HOW THE PACE OF RESIDENTIAL HEAT ELECTRIFICATION IMPACTS THE ENERGY SYSTEM?

Christian F. Calvillo*, Antonios Katris, Oluwafisayo Alabi, Jamie Stewart, Long Zhou, Karen Turner
Centre for Energy Policy, University of Strathclyde
**Corresponding author,* christian.calvillo@strath.ac.uk

Abstract

Heating buildings is the source of nearly a quarter of UK emissions (UK Government, 2021a). Thus, meeting net zero will involve virtually all heat in buildings to be decarbonised. In their Heat and buildings strategy, the UK Government (2021b) set out its plans to deliver at least 600,000 heat pump systems per year by 2028. This will involve significant changes to the energy system - including the upgrade of the energy networks and increasing renewable energy generation capacity - alongside the installation of new heating systems in people's homes. Understanding how these costs are distributed, where benefits might accrue and how the wider economy might be impacted will be key. These questions are set within a quickly changing policy environment where for example, surging global gas prices have driven a significant increase to the energy price cap for GB energy consumers. Although the significant increase in international gas prices has markedly narrowed the gap between the cost of electricity and gas, this price differential - where consumers currently pay significantly more per unit of energy for electricity - remains an important factor for understanding how different decarbonisation options will affect the affordability of heating systems.

Many studies have been developed to analyse the impact of heat electrification. However, most of them do not consider different heat pump adoption pathways and normally they only analyse the implications of a large penetration of heat electrification in the power sector, not considering, for example, the changes on emissions, energy use and consumer costs. The work developed in this paper aims to provide insight on this issue, analysing the implications of the electrification of residential heat under different adoption pathways, using the UK TIMES energy system model. Preliminary results show that the speed in which heat pumps are rolled out can have important impacts on energy use, emissions and the level of network investments, and thus higher costs for the final consumer.

1. Introduction

To tackle climate change and put the UK on course to meet emission reduction targets enshrined in law(Climate Change Act, 2008), significant system wide changes - such as those described in the UK Government's recently published Net Zero Strategy (UK Government, 2021a) - will be needed. Heating buildings is the source of nearly a quarter of UK emissions. Thus, meeting net zero will involve virtually all heat in buildings to be decarbonised (UK Government, 2021b). The UK Government has published strategies to reduce emissions from buildings over the coming decades. The electrification of heat is proposed to a key action in reducing emissions from homes where the majority of emissions are associated with boilers that currently run on methane gas. In their Heat and buildings strategy (UK Government, 2021b), the UK Government set out its plans to deliver at least 600,000 heat pump systems per year by 2028. The strategy also recognises the role that hydrogen might play in decarbonising heat, considering that up to 4 millions of homes could be served by hydrogen by 2035 (UK Government, 2021a). The UK Government are due to decide by 2026 on whether to take this option forward.

Regardless of what mix of technology options is taken forward, significant changes to the energy system - including the upgrade of the energy networks and increasing renewable energy generation capacity - will be needed alongside the installation of new heating systems in people's homes. Understanding how these costs are distributed, where benefits might accrue and how the energy system might be impacted is a key aim of this paper.

In this paper, we explore the type of challenges emerging around delivering a sustainable and equitable low carbon heat transition. We aim to provide insight on the potential impacts of the planned electrification of residential heat in the UK in terms of network investments, changes in fuel use, fuel cost and emissions. For this we use the UK TIMES whole energy system model (UCL, 2014). We have selected this model as it covers the whole integrated energy system (supply, conversion and demand, across all sectors: agriculture, services, residential, industry, transport) and not only the power sector. We consider two different heat electrification scenarios. These scenarios vary in the pace in which heat pumps are adopted.

The work developed in this paper aims to provide policy-relevant insight on the wider effects of the decarbonisation of residential heat, analysing the implications of the low carbon transition under different technology scenarios, and discussing best practices on informing energy policy. Section 2 describes the methodology used in this paper. Section 3 shows the considered low carbon residential heat scenarios. Section 4 shows the results and discussion of the analysis and section 7 presents the conclusions of this study.

2. Methodology

In this paper, two electrification scenarios are analysed using the UK TIMES model. TIMES is a bottom-up techno-economic energy system-wide model, which considers all the processes of the energy system, and produces future energy scenarios based on a cost minimisation objective function.

The Integrated MARKAL-EFOM System (TIMES) is a bottom-up energy system-wide model. The TIMES model generator is developed by the Energy Technology Systems Analysis Programme (ETSAP), which part of the International Energy Agency (IEA-ETSAP, 2022). TIMES has been used widely to analyse different policy questions including decarbonisation scenarios, as in (Fortes et al., 2019; Nerini et al., 2017), or the energy system impacts of specific technologies and policies, as in (Tattini et al., 2018; Venturini et al., 2019).

UK TIMES (UKTM) is the UK version of the TIMES model, and is a single region energy system model of the UK, used for medium to long-term analysis of energy systems. UKTM considers all the processes that transform, transport, distribute and convert energy to supply energy services (see Figure 1). The inputs (exogenous variables and parameters) of the model are: service demand curves, supply curves (e.g. primary energy resources such as wind power or availability of imports), and techno-economic parameters for each technology/process (e.g. technology efficiencies and availability factors, investment cost per capacity unit, O&M cost per unit of production, etc). The outputs (endogenous variables) include: energy and commodity flows and marginal costs, technology installed capacities, emissions, etc.

The sectors considered in UKTM include: industry (organised by subsectors: cement, pulp and paper, food and drinks, petrochemicals, etc.), agriculture and land use, transport, residential, services and the power sector. The power system in TIMES includes a very large number of electricity generation technologies and also models the transmission and distribution networks. The representation of these networks is limited due to the single region aspect of UKTM. However, it is useful to assess if current network capacity would be enough to accommodate the expected generation and demand.

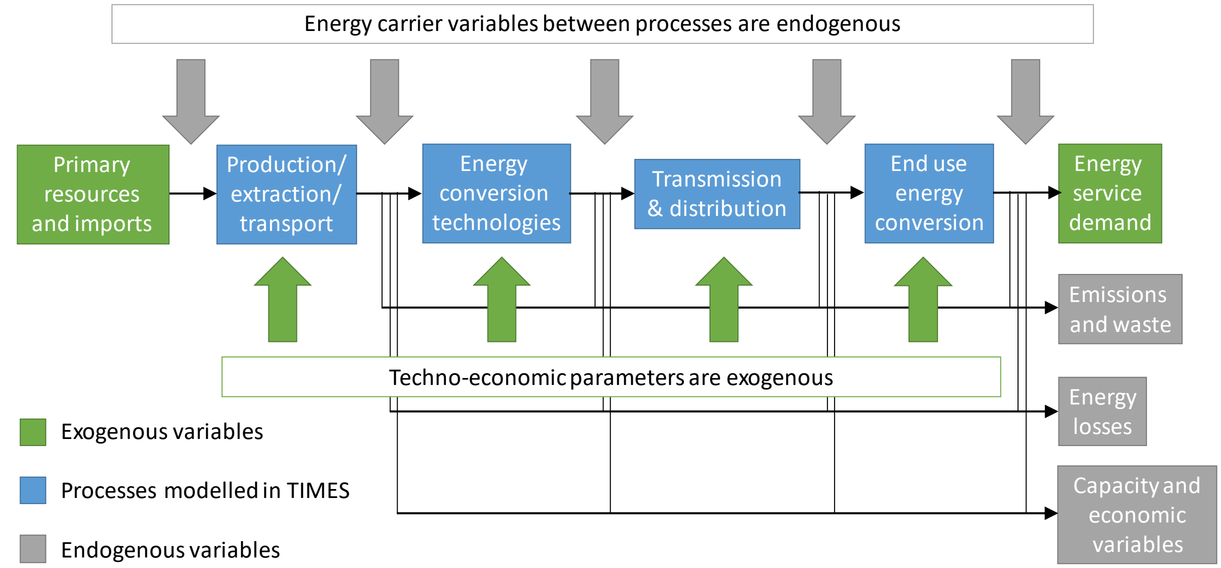

Figure 1. Modelling of the energy system in TIMES (Calvillo et al., 2017).

The time horizon in UKTM runs until 2050, with time periods of 5 years, taking 2010 as the base year. To reduce complexity in the optimization model, TIMES considers only some representative time-slices that work as an average of the elements of that time period. UKTM considers 16 time slices: four time divisions within a year representing seasons (spring, summer, fall and winter), and four daily divisions for each season (night, day, evening peak and late evening).

Moreover, UKTM is a partial equilibrium model-generator assuming perfectly competitive markets and full foresight. The model uses linear-programming to find a least-cost energy system (calculated as sum of investment, fixed and variable operation and maintenance (O&M), and import and export costs/revenues for all the modelled processes), able to meet specified energy service demands, according to a number of user constraints. The TIMES objective function minimises Net Present Value (NPV) (Loulou et al., 2005), as in the equation:

$$\min(NPV) = \min\left(\sum_{r=1}^{R} \sum_{y \in YEARS} \left(1 + d_{r,y}\right)^{REFyear} * ANNCOST(r,y)\right)$$

Where:

- ***NPV*** is the net present value of the total cost for all regions (the TIMES objective function);
- ***ANNCOST(r,y)*** is the total annual cost in region ***r*** and year ***y***. This includes capital costs (investment and decommissioning), operation and maintenance cost, and a salvage value of all investments still active at the end of the horizon;
- $d_{r,y}$ is the general discount rate;
- ***REFyear*** is the reference year for discounting;
- ***YEARS*** is the set of years for which there are costs, including all years in the horizon, plus past years (before the initial period) if costs have been defined for past investments, plus a number of years after EOH where some investment and decommissioning costs are still being incurred, as well as the Salvage Value; and
- ***R*** is the set of regions in the area of study. The UKTM version we are using is a single region model so *R* = 1.

The model uses demand projections as the main driver of the energy system. In other words, the model finds the least cost energy system configuration (technology mix and energy flows) to meet the expected demand. So the technology selection by the model is based on the cost-effectiveness of the technologies, considering their performance, capital, operation and maintenance, and fuel costs. Also, to avoid 'penny-switching' (i.e. dramatic technology changes in a short period of time, triggered by a small cost saving), technology adoption constraints are set in the model trying to replicate realistic technology adoption scenarios.

A more detailed description of the UKTM model and its database can be found in (Calvillo et al., 2017; Daly et al., 2014) and official TIMES documentation can be found in (Loulou et al., 2005, 2004).

3. Scenario description

The two analysed scenarios are based on recent UK Government policy targets as set in the the Heat in Buildings strategy (UK Gov. 2021b), stating that 600,000 heat pump systems are to be installed per annum from 2028 and 1.9 million per year by 2035, this will translate to arounf 11 million of households using heatpums by 2035. The difference between these scenarios is the pace in which electrification is adopted until 2050. The quicker electrification scenarios roughly follows the UK Government target, whereas the slower electrification scenario is assumed to have a slower uptake, not meeting the 2035 target, but ramping up adoption after this and reaching a similar total heat pump uptake by 2050.

The heat decarbonisation scenarios are:

- Slower electrification - Almost 20% of households using heat pumps for heating by 2035 (40% low carbon) and over 65% using heat pumps by 2050% (99% low carbon)

- Quicker electrification - Over 55% households using heat pumps for heating by 2035 (90% low carbon) and around 65% using heat pumps by 2050% (99% low carbon)

The results of the different scenarios are compared across one another and with a base case where no heat electrification takes place. The impact of the residential heat electrification pace of adoption is analysed in terms of network investments, energy use changes and emission reductions.

4. Results

Figure 2 shows the technology changes for the residential heat decarbonisation scenarios and of the base scenario. The base scenario (Figure 2.a) follows the current technology mix, maintaining a high penetration of gas boilers (over 85%), and it is used as the benchmark to compare against the four decarbonisation scenarios. The slower electrification scenario (Figure 2.b) present a slow start of heat pump adoption, with just over 6% of households using this technology by 2030, picking up by 2040, where heat pump use (34.4%) surpasses gas boilers (33.8%), and reaching almost 65% heat pump penetration by 2050. The second most important heating method in this scenario is district heating, with almost 20% of households using the technology by 2050. The quicker electrification scenario (Figure 2.c) also focuses on heat pump rollout, but as the name suggest, the adoption of this technology takes a quicker pace. For instance, heat pump use surpasses gas boiler use (around 35% vs 30%) by 2030, and continues with a rapid a heat pump adoption until 2050, where a similar technology mix is achieved for both electrification scenarios.

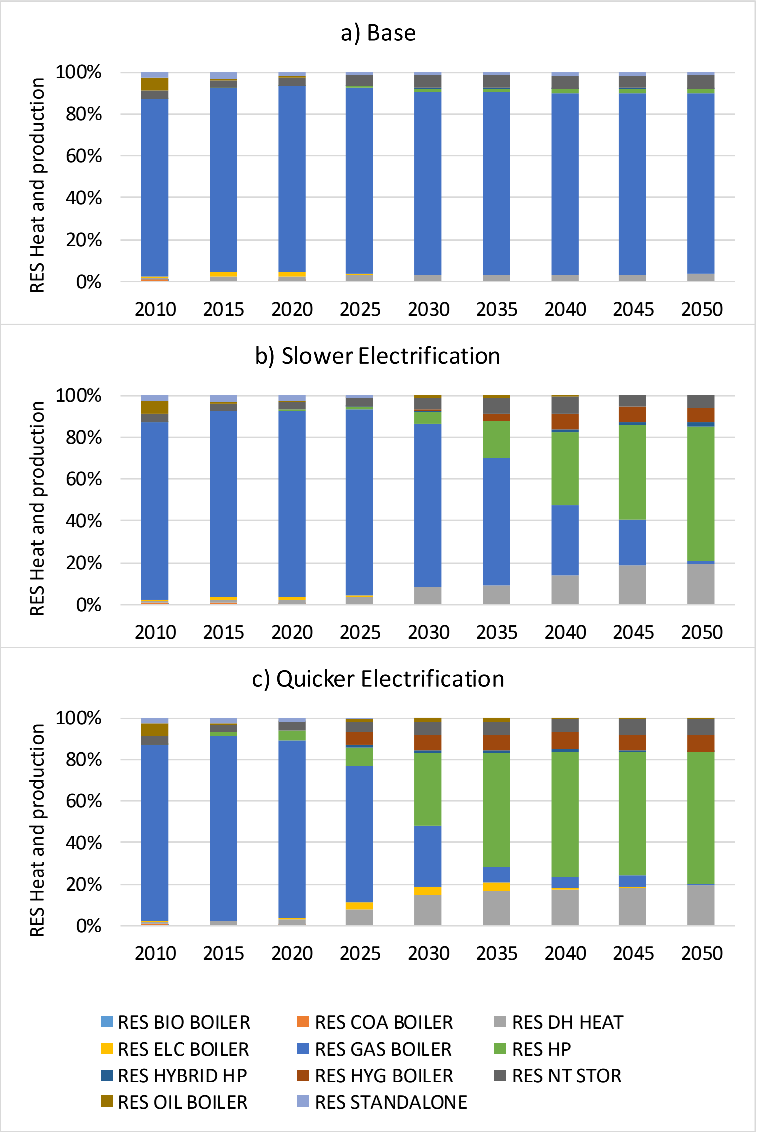

Figure 2. Residential heat technology mix: slower and quicker electrification scenarios.

Moreover, results show that these residential heat electrification pathways produce different results in terms of the timing and the level of fuel switching and energy reductions. For example, Figure 3 shows the changes in residential energy use for heat for the base case and the two electrification scenarios analysed. It can be noted that the quicker electrification drives energy savings earlier, relative to the base case. However, the 2050 energy use point is similar in both cases and achive almost 40% energy reduction in relation to the base case. These energy reductions are caused by the higher efficiency from heat pumps. However, price differential between residential electricity and gas is key in translating these energy use savings into reduced costs for households. For instance, recent costs in the UK put each kWh of electricity to be around 4 times more expensive than gas. This higher price per unit of energy can completely offset any cost savings from the higher efficiency.

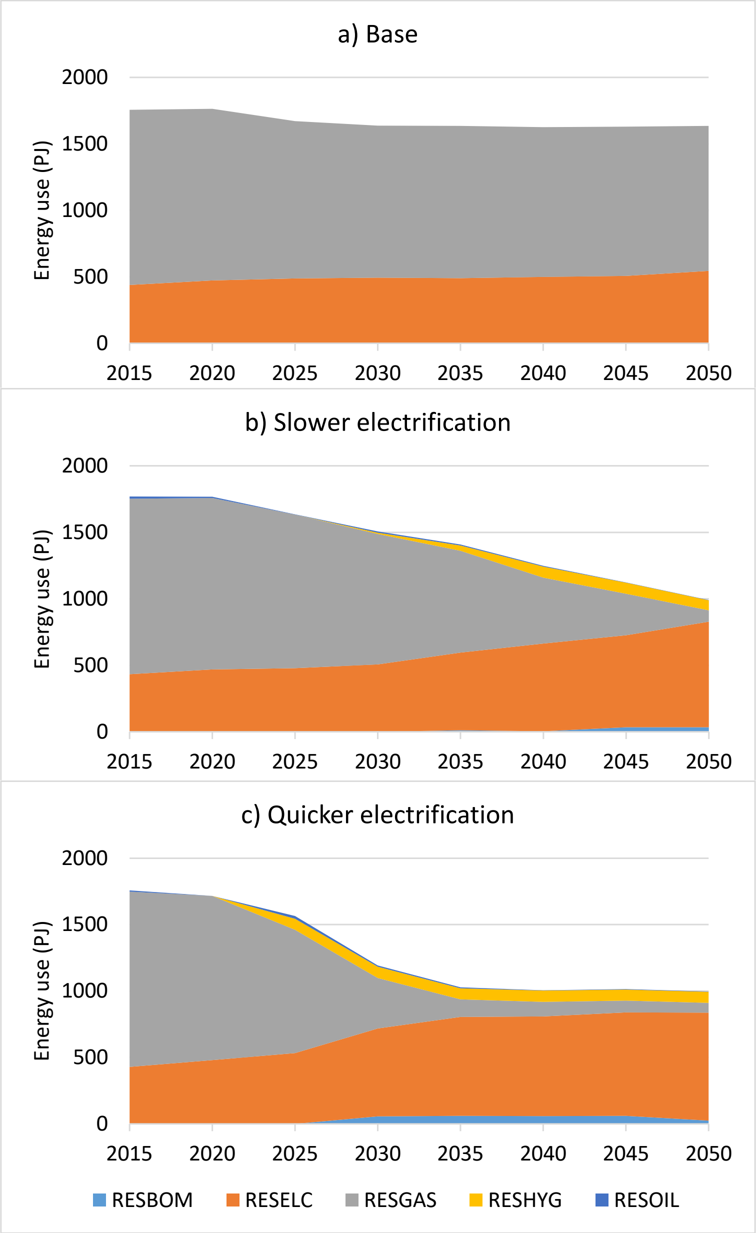

Figure 3. Energy use for residential heat in the slower and quicker electrification scenarios.

Additionally, the heat electrification pathways involve the expansion of generation and network capacity, and the investment patterns can change significantly in the different scenarios. Figure 4 show the extra network investments required, relative to the base case, to accommodate the increased electricity for the considered scenarios. The electrification scenarios have higher investment needs, with more than £21b investment in total. Further to this, the network investment costs are transferred to consumers as an increase in marginal costs (energy prices), and heating costs can be significantly different across scenarios and at different timetables. These and other relevant policy outcomes, such as emission reductions, are also important to take into account while designing energy tariffs and heat decarbonisation policies.

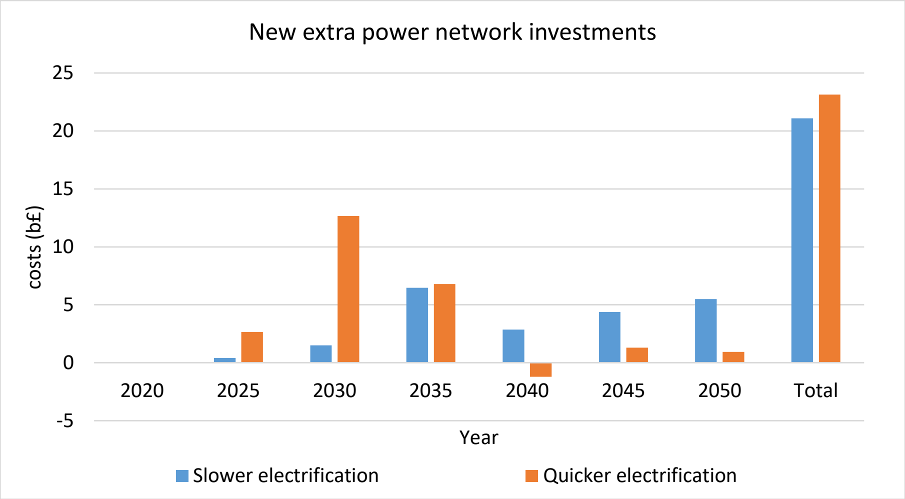

Figure 4. Extra power network investments, relative to base case.

Figure 5 shows the total sectoral emissions for all scenarios. The sectors are agriculture (AGR), electricity (power sector, ELC), hydrogen production (HYG), industry (IND), residential (RES), services (SER), and transport (TRA). In the electrification scenario, as expected, residential emissions decreased between 27% and 45% relative to the base scenario. However, the extra electricity required for heat pumps has produced an increase on electricity production, which translates to an increase on emissions in the power sector between 12% and 25%. Other sectors do not show significant changes. Note that the quicker electrification, with the faster uptake of heat pumps scenario have lower cumulative residential emissions (-45%) and overall (-3.9%), than the slower electrification one (-27% and -2.6%). This show that the speed in which low carbon systems are rolled out is important in tackling climate change.

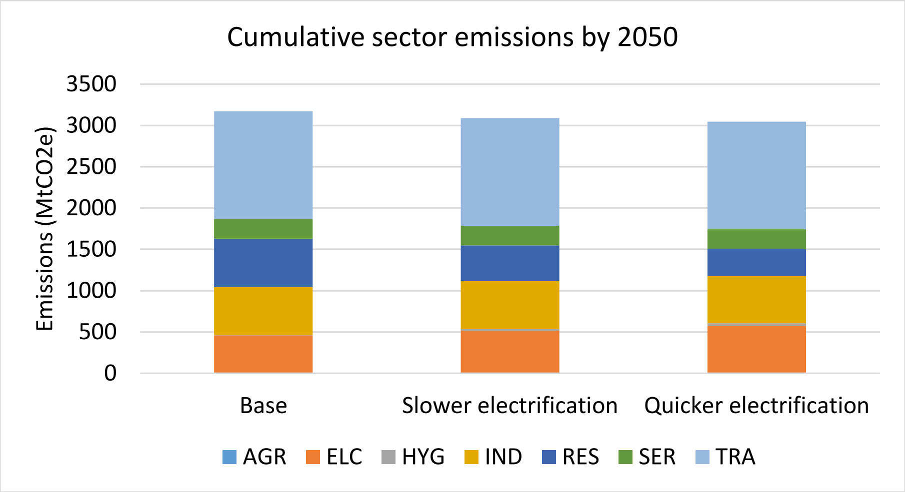

Figure 5. Cumulative CO2eq emissions per sector for all scenarios.

5. Conclusions

The UK Government, as part of their strategy to tackle climate change, is setting up policies for the decarbonisation of residential heat. The current policy expectation is that all new heating systems to be net zero compatible by 2035, with important targets on heat pump rollout from 2028. Moreover, the move towards low carbon heat will bring important changes to the energy system. This study provides insight on the wider effects of the transition to low carbon residential heat, analysing the implications of different electrification scenarios. We have analysed the impacts of these scenarios in terms of network investment needs to accommodate the increasing electricity demand, changes in fuel use for the final consumer and changes in CO2 emissions.

Our analysis highlights key issues, such the importance of the retail price differential between gas and electricity and how that may interact with other factors to impact the wider economy consequences of electrifying heat. We anticipate almost 40% energy savings for heating, largely due to the higher efficiency of heat pumps compared to gas central heating systems. However, where the electricity price is high relative to that of gas, monetary savings in delivering heat/hot water services can be significantly offset or completely eliminated. Such net impacts on bills must also be set in the context of the upfront and/or financing costs of purchasing and installing a new heating system.

In addition to this, the timing and level of network investments as also affected under the different scenarios. This could have important implications for the economy, as large investments concentrated in a short period of time could create adverse effects in the economy due to labour and/or capital scarcity (Alabi et al., 2020). We believe that these scenarios provide a range of outcomes that may help policymakers and network operators to plan and find solutions that do not overburden consumers and facilitate the transition to low carbon heat.

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