Residential Energy Efficiency in Times – Analysis of Modelling Approaches and Impacts on Energy Policy

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Abstract

The TIMES energy system model has been used for informing energy and climate change policies in several countries and regions around the world. The type and scope of the studies varies, but many works consider (at least briefly) energy efficiency in their findings. However, very few include explicit energy efficiency scenarios and/or direct analysis of energy efficiency improvements. The studies that consider explicitly energy efficiency scenarios (in some cases in combination with other type of scenarios such as emission reduction targets) show significant differences on the modelling approach taken, potentially affecting the results and the impact policy decisions. Moreover, a direct comparison between energy efficiency modelling approaches in TIMES has not been developed yet.

The work developed in this paper aims to provide insight on this issue, analysing the implications of different energy efficiency modelling approaches in TIMES, and discussing best practices on informing energy efficiency policy. Three types of residential energy efficiency scenarios are analysed using the UK TIMES model, all of them with the objective of reducing 10% of energy consumption on residential heating. Results show that these energy efficiency scenarios, which are in theory equivalent, produced different results, suggesting that the modelling approach taken can significantly impact the outcomes of the model. Also, not all energy efficiency scenarios performed as expected. In one of the scenarios, other user constraints (which are common to all the analysed scenarios) limited the amount of conservation technologies available, so the expected energy savings were lower than in other cases. Therefore, the outcomes obtained show the importance of not solely relying on a particular scenario or model for policy analysis, as this might lead to partial views or suboptimal solutions.

Keywords: Energy Efficiency, Energy Policy, Energy System Model, TIMES.

1. Introduction

1.1 Background

The Scottish Government has presented its Climate Change Plan, for meeting its greenhouse gas emission reduction targets from 2017-2032 (Scottish Government, 2018). This document sets the Scottish Government's vision and ambitions to tackle climate change and decarbonize the Scottish economy.

The Scottish Government's Climate Change Plan and its related policies, draws significantly on the Scottish TIMES model. TIMES is a whole energy system model that is widely used tool for informing climate change and energy policies, with applications all around the world (Connolly et al., 2010). In the Climate Change Plan, the Scottish TIMES model is used to find least-cost ways of achieving emission reductions, also assessing how effort is best shared across different sectors of the Scottish economy. In other words, TIMES allows to develop an optimal pathway for meeting Scotland's climate change targets, including the individual sector's carbon envelopes and the suggested policy outcomes needed (Scottish Government, 2018).

There are several potential approaches to modelling energy efficiency scenarios in TIMES and numerous examples of this can be found in the literature. For instance, energy efficiency improvements could be induced in the TIMES model by implementing fuel caps (e.g. a constraint in gas or electricity use), promoting the change to more efficient technologies. Alternatively, the energy efficiency representation in TIMES could be improved by setting minimum capacity levels of energy conservation technologies (passive technologies that do not require an input fuel), such as wall and loft insulation. Both approaches (among others) could achieve the same energy efficiency objective but the way of achieving it could differ importantly. This study addresses this modelling issue, analysing the implications of different energy efficiency modelling approaches on the results obtained with TIMES.

1.2 Literature review

The TIMES model has been used for informing energy and climate change policies in several countries and regions around the world. The type and scope of the studies varies, but most works consider (at least briefly) energy efficiency in their findings. However, very few include explicit energy efficiency scenarios and/or direct analysis of energy efficiency improvements. This section reviews studies using the TIMES model that consider energy efficiency, classifying them into:

- Studies that mention energy efficiency as part of the strategies to achieve their outcomes but does not assess it.

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- Studies that indirectly assess energy efficiency, considered as an outcome of other non-energy-efficiency scenarios.
- Studies that directly assess energy efficiency, implementing energy efficiency scenarios.

For the sake of brevity, only studies falling in the 3rd group are analysed here. Note that this category includes studies that claim to have energy efficiency scenarios, even if those scenarios does not actually involve energy efficiency. For instance, cases where an exogenous demand reduction is applied, not improving the efficiency of the systems.

Figure 1 shows how energy service demand is met in TIMES, and how energy efficiency scenarios have been applied in examples found in the literature. In TIMES, energy service demands can be met with the production of energy conversion technologies and with energy conservation technologies (see Figure 1). For instance, residential space heating demand could be met by using a gas boiler (energy conversion technology) and/or by improving wall insulation (energy conservation technology). Note that this a simple generic description, and not all demands can be met with energy conservation technologies.
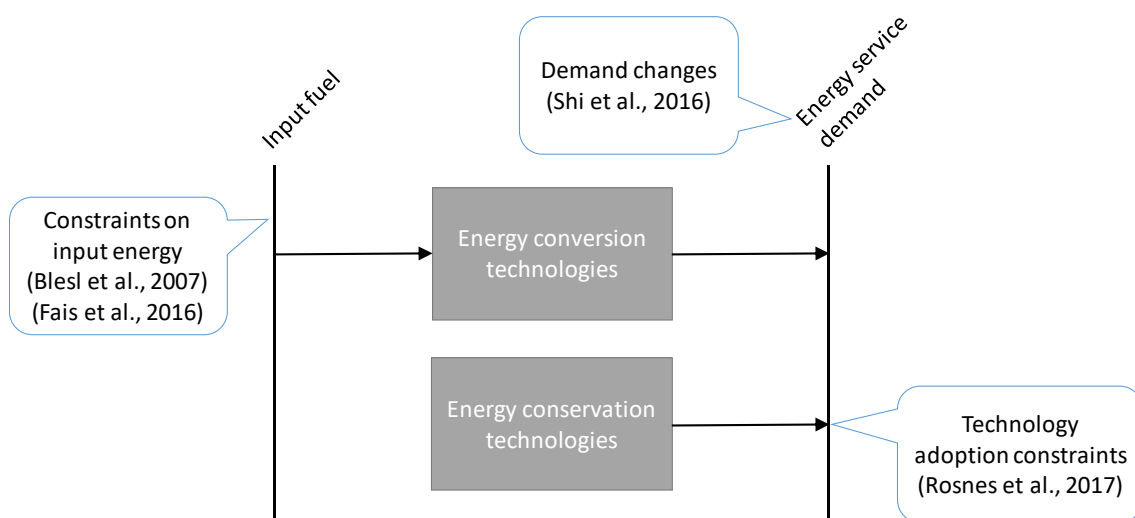

Figure 1. Energy efficiency scenario approach diagram (examples found in the literature).

The study presented in Blesl et al. (2007) approaches energy efficiency with total energy use constraints (reducing the energy input to produce the same demand), and with emission constraints, which is not directly implementing energy efficiency but could also produce improvements in this area. A similar approach is taken in Fais et al. (2016), implementing a combination of energy efficiency scenarios (energy use constraints) with emission constraints and minimum shares of renewable sources. These approaches implementing input fuel constraints could be effective to achieve overall energy efficiency improvements. Alternatively, if the final goal is to decarbonise the energy system, an emission reduction constraint could achieve more cost-effective solutions, indirectly driving energy efficiency. However, the results should be

analysed with caution as these approaches might place unrealistic burdens on certain sectors, obliged to make most of the energy efficiency improvements, or they might over rely on a limited number of technologies instead of a more realistic mix.

Conversely, Shi et al. (2016) implement their energy efficiency scenarios by adjusting their demand projections. However, it is not clear if the cost to achieve this demand reduction is considered, and how this affects the results produced with TIMES, so it could produce unrealistic technology adoption scenarios. Rosnes et al., (2017) take a different approach in their energy efficiency scenarios, implementing minimum technology adoption constraints (imposing energy conservation technologies). Certainly this approach produces energy efficiency improvements as less heat production will be required, but it is not clear what happens with the other technologies and the model might decide to change to a less efficient system that uses cheaper input fuels.

From this review, it can be seen that energy efficiency analysis in TIMES has been approached in many different ways. In addition, the way energy efficiency scenarios are modelled differs greatly between analyses, and as Blesl et al. (2007) and Rosnes et al. (2017) note, the model used and the approach taken considerably affect the results, potentially affecting policy decisions. The study developed in this paper intends to shed light on this issue, analysing the implications of different energy efficiency modelling approaches in TIMES, and discussing best practices for informing energy efficiency policy.

1.3 Scope and objectives of this study

From our initial review, we found that the studies including energy efficiency analysis with TIMES tended to lack depth or fail to follow through to the full suite of implications of energy efficiency policies. Moreover, best practices for energy efficiency policy analysis in TIMES has not been directly assessed in the literature.

Therefore, the main objective for this paper is to identify different approaches for energy efficiency scenario modelling in TIMES; provide an assessment of strengths and limitations of such modelling approaches, and give recommendations on how to use TIMES effectively for energy efficiency policy analysis.

To achieve this, the UK TIMES model is used to implement three different energy efficiency scenarios for residential heating, following different modelling approaches and replicating scenarios available in the literature. The results of these scenarios are analysed and compared against a 'business-as-usual' base scenario. The differences and potential limitations of the

scenarios is further analysed, and their implications on informing energy efficiency policy is discussed.

Note that energy efficiency is considered in this study as reducing the amount on energy input to produce the same energy service. Energy efficiency is mainly represented in TIMES by technology substitution, which involves using a more efficient technology or process to produce the same energy service. However, final energy service demands are exogenous to the model (Certain price elasticity on end user demand can be implemented in TIMES. However, this is a feature that is rarely used), so they do not react to changes in price. Also note that other typical motivations for technology change are not directly modelled in TIMES, such as consumer perception and preferences, and other economic effects, such as change on disposable income due to energy efficiency are not considered (see the report in Calvillo et al. (2017) for further discussion on these limitations). However, these issues fall outside the scope of this study, so behavioural changes and impacts on the wider economy are not analysed here.

The rest of the paper is organised as follows. Section 2 gives a brief overview of the TIMES model. Section 2 presents the scenarios and the methodology used in this study, including the description of the base scenario. Section 3 explains and discusses the results, remarking on potential limitations and drawbacks of the considered energy efficiency modelling approaches. Section 4 offers concluding remarks and recommendations on how to proceed in energy efficiency analysis using TIMES.

2. Model description

This section presents a brief description of the TIMES model, to assist the reader in gaining general understanding of the model. A more detailed description of the model can be found in Calvillo et al. (2017) and official documentation can be found in Loulou et al. (2004) and Loulou et al. (2005).

TIMES (The Integrated MARKAL-EFOM System) is an energy system-wide bottom-up model, which uses linear-programming to find a least-cost provision of energy to meet specified energy service demands, according to a number of user constraints (such as GHG emissions, energy use, etc.).

TIMES considers all the processes of the energy system. From the extraction of primary resources to the end use of energy services, the model considers all the processes that transform, transport, distribute and convert energy to supply energy services. Figure 2 shows how TIMES models the energy system. The inputs, or exogenous variables of the model, are the data of the supply and

demand side. The former is composed by the primary energy resources and imports availability (block 1), and the latter corresponds to energy service demands (block 6). Note that the energy demands drive all the energy system in the model and are structured by sectors: residential, commercial, agricultural, transport and industrial ("IEA-ETSAP | Times"). The outputs of the model, or endogenous variables, include emissions and waste (block 7), energy losses associated to the processes (block 8), technology capacity planning (investment decisions) and different economic variables (block 9), including energy prices, costs, profits, etc. Additionally, energy flows (energy carrier variables) are also endogenous to the model, while the technology and processes techno-economic parameters (costs, discount rates, efficiencies, and other technical constraints) are exogenous.
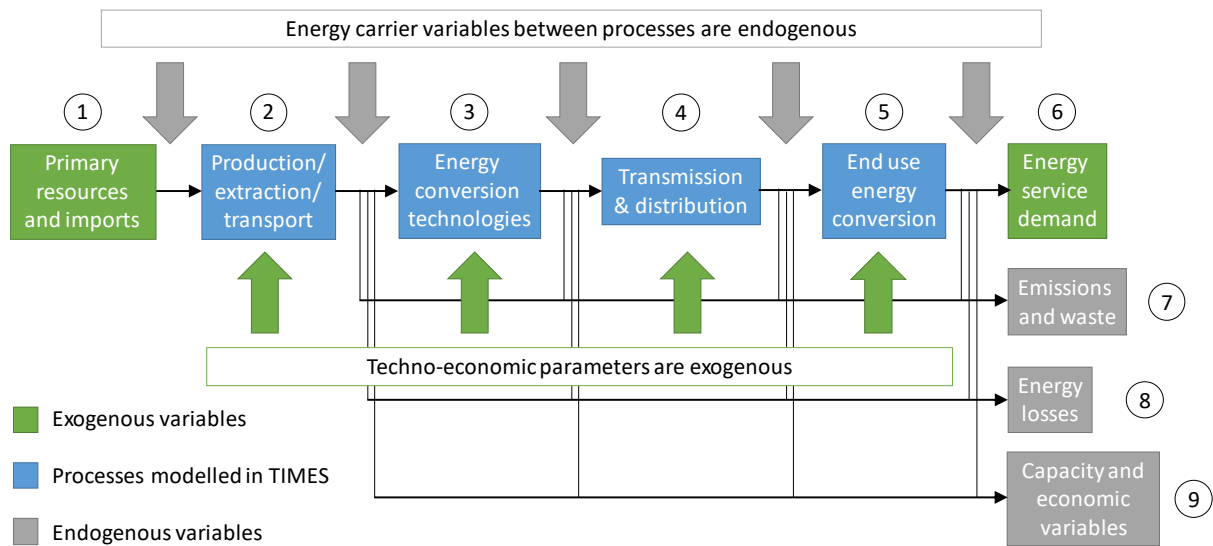

Figure 2. Modelling of the energy system in TIMES (Calvillo et al., 2017).

3. Scenarios and case studies

This section describes the energy efficiency scenarios used in this study to assess the impacts of the different modelling approaches. It also presents the methodology used to compare and analyse the scenarios, including a description of the base scenario that is used as a benchmark.

3.1 The UKTM model and the base scenario

The UK TIMES model (UKTM) is used in this study to test the energy efficiency scenario (The UKTM version used for this study is V.1.2.2). This model differs from other TIMES versions, especially on the input data used, which should reflect the characteristics of the country or region

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modelled. However, the general structure of the models will be similar, so the insights obtained here are very likely to be useful and could be applied in other TIMES models.

UK TIMES is a very large model with thousands of variables, parameters and constraints. For the sake of brevity, only data and variables related to the residential modelling and heating demand in the base scenario are presented here (see ("UKTM-UCL") for more information on the UK TIMES model).

Figure 3 shows the total energy use for residential heating purposes in the base scenario. In the UKTM model, residential demand is organised in two groups: existing aggregated houses (labelled 'EA' in Figure 3), which represent the combined energy service demands for all existing houses in the UK by the start of the baseline year (2010), and new aggregated houses (labelled 'NA' in Figure 3). It can be seen that EA demand decreases in time (blue line with marker 'o' in Figure 3), as existing houses are replaced by new houses, so NA demand increases (red line with marker '∗') accordingly. The sum of both groups of houses is the total residential heating demand in this base scenario (yellow solid line).

The energy efficiency target to be applied in this study for all scenarios (described in detail in section 3.2) is illustrated with the purple dashed line in Figure 3. The resulting energy use value of this target is computed as 10% less the total energy consumption value in 2010.
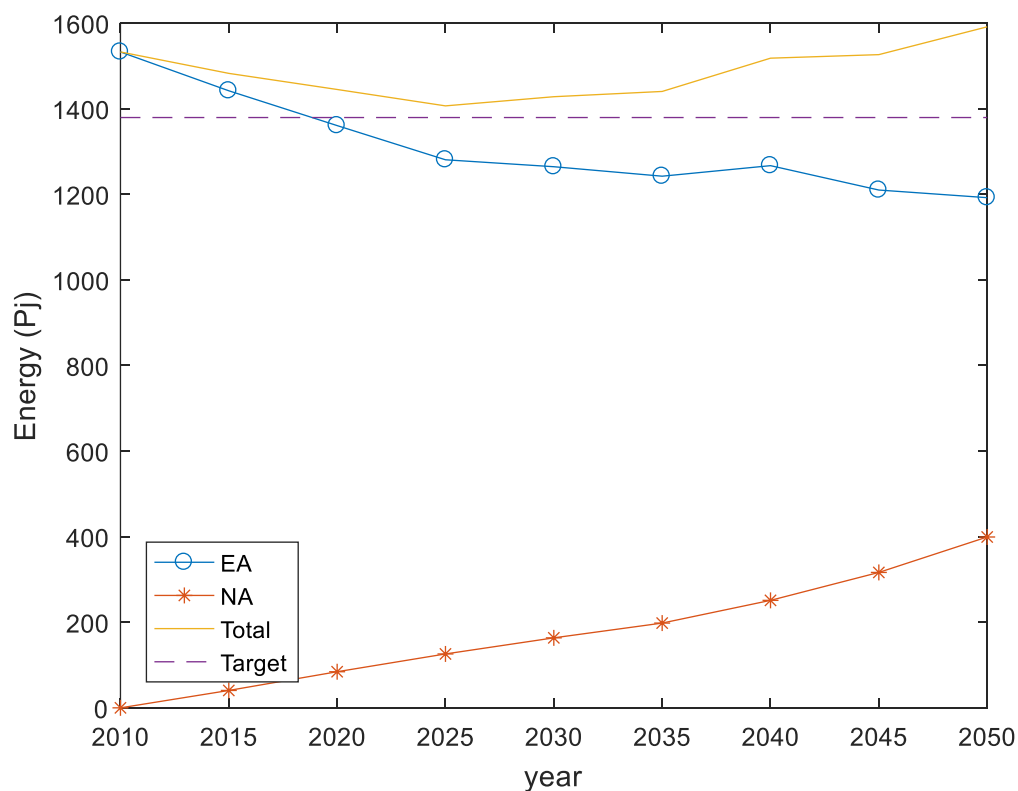

Figure 3. Aggregated residential heat energy use – Base scenario.

Figure 4 shows the fuel mix to meet the residential heating demand in the base scenario at different years. Looking at the figure it is clear that the main input fuel for heating is gas, starting with around 85% of total energy consumption in 2010 and increasing up to around 90% in 2030 and 2050. Other important fuels in 2010 (see left column in Figure 4) are oil (OIL 7.4%), electricity (ELC 5.3%) and small shares of coal (COA 1.7%) and biomass (BIO 0.4%). For 2030 (see middle column in Figure 4) oil and coal disappeared and are manly replaced by electricity (ELC 9.9%). Lastly, 2050 maintains a similar image to 2030 fuel mix with very minor variations (see right column in Figure 4).
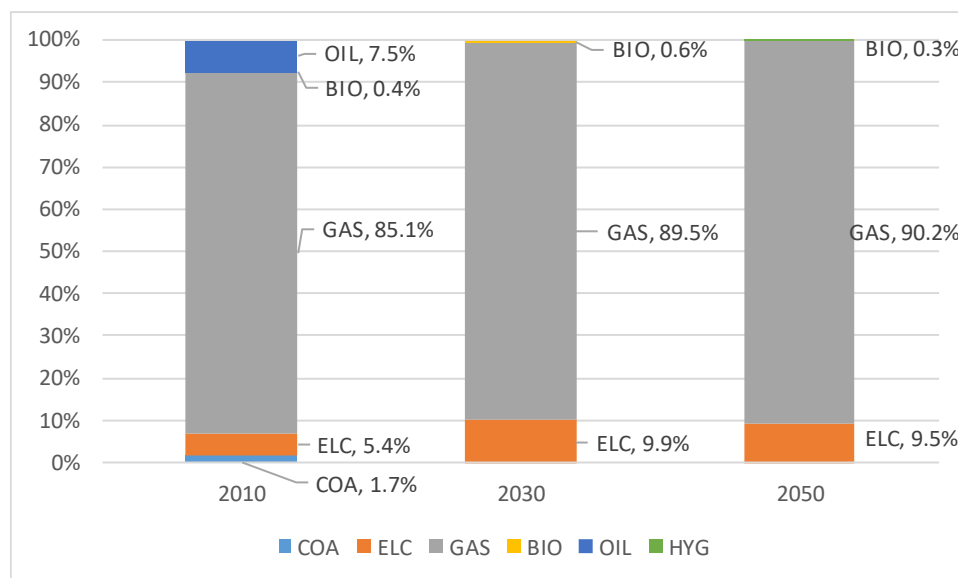

Figure 4. Residential heating energy consumption by fuel in 2010, 2030 and 2050 – Base scenario.

Figure 5 shows the technology production mix. In 2010 (left column in Figure 5), the technology with the largest penetration is the gas boiler (91%), with the oil boiler in second place (6.5%). Other technologies are also present but with considerably smaller penetration levels: coal boiler (1.2%), district heating (1.1%), electric boiler (0.2%) and heat pumps (HP, 0.1%). In 2030 (middle column in Figure 5) an important change appears, as the oil and coal boilers, HP and partly gas boilers are replaced with gas-fired combined heat and power systems (CHP, 16.6%) but gas boilers remain the main technology with 82.1%. By 2050 (right column in Figure 5) the CHP increasing trend continued and it now fully replaces gas boilers, reaching 95.9% of technology penetration. The technology mix is complemented with electric boilers (2.4%) and district heating (1.7%).

These shares correspond to the fuel mix shown in Figure 4, where gas is the main input fuel, so the main technology used in this base scenario is the gas boiler and CHP. Note that these TIMES results show the potential least cost energy system according to the data and modelling

constraints set in UKTM and this base scenario, which is used as a bench mark for this analysis. However, it does not necessarily reflect most probable or practical scenario for the UK in 2050.
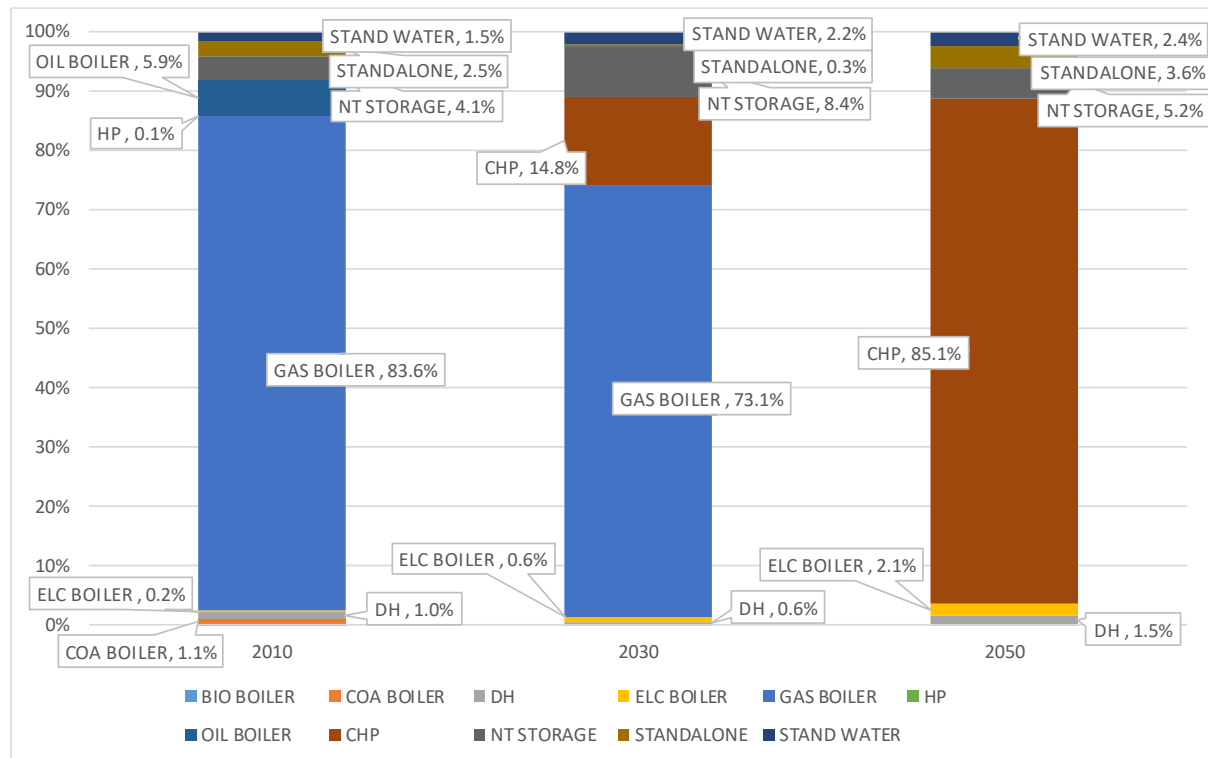

Figure 5. Residential heating production by technology in 2010, 2030 and 2050 – Base scenario.

3.2 Energy efficiency scenarios formulation

Figure 6 shows the residential heating modelling approach used in TIMES. Residential heating is an energy service demand modelled as two demand commodities: domestic hot water and space heat (right-hand side of Figure 6). The domestic hot water demand in TIMES can be met with energy conversion technologies, such as water boilers, that transform energy carriers (e.g. electricity, gas, oil, etc.) in the required service. The space heat demand in TIMES uses the same energy conversion technologies as for the hot water demand, but it can also be met with energy conservation technologies, which are passive elements that reduce the need of space heating demand (e.g. insulation materials, smart thermostats, etc.). As demands are mainly static in TIMES (i.e. they are exogenous user-defined parameters that cannot be modified endogenously by the model), these energy conservation measures are modelled as a technology that also produces that service, indirectly reducing that demand, but without an input fuel (see the lower block of technologies in Figure 6).

Many types of scenarios can be modelled and analysed in TIMES. Unfortunately, the creation of energy efficiency scenarios is not straightforward: it is not possible just to set a 10% energy

efficiency constraint. Therefore, and as described in section 1.2, energy efficiency scenarios have been modelled in a variety of ways, which are likely to affect the outcomes.

In this study, three different energy efficiency scenarios for residential heating are proposed, with the objective of analysing the implications of the chosen modelling approach on the TIMES outcomes. The energy efficiency scenarios (for residential heating) are:

- Scenario 1 – all input fuels constraint.
- Scenario 2– minimum energy conservation technology adoption constraint.
- Scenario 3 – space heat energy service demand reduction.

Figure 6 also shows where the specific modelling constraints apply. Note that these scenarios have been selected as they represent similar approaches found in the literature (see section 1.3).

Note that all scenarios are modelled to indirectly increase energy efficiency in residential heating (space heat demand) by 10% from 2030 (relative to 2010).
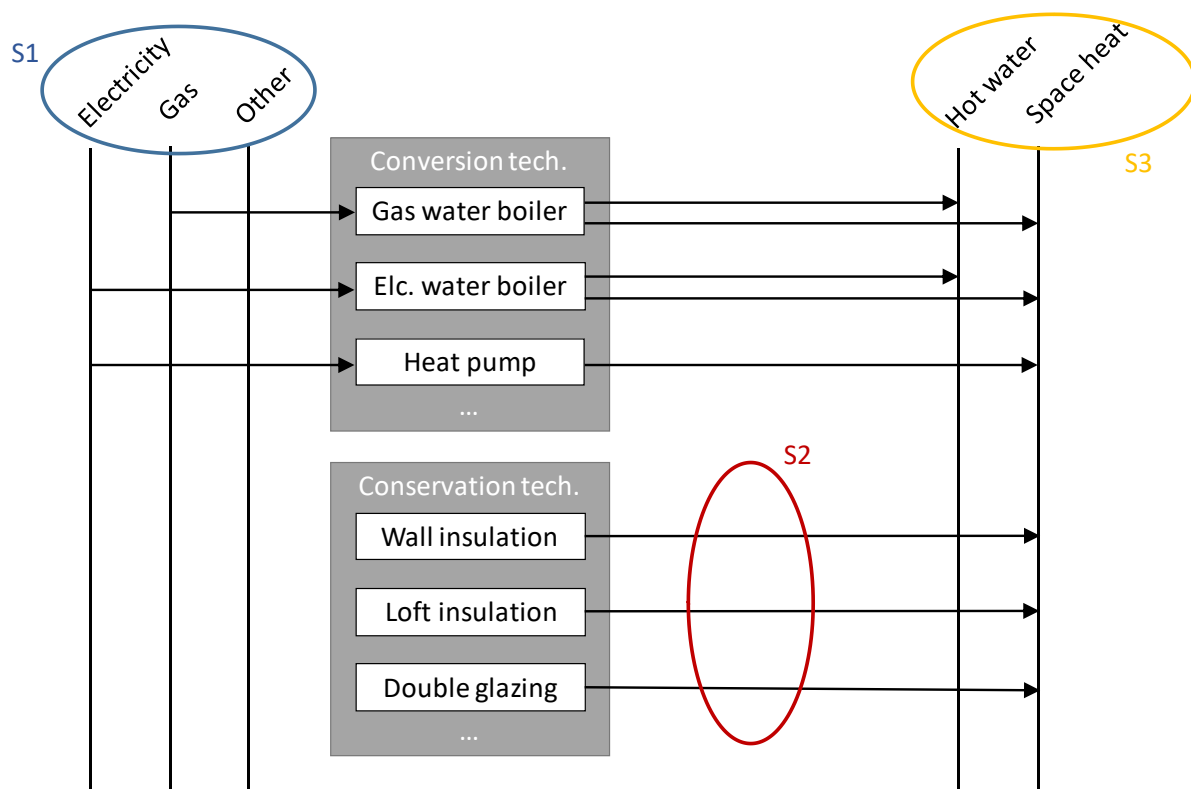

Figure 6. Summary of energy efficiency scenarios for this study.

3.2.1. Scenario 1: input fuels constraint

The input fuels constraint scenario is similar to the one presented by Blesl et al. (2007). In this scenario the total amount of input energy for residential heating processes (in peta Joules 'Pj') is

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reduced by 10% from 2030, relative to the energy input on the base case at 2010. Equation (1) shows this constraint, where the sum of energy input for heat technologies (*energyInputHeat*) for all energy carriers '*e*' and technologies '*t*' in scenario '*S1*', is lower or equal to the sum of the energy input for heat technologies in the base scenario '*SB*' in 2010. Note that this applies to all years between 2030 and 2050, and that the constraint set in this scenario will apply to all residential heating technologies (heat pipe and standalone), but does not directly affect energy conservation technologies.

$$\sum_{e,t} energyInputHeat_{S1,y,e,t} \leq 0.9 * \sum_{e,t} energyInputHeat_{SB,2010,e,t}$$

$$\forall y = [2030, \dots, 2050]$$

(1)

By reducing the use of fuels for heating technologies, the effects of this constraint are likely to be a higher implementation of energy conservation measures, which do not use any input fuels. Also, as this constraint limits the sum of all energy types, changes to more efficient technologies are likely to happen. That is, changes to technologies that produce more units of heating services per unit of input energy (e.g. heat pumps), independently of the type.

3.2.2. Scenario 2: minimum level of conservation technologies

This scenario is similar to the one presented in Rosnes et al. (2017). In this case, the implementation of energy conservation technologies is set to increase (see S2 in Figure 6), so heating production technologies are not directly affected, but their participation to meet the energy services demand is reduced. Eq. (2) shows this, where the sum of the energy output (*energyOutputHeat*) of all energy conservation technologies '*tcs*' has to be greater or equal to the energy savings of the energy efficiency target (10% of total energy use in SB at 2010) plus the energy conservation production on the base scenario in 2010 (the original implementation level).

$$\sum_{tcs} energyOutputHeat_{S3,y,tcs}$$

$$\geq 0.1 * \sum_{t} energyInputHeat_{SB,2010,e,t}$$

$$+ \sum_{tcs} energyOutputHeat_{SB,2010,tcs} \qquad \forall y = [2030, \dots, 2050]$$

(2)

This constraint takes a complementary approach to previous scenarios, as it forces the model to implement energy conservation measures so the need to use fuels for heating is reduced. Instead of limiting the use of fuels (the case of S1). Therefore, the outcomes of this scenario are likely to

be similar to those of previous scenarios, with a potential larger share of energy conservation technologies.

3.2.3. Scenario 3: demand reduction

A demand reduction scenario is implemented, similar to the one used in Shi et al. (2016). In this case, the residential heating and domestic hot water demand projections are modified and no extra constraints are needed. Figure 7 shows the change in demand for this scenario, where all four types of heating service demands modelled in UKTM (RHEA, residential heating existing houses; RHNA, residential heating new houses; RWEA, residential hot water existing houses; RWNA, residential water new houses) are reduced by 10% from 2030 (see the dotted lines in the Figure 7). This is demand change is implemented in TIMES by modifying directly the demand projection values of these commodities.
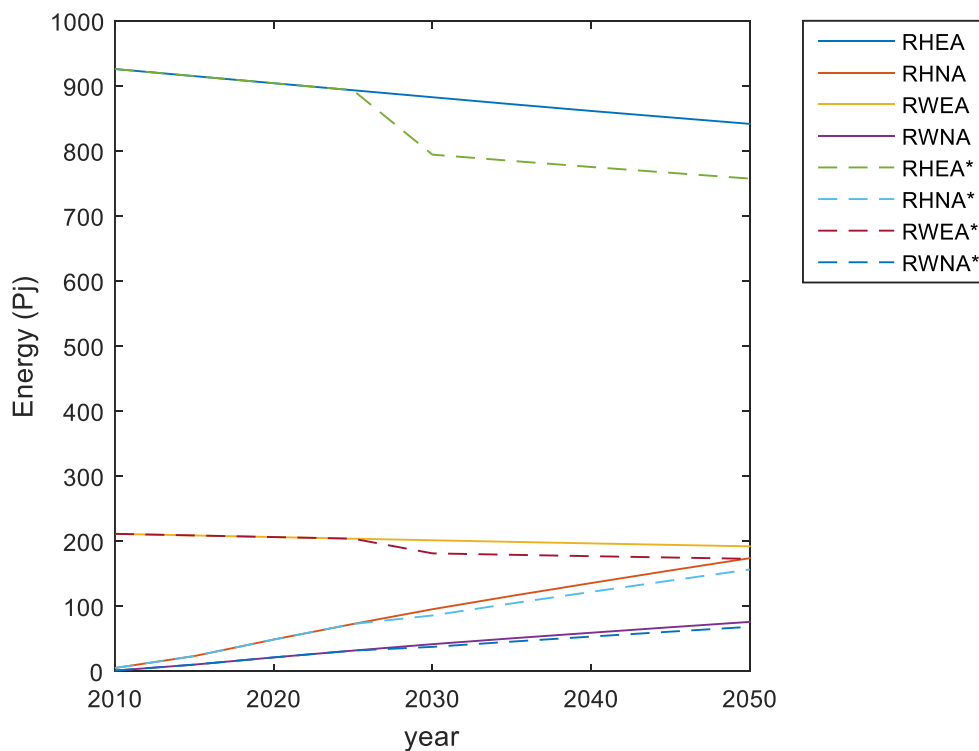

Figure 7. Residential heating – Demand reduction scenario.

This scenario does not implement any constraint so the model has the flexibility to modify the use and investments of heating technologies. Considering the reduction in demand, an overall reduction of technology use is expected, and the most expensive technologies are likely to show the largest reductions.

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Note that this scenario implies a change on consumer behaviour which occurs outside of the model, and this demand reduction does not represent an improvement in energy efficiency in TIMES. Even though this scenario does not represent a real energy efficiency scenario, it is considered in this study as it exemplifies an approach found in the literature claiming to be 'energy efficiency'.

4. Results discussion and policy implications

TIMES produces a very large quantity of results for all the energy system. For the sake of brevity, only results related to residential heating energy use, technology changes CO_2 emissions and total costs are reviewed here.

Note that the original energy efficiency target used for S2 has to be modified. The target set for this scenario was a minimum of 168.6 Pj of annual energy conservation technology production (this replaces the heating produced from other technologies such as gas boilers or HP), from 2030 to 2050 (see section 3.2.2). However, this constraint has proved to be problematic for the model as the total costs obtained for this scenario is almost 9 times higher (873%) than the costs in the base scenario. Analysing the results, it was found that the constraint in S2 is infeasible, as the energy conservation technology present a technology cap (set by the UK TIMES modellers), and the total possible production of these technologies is 154.3 Pj which is slightly below the desired target. This infeasibility therefore explains the enormous increase in total costs. TIMES implements "dummy" variables that help the model to find feasible solutions where otherwise would not be possible, but at a considerably higher costs (to avoid to be used unless absolutely necessary).

To obtain reliable results, a new target has been set for this scenario (labelled S2*), adjusting the minimum level of annual energy conservation technology production to 154 Pj. The problem presented in this scenario is an example of potential issues caused by constraints and considerations set by TIMES modellers, which if they are not set based on adequate projections or assumptions, could unnecessarily limit or bias the solutions.

4.1 Result discussion

The results of the different scenarios illustrate the wide range of solutions that could be obtained with TIMES when simulating equivalent (in principle) energy efficiency scenarios. To facilitate the comparison of scenarios, the main outcomes of these scenarios are summarised in this section, and a discussion on their potential policy implications is provided.

Table 1 and Figure 8 show the overall changes in technology adoption for all scenarios. The total amount of residential heating technology production decreases in all cases and does not vary significantly across scenarios. Energy conservation technologies present larger changes and higher variability between scenarios (see the second column in Table 1). For instance, S2*, implementing a minimum level of energy conservation technologies, show the largest increment on energy conservation (around 45%). S1, implementing input fuel constraints, also show an increment but not as important (around 21%). Conversely, the demand reduction implemented in S3 produced a decrease in energy conservation (-10.63%).

Driving technology adoption through policy (for example, by subsidising or giving credits to purchase certain technologies) could be an effective way of achieving different goals, such as energy efficiency improvements. Models such as TIMES could provide valuable insight on which technologies could be supported and which ones should be analysed further. However, as shown in Figure 8 (the technology mix for all scenarios), the implications of decisions could be very different depending on the energy efficiency modelling approach taken. For example, S1, presents a radically different technology mix than the other scenarios, even though they achieve very similar total energy efficiency improvements. The technology mixes presented in the other scenarios are similar to one another, with some very similar to the base case (see for example S2* in Figure 8).

Note similar energy efficiency scenarios to the ones presented here have been used in the literature. For instance, S1 is comparable to the scenario in Blesl et al. (2007), S2 follows the same approach used in Rosnes et al. (2017), and S3 resembles the scenario analysed in Shi et al. (2016). Also note that none of these approaches is 'wrong' in principle, but as clearly seen in these results, the scenarios impact the system in different ways. It is important to analyse different modelling approaches and look into other relevant outcomes as well, such as the changes in cost and emissions.

Table 1. Residential heating and energy conservation technology changes for all scenarios (relative to base scenario).

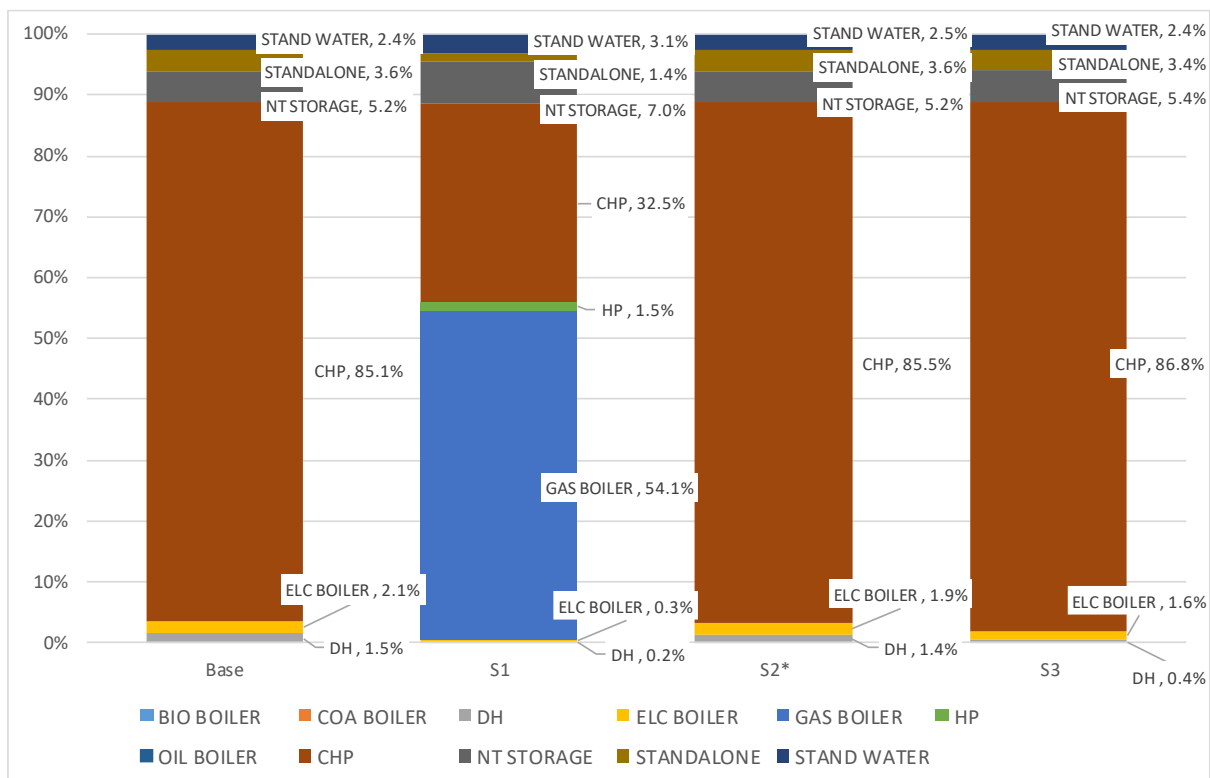| Scenario	Heating tech. change (%)	Energy cons. tech. change (%)
S1	-1.26	21.91
S2*	-2.55	43.94
S3	-5.31	-10.63

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Figure 8. Comparison of heating technology shares across scenarios.

Table 2 summarises other main results of the analysed scenarios, including reductions in CO_2 emissions, reduction on total fuel use for residential heating (the energy efficiency improvement) and changes in total system costs. With the exception of S2*, the CO_2 emission reductions in the residential sector in 2050 is around 10%. However, this reduction in the residential sector does not necessarily translate to equivalent reductions in total system emissions. For example, scenario S1, presented a better sectorial performance than S2* on residential emissions but it presents the worst overall result in total CO_2 emissions. This shows that sectorial targets alone might be misleading and – at least in terms of the TIMES model – could be counterproductive.

In S1 and S3 the energy efficiency improvements (residential heating fuel use, see third column in Table 2) is more than 10%. The exception once again is S2*, which presents a reduction of less than 1%. It should be noted once again that this scenario was 'relaxed' from its original target as it was creating an infeasible solution due to modelling constraints in UKTM. However, the target adjustment was relatively small so such a big difference in energy efficiency performance with the other scenarios was not expected. However, the energy conservation target forced the model to invest in more expensive energy conservation technologies, increasing the overall costs. The model, thus tried to reduce the cost by shifting to cheaper but less efficient technologies and fuels, using more energy and reducing considerably the benefits of energy conservation.

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Interestingly, when this energy efficiency approach has been used in the literature (as in Rosnes et al. (2017)), it did not perform as in this study. This reinforces the point that the presence of modelling considerations and user constraints in TIMES can influence the outcomes of scenarios, potentially limiting and/or biasing the results. Therefore, it is important to analyse in detail such model constraints, making sure they follow realistic and sensible considerations and projections.

Lastly, the total system cost (see fourth column in Table 2) increases for all scenarios with the exception of S3. This scenario implements a demand reduction in residential heating services, which is similar to the scenario developed in Shi et al. (2016). Just considering the change to total costs, modelling scenario S3 seems to perform best to achieve the energy efficiency targets. However, the results should be analysed with caution as it does not represent (strictly speaking) energy efficiency, rather it implements a 'free' demand reduction. In other words, the benefits obtained in this scenario should be contrasted with the potential costs for producing this change in consumer behaviour. TIMES cannot readily model the costs of any policies required to achieve this (if indeed it is achievable), so it is difficult to do a fair comparison of this scenario with the others.

Table 2. Residential heating and energy conservation technology changes for all scenarios (relative to base scenario).

Scenario	CO_2 emissions Res. sector change (%)	CO_2 emissions change total (%)	Res. heat fuel use change (%)	Total system cost change (%)
S1	-3.69	-0.15	-13.58	0.08
S2*	-2.34	-0.29	-0.82	0.04
S3	-5.07	-0.69	-10.37	-0.48

4.2 Limitations and future work

We believe that this study and the selected approaches provide a wide spectrum of modelling possibilities and valuable insight. However, there are some opportunity areas and limitations of this study that should be taken into account. For instance, the list of scenarios considered is not exhaustive, as other variations could also be considered for energy efficiency analysis. It is, therefore, part of future work to analyse in more detail other energy efficiency modelling scenarios.

Moreover, the performance and specific issues presented in these scenarios cannot be generalised, as they derive (at least partly) from the way the UKTM is modelled and the input data considered in the base scenario. Other TIMES models and different input parameters are likely to show different behaviour across scenarios. For instance, more constrained base models are likely

to show more similar results for the different approaches (less flexibility to achieve the targets) and vice versa. On the other hand, less constrained models might not present the infeasibility issues presented here.

Lastly, this study analysed solely energy efficiency scenarios without any other type of scenario. However, many 'real' TIMES applications (referring to TIMES analyses commissioned for or used directly by policy makers to inform their policies, and not just academic exercises) consider several scenarios, including constraints affecting all sectors, run simultaneously. An example of this could be an analysis including a sectorial energy efficiency scenario, plus a minimum level of renewable energy generation, and an overall CO_2 emission constraint. Therefore, the endogenous dynamics of the model considering several scenarios are likely to change, and the difference between the energy efficiency modelling approaches might be reduced. In other words, other constraints could be more restrictive in obtaining the optimal solution than the energy efficiency ones, in which case, the energy efficiency approach taken is less relevant.

5. Concluding remarks and recommendations

The TIMES model has been widely used to analyse and inform policy, by creating and contrasting future energy system scenarios. TIMES applications vary not only on geographical scale but on type of scenario objectives as well. Energy efficiency in the residential sector is one example of such applications, with several studies available. However, the modelling approach taken on the energy efficiency scenarios varies considerably between them.

This study analysed three energy efficiency scenarios for residential heating using UK TIMES. These scenarios are similar to the ones available in the literature. The results obtained show important differences across scenarios. While almost all of them achieved the energy efficiency target, no scenario showed an overall best performance in terms of emissions reduction, energy efficiency improvements and total cost. So the decision on which modelling approach to use to inform policy development is not straight forward.

Therefore, it is important to check if modelling constraints are not over-limiting or biasing the results. In TIMES, the modelled technologies and processes use parameters and constraints that limit (or set) the capacity, production, and/or the adoption rate of technologies, with the objective of replicating (to some extent) consumer adoption profiles, avoiding dramatic 'overnight' technology changes. In this study, these types of modelling constraints were limiting the implementation of energy conservation technologies, so the energy efficiency target could not be reached by solely using such alternatives. Certainly, this is not necessarily an erroneous outcome,

but it is important to analyse the reasons behind these modelling constraints, checking if they are based on reliable/sensible considerations and projections.

Decision makers should also consider other outcomes of the policies besides the main energy efficiency improvement objective. For instance, considering the policy priorities, the preferred scenario could be that which, in addition to achieving the energy efficiency target, also has the better CO_2 emissions performance, or the lower costs.

Lastly, it should be noted that there are external factors that are not be considered in TIMES. In the case of energy efficiency, many benefits go beyond the energy system, including benefits on the economy, health and well-being (IEA, 2014). Therefore, it is highly recommended to use other models alongside TIMES to test the feasibility or plausibility of the outcomes and to understand better the implications of energy efficiency. For instance, a Computable General Equilibrium (CGE) model could be used to assess economy wide impacts of changes in the energy system.

The analysis in this study provide insight on some of the modelling challenges for energy efficiency analysis. This insight could be relevant for policy makers and wider stakeholders, increasing knowledge about potential conflicting targets, such as decarbonisation of heat vs system costs, while also assisting them to assess best practices in energy efficiency modelling and to understand better the potential impacts of energy efficiency measures in the residential sector.

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