2020) 111198.
[26] T.A. Deetjen, L. Walsh, P. Vaishnav, US residential heat pumps: the private economic potential and its emissions, health, and grid impacts, Environ. Res. Lett. 16 (8) (2021) 084024.
[27] A. Hope, T. Roberts, I. Walker, Consumer engagement in low-carbon home energy in the United Kingdom: implications for future energy system decentralization, Energy Res. Social Sci. 44 (2018) 362–370.
[28] P. Carroll, M. Chesser, P. Lyons, Air Source Heat Pumps field studies: a systematic literature review, Renew. Sustain. Energy Rev. 134 (2020) 110275.
[29] M. Jarre, M. Noussan, M. Simonetti, Primary energy consumption of heat pumps in high renewable share electricity mixes, Energy Convers. Manag. 171 (2018) 1339–1351.
[30] S. Poppi, N. Sommerfeldt, C. Bales, H. Madani, P. Lundqvist, Techno-economic review of solar heat pump systems for residential heating applications, Renew. Sustain. Energy Rev. 81 (2018) 22–32.
[31] X. Li, D. Lepour, F. Heymann, F. Maréchal, Electrification and digitalization effects on sectoral energy demand and consumption: a prospective study towards 2050, Energy 279 (2023) (2023) 127992.
[32] Phil Heptonstall, Mark Winskel, 'Decarbonising home heating: an evidence review of domestic heat pump installed costs'. UKERC, april 2023. https://ukerc.ac.uk/publications/heat-pump-cost-review/, 2023.
[33] P. Lecca, P. McGregor, J.K. Swales, K. Turner, The added value from a general equilibrium analysis of increased efficiency in household energy use, Ecol. Econ. 100 (2014) 51–62.
[34] O. Alabi, K. Turner, A. Katris, C. Calvillo, Can network spending to support the shift to electric vehicles deliver wider economy gains? The role of domestic supply chain, price, and real wage effects, Energy Econ. 110 (2022) 106001.
[35] C.F. Calvillo, A. Katris, O. Alabi, J. Stewart, L. Zhou, K. Turner, Technology pathways, efficiency gains and price implications of decarbonising residential heat in the UK, Energy Strategy Rev. 48 (2023) 101113.
[36] ONS, UK Input-Output Analytical Tables, Industry by Industry - Office for National Statistics', 2022. https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/ukinputoutputanalyticaltablesindustrybyindustry.
[37] F. Hayashi, Tobin's marginal q and average q: a neoclassical interpretation, Econometrica: J. Econom. Soc. 50 (1) (1982) 213–224.
[38] D.G. Blanchflower, A.J. Oswald, The wage curve, Europe-Revue Litteraire Mensuelle 92 (2009) 215–235.
[39] R. Layard, S. Nickell, R. Jackman, Unemployment: Macroeconomic Performance and the Labour Market, Oxford University Press, Oxford, 1991.
[40] P.S. Armington, A theory of demand for products distinguished by place of production, Staff Papers (International Monetary Fund) 16 (1) (1969) 159–178.
[41] K. Turner, A. Katris, J. Race, The need for a Net Zero Principles Framework to support public policy at local, regional and national levels, Local Econ. 35 (7) (2021) 627–634.
[42] Ofgem, RIIO-ED2 final determinations. https://www.ofgem.gov.uk/publications/riio-ed2-final-deter0minations, 2022.
[43] ONS, Labour Market Statistics Time Series - Office for National Statistics, 2023.