Research paper

Demand-side CO_2 mitigation potential in the UK heating and transport sectors

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ABSTRACT

Lifestyle change and demand-side measures will likely to be inevitable in the fight against climate change, nevertheless modelling their effects so far have been limited. We intend to contribute to this discussion, with modelling the socio-economic impacts of sufficient consumption pathways, employing a demand-led IAM with endogenous economic growth, the E3ME economy-energy-environment model. Our scenario setups build on existing low energy demand scenarios and systematic reviews of demand-side climate mitigation measures to achieve mitigation targets. We provide a quantitative definition of sufficient consumption and input the sufficient values as scenario inputs for macroeconomic modelling. The results clearly show the potential CO2 mitigation potential of the demand-side solutions. Furthermore, we see different pathways about how technology take-up is affected by the decreased demand and also sectoral changes in consumption and employment arise. The novel contribution of the exercise is the endogenous modelling of economic growth, within a scenario with decreasing energy demand.

Keywords: demand-driven mitigation, scenario, analysis, E3ME, impact assessment model

1 Introduction

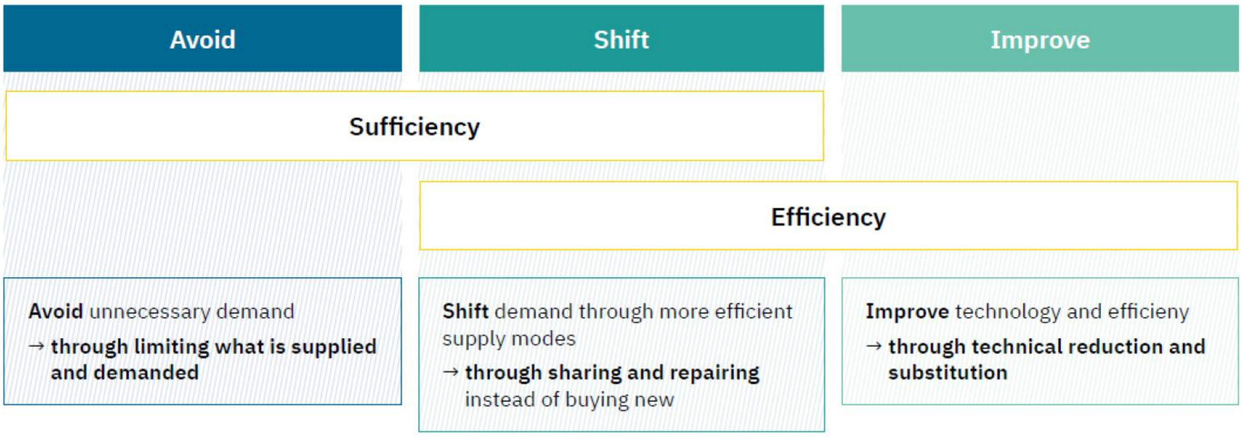
Assessment Report 6 (AR6) was the first ever IPCC report to dedicate a chapter to lifestyle change and demand-side mitigation measures (Creutzig et al., 2022a), while post-growth approaches to mitigation have been gaining traction on their own as well (Creutzig et al., 2018; Hickel et al., 2021). Prompted by an uncertainty around technological solutions to climate change (i.e., CCS and DAC technologies) and questions around the possibility of absolute decoupling (Keyßer & Lenzen, 2021).

However, integrated assessment modelling (IAM) of scenarios with reduced consumption is limited. Only 5% of IPCC mitigation scenarios have final energy reductions by 2100 (Scott et al., 2022) and even in these cases economic impacts are limited or based on exogenous assumptions (Keyßer & Lenzen, 2021). While important work has been done by Grubler et al. (2018), even their “Low Energy Demand” scenario has not investigated economic effects such rebound effects and impacts induced by reduction of energy demand [Grubler et al., 2018, p. 522]. Other exercises outright exogenously assume negative or stagnant economic growth, such as Keyßer and Lenzen (2021). Who use a “simplified quantitative model, which only addresses the fuel-energy-emissions nexus top–down” (Keyßer & Lenzen, 2021, p. 11) and employ exogenously defined GDP pathways. Their conclusion is that decarbonization effort needed is the less when we assume stagnant GDP, as with a growing global economy we need to decarbonize not just what is but also what will be.

These works all consider exogenously defined economic growth pathways, while they assume changes in energy use and the energy system. However, in our understanding, in line with post-Keynesian theory effective demand is the key driver of economic activity. This means, that changes in consumption (e.g., sufficiency, post-growth, degrowth, etc.) will inevitably be connected to economic activity, as well as energy use and – finally – with endogenous growth and innovation.

To overcome this limitation in our work we employ the E3ME energy-environment-energy assessment model (Mercure et al., 2018; Mercure et al., 2021). A demand-driven macroeconomic assessment model, which, due to its demand-led nature provides an excellent choice for modelling demand-side changes and sufficient consumption pathways. Using the model provides use with a novel approach to modelling the effect of demand-side changes: as economic growth is endogenous in the model, we can model the complex economic impacts of decreasing energy consumption in the target areas to sufficient levels (levels which are compatible with living standards). Thus, we can capture induced economic growth effects (e.g., effects in sectors of energy production), potential rebound effects (as spending is shifted away from energy). We use the model to build scenarios of sufficient energy consumption in the residential heating and passenger road transport sectors.

Figure 1: Schematic overview of ASI framework, source: Lorek et al. (2021)



We pay particular attention to “sufficiency” measures, measures that are associated with the first two parts of the ASI framework (see Figure 1): limiting demand and shifting demand to more efficient modes of supply. Both of which can lead to decreased production and therefore economic activity, but not necessarily lead to losses of life quality or employment, while it is assumed that they can contribute to achieving sustainable development goals. Our aim is not to determine the exact level of sufficient consumption in these sectors, but to shed light on the underlying economic mechanisms in such a world. We therefore construct scenarios with moderate and ambitious levels of demand reduction and compare them to a baseline scenario where no change in the demand is assumed.

2 Methodology

Our empirical strategy to assess the economic and environmental consequences of sufficient consumption consists of two steps with the goal of providing a complete macroeconomic modelling framework for the proposed problems.

First, we identify the most relevant sectors where the potential for sufficiency measures is the greatest and define demand-side mitigation targets based on empirical data, considering practical issues such as data availability and the modelling capabilities of E3ME. According to Ivanova's (2019) modelling results, consumption types with the highest emissions mitigation potential are in either the transport or housing sectors. Therefore, in our scenarios we focus on these two sectors, narrowing down the housing sector to heating since it is the most significant contributor to household emissions (apart from transport). We then seek to derive realistic assumptions about sufficient demand levels from empirical distributions of energy demand. However, the scenarios do not aim to perfectly define the sufficient levels of travel and heating. They attempt to assess the economic challenges of different levels of ambition in demand reduction. More detailed scenario descriptions follow in section 2.2, where the method for defining sufficient consumption levels is outlined.

In the second step of our process, we leverage the defined measures of sufficient consumption and use them as inputs to the E3ME macroeconomic model. We build E3ME scenarios to model the potential socioeconomic and environmental impacts of reduced energy consumption in the residential heating and passenger road transport sectors. We used residential space heating data from Enerdata, heating degree days from Eurostat and UK Government. Transport data is taken from Lam (2019). The extensive list of sources datasets used in the E3ME-FTT model can be found in the E3ME Manual (Cambridge Econometrics, 2022).

2.1 E3ME-FTT

To gain a deeper understanding of the global consequences of the conflict and the resulting shifts in the energy market, this paper utilizes the E3ME-FTT macroeconomic modeling framework. The E3ME-FTT framework consists of two integrated components: the core E3ME model (Mercure et al., 2018; Lewney, Pollitt, and Mercure, 2019; Cambridge Econometrics, 2022) and the FTT (Future Technology Transformation) suite of models (Mercure, 2012; Lam et al., 2018). The core E3ME model focuses on fundamental interactions among regions, economics, energy, and the environment. In contrast, the FTT models provide detailed, bottom-up modeling for specific sectors crucial from a climate and environmental perspective. In this section, we provide a brief introduction to both models.

E3ME operates as an E3 (economy-energy-environment) model, sharing similarities with integrated assessment models (IAMs). However, unlike typical IAMs, E3ME is constructed based on post-Keynesian economic theory, complexity economics principles, and an econometric approach (Mercure et al., 2018; Lewney, Pollitt, and Mercure, 2019; Pollitt et al., 2021; Cambridge Econometrics, 2022). The complete model, including its equations and data sources, is comprehensively described in Mercure et al. (2018) and the E3ME manual (Cambridge Econometrics, 2022). Here, we provide a brief overview of the model's capabilities and fundamental mechanisms.

The model's structure revolves around an input-output model for each represented economy, with interconnected economies linked through bilateral trade relationships. This model achieves high granularity, distinguishing among 70 world regions (often corresponding to individual countries), 43 industrial sectors for each region, several consumption categories (following COICOP classifications), and 23 fuel user categories with the flexibility to use 12 different fuel types. E3ME adopts a demand-driven approach, where aggregate consumption propels output, trade, and the demand for intermediate goods and other inputs (e.g., labor, energy). The utilization of these inputs has its own repercussions: energy demand is meticulously modeled by fuel type and sector, which is then converted into physical units. Unit costs, influenced by factors like labor availability and input prices, as well as prior investments, determine prices (Lewney, Pollitt, and Mercure, 2019; Pollitt et al., 2021; Cambridge Econometrics, 2022; Kiss-Dobronyi et al., 2023).

In conjunction with the core economic module, the model calculates energy consumption using its own sector- and region-specific parameters, accommodating endogenous fuel switching and fuel-specific demand responses. Energy consumption is presented in both monetary and physical terms. Meanwhile, greenhouse gas (GHG) emissions are computed based on fuel consumption, effectively linking emissions to fuel usage, with process emissions separately linked to output (Cambridge Econometrics, 2022; Kiss-Dobronyi et al., 2023).

The FTT models have been integrated into the modeling framework to address innovation in high-impact sectors (Mercure, 2012; Mercure et al., 2018; Cambridge Econometrics, 2022). The FTT models simulate the diffusion of technology in selected sectors, including transport (Lam et al., 2018; Knobloch et al., 2020), power generation (Mercure, 2012), and heating (Knobloch et al., 2020).

The FTT models employ a differential equation structure to represent technology choices from an investor's perspective. Investors make decisions based on levelized costs, which are defined as cost distributions rather than single points, allowing local, unobserved conditions to influence investment decisions (Mercure, 2012). Technology adaptation, inspired by ideas from Rogers (2003) and akin to the Bass diffusion model (Bass, 1969), depends on technology shares. In other words, technology choices are **influenced** by the overall system's historical adoption of that technology. This is reinforced by learning-by-doing effects and decreasing costs due to increased competition; higher adoption of a technology in one period can lead to even greater adoption in the following period and potentially lower technology prices due to cumulative adaptation (Mercure, 2012; Cambridge Econometrics, 2022; Kiss-Dobronyi et al., 2023).

2.2 Scenario design

2.2.1 Heating scenarios

The vast majority of household energy consumption is comprised of residential heating and therefore we focus on modeling this aspect of the sector. Our methodological approach is based on the empirically observable connection between final residential heating consumption and outside temperature measured as HDD which is an accepted and proven determinant of final energy demand (Borozan, 2018), which is the first step of our approach. The idea of sufficient consumption is built on the quantitative relationship between final energy consumption of European countries and their observed yearly average outside temperature.

The connection between energy consumption and outside temperature is captured through simple regression analysis. It is based on empirical observations and grasps the idea of sufficient consumption to be calculated based on observed historical levels of consumption. The fitted values of the regression model show the historical level of sufficient consumption dependent on outside temperature. Similarly, the residuals of the regression model show the aspect of energy consumption that cannot be explained by outside temperature levels. Therefore, the model residuals capture how much energy is used for heating or cooling by households for other reasons, which we define as comfort level. Finally, we look at the residuals across all countries which follow the shape of a normal distribution.

The residual distribution is used to determine the exact consumption level which can be considered as sufficient. We created two household energy consumption scenarios which differ in the selected target point that we consider as the sufficient level. The residual ratio of the UK is 1.33, which implies that approximately 25% [0.25 = (1/1.33)-1] of the final heating energy consumption is for comfort and above the level which can be considered necessary due to outside temperature, which refers to 6.1 Mtoe decrease in absolute terms.

The median level of the residual distribution represents the average comfort level of the observed countries, which we consider as the target of the first scenario. The reason why it represents the average comfort level is because each residual shows how much is consumed for comfort in the observed EU countries. Using the 1.06 median residual ratio level, we calculate that the UK should decrease its heating consumption by 20.4% to reach this. In absolute values, this means a 4.98 Mtoe decrease for annual residential heating energy consumption and leave the UK with a total of 19.4 Mtoe energy consumption. The corresponding residual ratio of this level of consumption is similar to the consumption residual of Poland, which shows how much of the energy use happens for comfort reasons. In the first scenario, we expect the UK to achieve this consumption level by 2050 and get there following a linear trend. The linear trend assumption of consumption decrease levels remains through for all the following scenarios.

The second scenario includes a more stretched target than the first one. We define the sufficient level of consumption as the 25th percentile of the residual distribution of the countries. This means a residual ratio value of 0.77, which implies that the UK must decrease its consumption levels by 39.8% to reach it. This is quite a high expectation which would require complex structural and policy changes, which we elaborate more in the discussion chapter. An almost 40% decrease in consumption refers to an annual decrease of 9.7 Mtoe. Reaching this target would mean that the UK is at the heating energy consumption level of Sweden. This is a much more optimistic target than the previous one, however still within the range of technical feasibility, considering that there is a vast potential in improving the energy efficiency of the UK building stock (Eyre 2015 & Flower 2020).

2.2.2 Travel scenarios

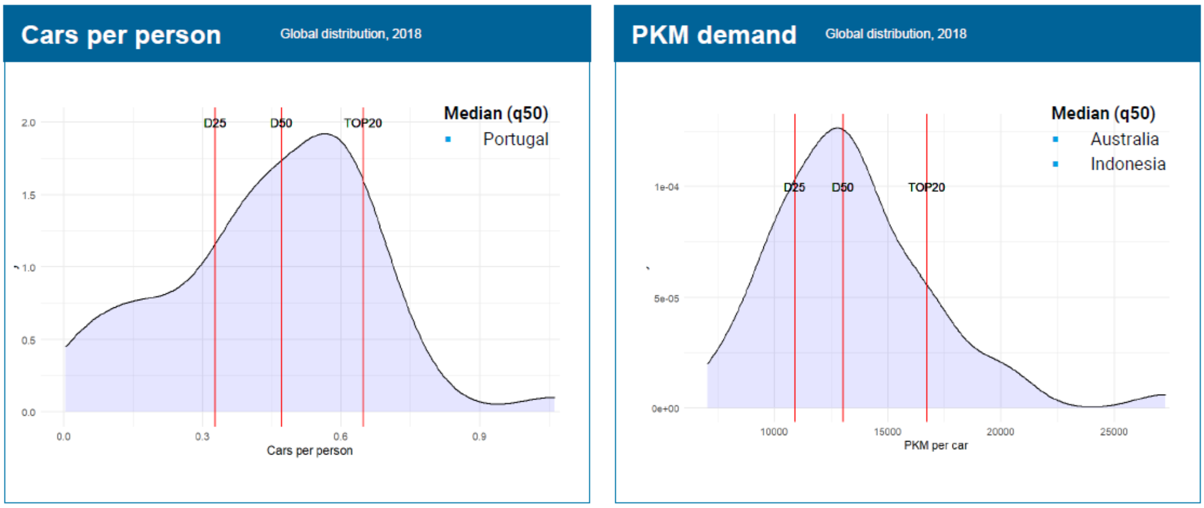
In the travel scenarios we adjusted two main variables of FTT: Transport. The first one is the passenger kilometre demand per car (PKM) which measures the distance that is equivalent to transporting a passenger over one kilometre. In other words, it describes on average how much the residents of a given country travels by car in a given year.

To establish a benchmark for empirically sufficient levels of passenger kilometres per car, we have employed a global PKM distribution derived from 2018 data encompassing 50 countries as recorded in the E3ME database (Cambridge Econometrics, 2022). In 2018, the PKM stood at 15,500 kilometres for the UK, situating the country within the upper echelon of this distribution, as depicted in Figure 2. In comparison to that, the median value of PKM was 13 000 km which was measured in Australia and Indonesia, while the first quartile value was 10 900 km in Portugal. The median PKM value observed in Australia suggests that it is reasonable to conjecture a 16% reduction in passenger road transport demand, lowering it to 13,000 kilometres, particularly given Australia's significantly lower population density, attributable to its vast territorial expanse. Consequently, achieving a PKM reduction to the median UK value is deemed achievable.

However, striving to reach PKM levels akin to Portugal's first quartile demands more ambition. While Portugal is a smaller nation in terms of geographical size, its population density remains less than half that of the UK (112 inhabitants per km^2 in Portugal as compared to 277 in the UK in 2020 (World Bank, 2023). Therefore, reaching the 10,900-kilometer PKM level (reflecting a 30% reduction) should likewise be within reach for the UK.

Similarly, we set the sufficient car ownership targets to the median and the first quartile values of the global distribution of passenger car per person calculated based on the same 50 countries. In 2018, car ownership in the UK stood at 0.46 cars per person, contrasting with a median value of 0.47 (observed in Portugal) and a first quartile value of 0.33 (recorded in Latvia). Consequently, under the scenario targeting the median, car ownership in the UK is projected to increase relative to 2018 levels, while the more ambitious scenario anticipates a 29% reduction. Nevertheless, in the reference scenario, car ownership in the UK is projected to increase even further, reaching 0.5 cars per person by 2050. Therefore, despite a projected increase in car ownership under the median scenario compared to 2018, there remains a 6% reduction relative to the reference scenario.

Figure 2: Global distribution of cars per person and PKM in 2018, source: Lam (2019



2.2.3 Modelling rebound effects of lower demand

The specifications of the scenarios for decreased energy demand in both the transportation and residential heating sectors are further leveraged through a complete macroeconomic modelling, using the E3ME-FTT model.

A natural consequence of lower demand scenarios is that consumers do not spend the amount of money which they normally would have spent on either residential heating or transportation. The important economic question that arises from this is to calculate the rebound effects of lower consumption, in other words find how consumer's overall consumption structure and demand choice elasticities change.

Consumers budget share spending on specific goods and services is estimated with co-integrated regression analysis using historical time-series data, for which the exact model specifications can be found in the E3ME Manual (Cambridge Econometrics, 2022). Explanatory variables generally include real gross disposable income, relative prices of consumption, inflation and interest rates, and demographic profile variables, which have been adjusted to the scenarios. Furthermore, E3ME uses a sub-model to calculate socioeconomic effects of income and expenditure changes by decile, in other words elasticities.

3 Results

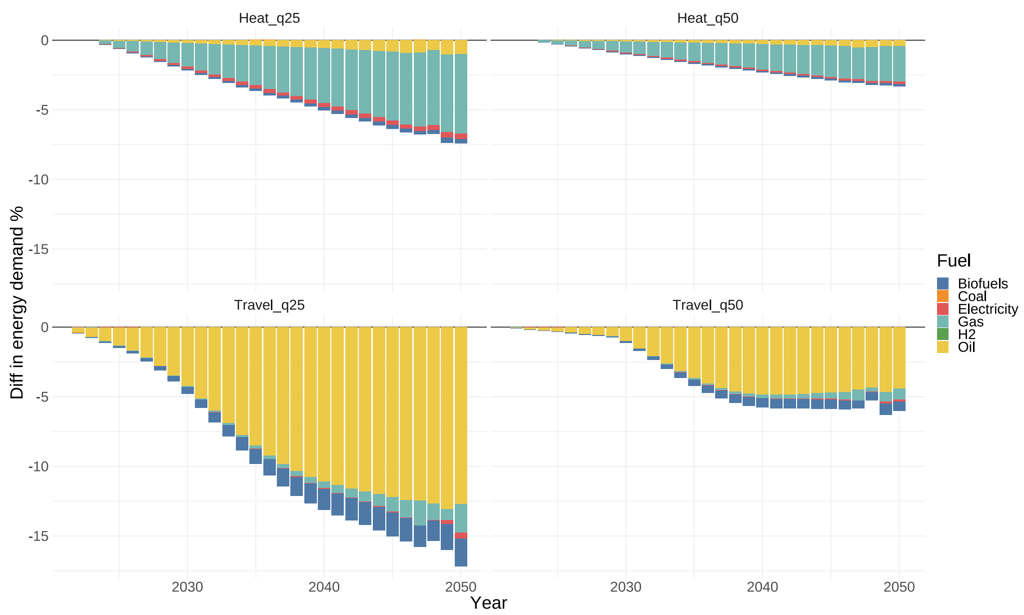
The main results of E3ME-FTT include multiple variables describing the economy, the energy system and emissions. In the followings we highlight the most important outcomes of the scenarios described in Section 4.

3.1 Energy demand reduction

In both sectors we implemented a moderate and an ambitious demand reduction scenario aiming the median (q50) and the first quartile (q25) values of the respective distributions. Based on the outcomes we can see that meeting the demand targets in the travel scenarios have substantially higher impacts on the overall energy consumption. In the travel q50 scenario oil demand is almost 5% lower than in the baseline, while in the more ambitious q25 scenario the achieved reduction is even more than 12.5%.

In the heating scenarios we see a more moderate drop in energy demand. Gas consumption decreases by around 2.5% and 6% in the heating q50 and q25 scenarios, respectively. The impacts are more pronounced in the travel scenario as in those scenarios not only the use of the cars (PKM) is restricted but the number of total cars is also lower due to the car ownership targets.

Figure 3: Impacts on energy demand, % difference from baseline

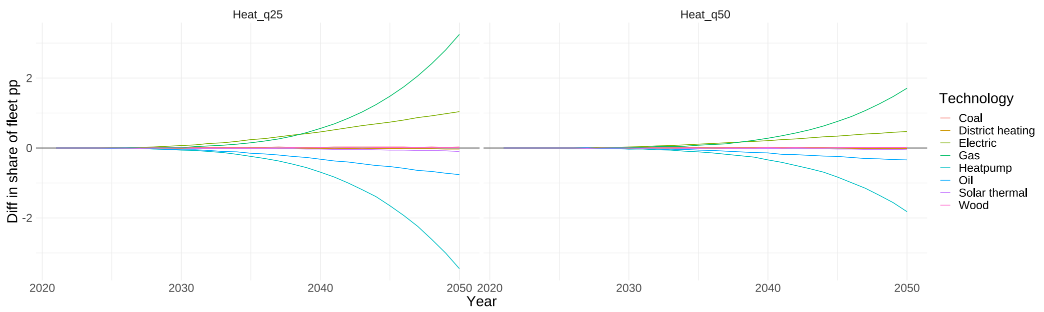


3.2 Technological transition

Technological change and innovation are heavily driven by demand. The modern technologies, like electric vehicles (EVs) and heat pumps have become competitive due to their efficiency. Although the upfront costs are still higher than their traditional competitors' like ICE vehicles or gas boilers, the fuel costs are substantially lower.

Consequently, lowering the usage of cars and heating appliances influences investor decisions as well. The bottom-up approach of modelling investor preferences through FTT helps determining the rate of technology pick-up in each sector.

Figure 4: Impacts on heating technology transition, pp difference from baseline



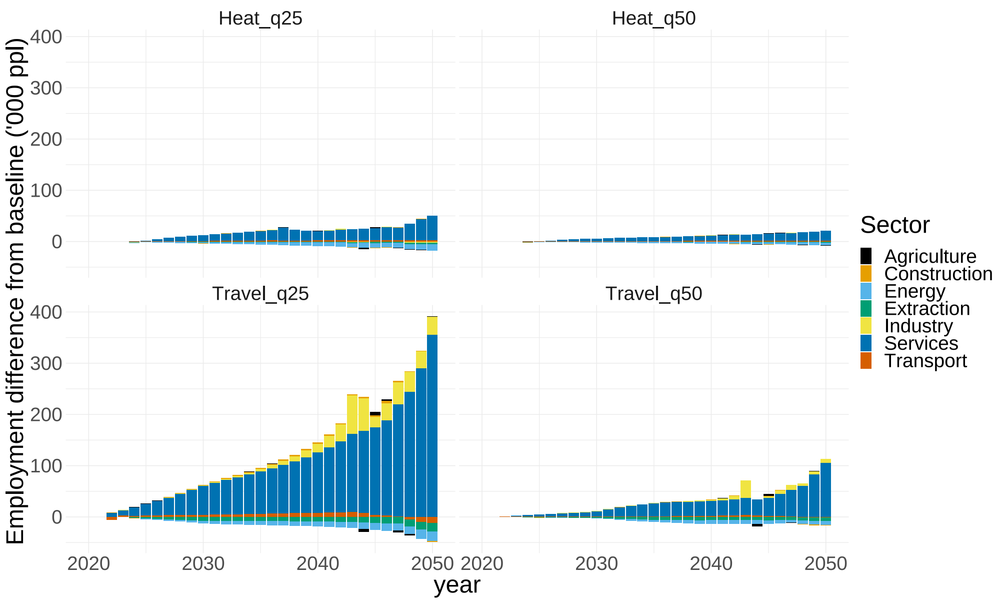
The lower capacity factor of heat pumps has a visible impact on their spread, as shown on Figure . Since the LCOH (levelized cost of heating) of heat pumps is not drastically lower than gas and electric heating, the decreased role of the fuel component makes the competitors more appealing. Consequently, the deployment of heat pumps is slower in the heating scenarios resulting in more than 3% points lower fleet share in the q25 and almost 2% points lower in the q50 scenario. Instead, more households choose gas and electric boilers for heating.

Nevertheless, we cannot see similar trends in the travel scenarios. The share of EVs is only 0.1% points lower in the travel q25 scenario than in the baseline by 2050. This could be attributed to the LCOT (levelized cost of transport) difference of the different technologies of the sector. The cost of EVs is low enough compared to other petrol fuelled vehicles that even in case of lower expected returns on investment, it is a favourable option.

3.3 Economic outcomes

There is small but positive GDP impact. Nevertheless, from Figure 5 we can see that employment effects are considerable. Employment in the most ambitious scenario in terms of energy demand decrease, in travel q25, increases by almost 400 000 people, mostly in the services sector. The sector benefits from the rebound effect as people spend their disposable income on services rather than fuel.

Figure 5: Impacts on employment by sector, absolute difference from baseline



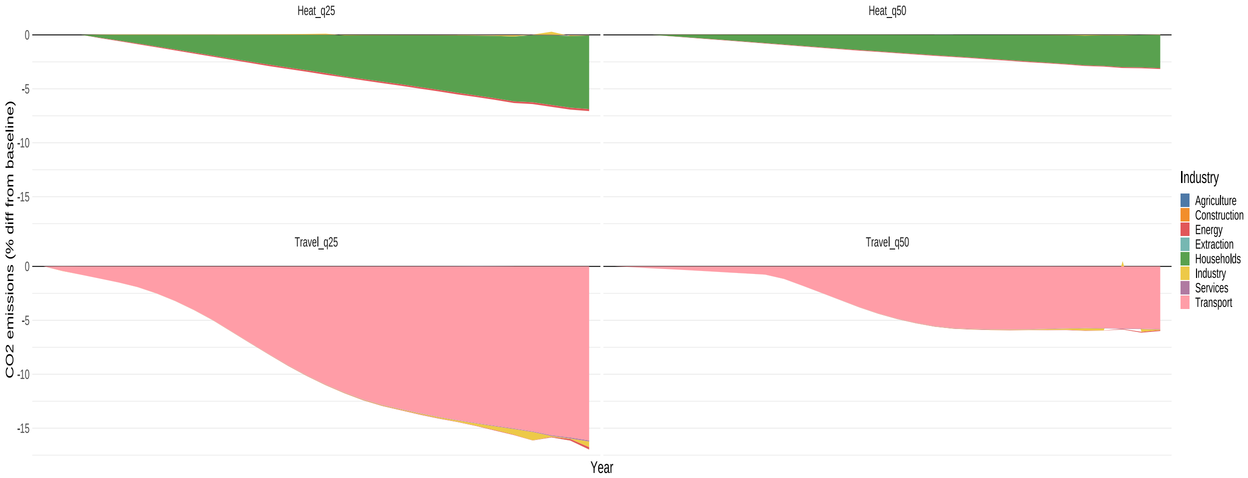
Furthermore, we model complete consumption profiles of households by income deciles. Most of the scenarios showed rather small or moderate overall effects for each of the income groups. This further highlights the suggested rebound effects, that the demand decrease of either heating or transport can turn into other consumption. An interesting aspect of consumption is how the mixture of consumption profiles change after decreasing heating or transport consumption. It can be relevant to understand how consumption changes for potential policy design on the topic. Further analysis on this issue needs to be done to provide a full picture of it.

3.4 Emissions reductions

The initial goal with decreasing household energy consumption demand has been to reduce CO_2 final emissions. Both sectors show substantial reductions in total emissions, which is a rather unsurprising, however positive first result. Figure 4 shows that the heating scenarios achieve approximately 3-7% reductions, while the transport scenarios have a higher impact of 6-17% overall emission reductions compared to the baseline scenario.

Figure 6 also represents which sectors are responsible for how much of the emissions reductions in each scenario. It is an important aspect because it shows how connected overall household emissions are. In case emissions are more connected it could be argued that a demand-side mitigation target can have a multiplicator effect and help the pick-up of other demand-side mitigation options. It is obvious from the figure, that almost all of the emissions reductions come from either the 'households' (residential heating) or transport sectors, depending on the scenario. This indicates that a more conscious energy consumption in one sector does not incentivise lower energy consumption in other sectors.

Figure 6: Emissions reductions by sector, relative difference from baseline



4 Conclusion

Demand-side CO_2 emissions mitigation potential has gained far less attention than other options such as market design, technology innovations and supply-side solutions. However, it has already been researched and modelled that they could have a serious impact on total emissions which shall not be neglected in net-zero emissions plans. Our research aims at extending our understanding of its potential by modelling demand decrease scenarios endogenously in E3ME, a macroeconomic integrated assessment model.

At first, we defined a sufficient level of energy consumption by separating the part of consumption which is due to external circumstances and therefore shall be considered as sufficient and the part on top of that which is considered as comfort consumption. Afterwards, we defined four scenarios for the UK residential heating and transport sectors. For each of them, we assumed a reduction in UK energy consumption to meet the 50^{th} or the 25^{th} percentile of the comfort consumption levels, compared to other countries. Finally, we used the scenario definitions and inputted them into E3ME modelling.

The results of the modelling clearly showed a substantial impact of CO_2 emissions reduction for both sectors, with higher relative potential in the transport sector. The technological impact varies between scenarios as there is no visible change in the technology mix of transport however the reduction in residential heating results in lower levels of heat pump adoption. Finally, the overall economic effects on GDP are negligible, however the services sector shows a higher growth due to rebound effects.

Our research provides insights into the potential economic and environmental effects of demand-side mitigation. The results of our analysis strengthen the argument that demand-side mitigation can be a substantial component of global mitigation targets, without damages to economic performance. We see however structural changes between both sectors and demographic groups. This raises the question of how to achieve any of the demand targets assumed in our scenarios? What would be the policy implications and best practices to provide incentives or regulations on consumer energy demand?

This calls for further research about tackling more and more details of the real-life feasibility of demand-side options. Moreover, the external validity of regional analysis shall be debated and differentiated analysis conducted for various regions and economic systems. Within the scope of our current research, we aim to extend the current empirical strategy to cover global regions and therefore provide more robust estimates on energy demand distribution.

5 Resources

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