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Energy efficiency policy analysis with TIMES

Assessment of energy efficiency modelling approaches and their potential impact on policy

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Executive summary

This report looks at different approaches to modelling energy efficiency within TIMES, the whole energy system modelling framework used by the Scottish Government to inform energy and climate change policy decisions. The approach taken can affect the results significantly, potentially affecting policy decisions. The research examines the implications of these different approaches and discusses best practice in order to inform energy efficiency policy.

The main objectives for this report are:

1. To identify different approaches for energy efficiency scenario modelling in TIMES, and provide an assessment of strengths and limitations of each modelling approach.
2. To give recommendations on how to use TIMES effectively for energy efficiency policy analysis.

To achieve this, the UK TIMES model is used to implement six different energy efficiency scenarios for residential heating (i.e. reducing the energy use for heat demand of the residential buildings, via the implementation of different user constraints, while still meeting end user requirements), 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 main findings include:

- Energy efficiency scenarios which are, in theory, equivalent produced different results in terms of technology mix, energy use, CO_2 emissions and costs. This suggests that the modelling approach taken can significantly impact the outcomes of the model, potentially translating to very different policies.
- Pre-existing user-defined constraints within the model could limit or bias the policy solutions resulting from modelling runs. In this study, user constraints (not related to the analysed energy efficiency scenarios) were limiting the implementation of energy conservation technologies so the energy efficiency target could not be reached solely by using such alternatives.
- Some scenarios can provide better insight to informing policy as they more accurately reflect the impact of energy efficiency improvements in real life.
- There is no single energy efficiency scenario which is superior to the others, as each focuses on different policy targets which could come into conflict with each other. For example, the results of some scenarios prioritise energy efficiency improvements whereas others prioritise cost reduction or emission reductions. Policy makers should understand the compromises involved in using each of these scenarios and prioritise certain indicators over others.

The expected next steps in this research are;

i) to analyse energy efficiency scenarios in tandem with other types of scenarios, assessing if energy efficiency measures alone can deliver the relevant decarbonisation targets or if other measures are also required;

ii) to perform energy efficiency scenario analysis using TIMES and Computable General Equilibrium (CGE) economic models, with the objective of analysing the impact of energy efficiency measures in the wider economy as well as in the energy system.

We believe that the insight produced in this study could be relevant for policy makers and wider stakeholders in analysing and designing the best energy efficiency policy measures, with the assistance of TIMES. In the Scottish context, the insights from this research could inform the modelling of energy efficiency scenarios in TIMES to help design policies which most effectively meet the objectives of the Scottish Government's Energy Efficient Scotland programme.

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1. Introduction

1.1 Background

In 2018 the Scottish Government published the Climate Change Plan for meeting its greenhouse gas emission reduction targets from 2017-2032 (Scottish Government, 2018a). The document sets out the Scottish Government's vision and ambitions to tackle climate change and decarbonise the Scottish economy. In addition to the Climate Change Plan, the Scottish Energy Strategy, published in 2017 (Scottish Government, 2017a), presents the Government's plans for the transition to a highly decarbonised energy system. Meanwhile the Energy Efficient Scotland Route Map (EES, Scottish Government, 2018b) sets out the Scottish Government's plans to reduce energy demand, decarbonise the heating of Scotland's built environment and tackle fuel poverty in a way that is socially and economically sustainable, reflecting the Government's designation of energy efficiency as a National Infrastructure Priority.

The main milestones set in the Climate Change Plan for energy efficiency are:

- "Where technically feasible by 2020, 60% of walls will be insulated and 70% of lofts will have at least 200mm of insulation in the residential sector.
- By 2032, 35% of domestic buildings' heat will be supplied using low carbon technologies (including electrification of heating), where technically feasible, and the buildings will be insulated to the maximum appropriate level.
- By 2032, 70% of non-domestic buildings' heat and cooling will be supplied using low carbon heat technologies.
- By 2032, improvements to the building fabric of domestic buildings will result in a 15% reduction in domestic heat demand.
- By 2032, improvements to the building fabric of non-domestic buildings will result in a 20% reduction in non-domestic heat demand." (Scottish Government, 2018a).

Meeting these targets will require a transition of all buildings: homes, commercial properties and the public sector in Scotland to be near zero carbon by the middle of this century.

The Scottish Government's Climate Change Plan and its related policies draw significantly on the results of applications of the Scottish TIMES model. TIMES is a whole energy system modelling approach that is a widely used tool for informing climate change and energy policies, with applications all around the world (Calvillo et al., 2017; 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 effect, TIMES allows the development of a least cost pathway for Scotland's energy system in meeting climate change targets (Scottish Government, 2018a).

1.2 Limitations and considerations of energy efficiency modelling and analysis with TIMES

The literature examined for this report suggests that there are certain limitations and considerations that should be taken into account when analysing energy efficiency scenarios with TIMES. Some of the key issues in energy efficiency analysis with TIMES are explored below.

1.2.1 Issue 1 – Energy efficiency impact analysis with TIMES only addresses technology substitution

Energy efficiency is mainly represented in TIMES via 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, so that they do not reflect the elasticity of demand[1]. Moreover, besides cost, other typical motivations for technology change are not directly modelled in TIMES. For

[1] A certain price elasticity on end user demand can be implemented in TIMES. However, this is a feature that is rarely used.

instance, consumer perception and preferences are not endogenous variables of the model, and other economic effects, such as change on disposable income due to energy efficiency or growth or contraction in different sectors of the economy that, in turn, affect energy service demand in these sectors, are not considered[2].

These characteristics limit the capability of TIMES to model and analyse the impacts of a broader range of energy efficiency actions on the wider economy and on energy user and supplier behaviour. (See Calvillo et al., 2017, for further discussion of these limitations). Whilst this issue is not the focus of the current report, it warrants further study.

1.2.2 Issue 2 – The user must choose how to test specific policies or targets with TIMES – The 'what if…' (Intervention driven) vs the 'how to…' (Goal driven) question

The TIMES model can be used to analyse a great variety of scenarios. However, two main types of approaches are normally used for informing policy:

1. Test a previously defined policy in the TIMES model to explore its potential impact. This is the 'what if' question, where the policy makers have an idea of the type of policies they intend to implement and analyse the impact of their implementation using TIMES. For instance, the 'what if we set a carbon tax?' question could be analysed by setting a cost (charge) for CO_2 emissions in TIMES. The results of such a scenario could then be used to inform the policy formation process.
2. Set up targets in TIMES and analyse the results to identify potential policies that could be implemented to achieve the desired target. This is the 'how to' question, which differs from the previous approach as specific policies are not implemented in TIMES (intervention driven). Instead, the overall outcome or final policy target is specified in a scenario, allowing the model to decide the least-cost way to achieve it (goal driven). This approach is commonly used in decarbonisation scenarios. For example, the 'how (the least cost way) to reduce emissions in the transport sector by 20%' question can be set in TIMES with a constraint on total emissions for this sector. The results can then be analysed and the resultant simulated changes in technology use could help to design policies supporting certain types of vehicles or fuels.

The first approach is more straightforward, as a specific policy is tested in the TIMES model and the results are used to see if the policy is likely to perform as expected or not. The second approach is useful for complex problems where the solutions (in terms of technology mix) are not always evident. Note that both of these approaches could be used effectively to inform policy and they could complement each other.

This study considers energy efficiency scenarios following the second approach, analysing how the precise way in which energy efficiency scenarios are implemented in TIMES (mainly through the use of constraints) could impact the results, and consequently, how the modeller's chosen approach could lead to different policy recommendations. Accordingly, this study focuses on issues around modelling energy efficiency and not on specific policy options or actions.

1.2.3 Issue 3 – Different approaches to modelling energy efficiency are possible in TIMES

There are several potential approaches to modelling energy efficiency scenarios in TIMES and numerous examples of this can be found in the literature. (See Section 2 for a literature review). For instance, energy efficiency improvements could be induced in the TIMES model by implementing a constraint in gas or electricity use, thereby promoting the change to more energy efficient technologies. Alternatively, the energy efficiency representation in TIMES could be improved by setting minimum 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 means of achieving it could differ importantly. This study addresses this modelling

[2] The economy is typically taken to be exogenous in this and other types of models. The potential problem with this is that the energy and economy subsystems are, in practice, interdependent. So the exogenous energy service demands in TIMES do not reflect the impact on the economy due to changes in the energy system, and vice versa.

issue, analysing the implications of selecting different energy efficiency modelling approaches on the results obtained with TIMES.

1.3 Scope and objectives of this study

There are several potential approaches to modelling energy efficiency scenarios in TIMES and numerous related research works can be found in the literature. However, from our initial review, we found that the analysis tended to lack depth or fail to follow through to cover all the implications of energy efficiency policies. Moreover, best practices for using TIMES to inform energy efficiency policy have not been directly assessed in the literature.

Therefore, the main objectives for this report are:

1. To identify different approaches for energy efficiency scenario modelling in TIMES, and provide an assessment of strengths and limitations of such modelling approaches.
2. To give recommendations on how to use TIMES effectively for energy efficiency policy analysis.

This report seeks to support policy makers in analysing and designing the best energy efficiency policy measures, with the assistance of TIMES. In the Scottish context, the insights from this research could inform the modelling of energy efficiency scenarios in TIMES to help design policies which most effectively meet the objectives of the Scottish Government's Energy Efficient Scotland programme.

To achieve this, and in the absence of direct access to the Scottish TIMES, the UK TIMES model is used to implement six 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 are further analysed, and their implications for informing energy efficiency policy are discussed.

The rest of the report is organised as follows;

- Section 2 presents a brief literature review of TIMES research related to energy efficiency.
- Section 3 gives a brief overview of the TIMES model.
- Section 4 presents the scenarios and the methodology used in this study, including a description of the base scenario.
- Section 5 presents the results of the different energy efficiency scenarios.
- Section 6 explains and discusses the results, remarking on the potential limitations and drawbacks of the energy efficiency modelling approaches that are analysed.
- Lastly, Section 7 offers concluding remarks and recommendations on how to proceed with energy efficiency analysis using TIMES.

2. Literature review

The TIMES modelling framework has been used to inform energy and climate change policies in a number of countries and regions around the world. The type and scope of the studies varies, but most consider energy efficiency in their findings to varying extents. However, very few include explicit energy efficiency scenarios and/or direct analysis of energy efficiency improvements. This section reviews studies using TIMES that consider energy efficiency, classifying them into:

- Studies that mention energy efficiency as part of the strategies to achieve their outcomes but do not assess it.
- 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[3].

Note that the aim of this section is not to provide a comprehensive review of the literature but rather to highlight, by reference to a limited number of examples, some of the different approaches to the treatment of energy efficiency in studies using TIMES.

Moreover, note that energy efficiency can be interpreted as using less energy to produce the same amount of a service, or as producing more service output with the same energy input (IEA, 2014). In this study, as end user demands in TIMES are mainly static and exogenous to the model, energy efficiency is considered as reducing the amount of energy input to produce the same energy service (as reflected in fixed end user demand). See section 3.1 for a description of residential end-user demands in TIMES.

[3] This category includes studies that claim to have energy efficiency scenarios, even if those scenarios do not actually involve energy efficiency. For instance, cases where an exogenous demand reduction is applied, not improving the efficiency of the systems.

Table 1. Summary of energy efficiency related research works using TIMES.

			Energy efficiency			
Ref	TIMES version	Focus	Mentioned	Indirectly assessed	Directly assessed	Energy efficiency scenario type
Weilong et al. (2014)	China TIMES	CCS technology role on decarbonisation	x			Decarbonisation targets (emission constraints)
Simoes et al. (2015)	TIMES_PT (Portugal)	sensitivity analysis of different assumptions	x			Relaxing technology adoption
Cayla and Maïzi (2015)	France TIMES	Residential technology adoption patterns	x			N/A
Dai and Mischke (2014)	TIAM global	Decarbonisation scenarios with a soft-linking approach	x			N/A
Fortes et al. (2014)	TIMES_PT (Portugal)	Decarbonisation scenarios with a soft-linking approach	x			Decarbonisation policies, carbon tax, support to renewables (minimum shares)
Arndt et al. (2016)	SATIM (South Africa)	Decarbonisation scenarios with a soft-linking approach	x			Decarbonisation policies, carbon tax, relaxation of import restrictions
Føyn et al. (2011)	TIAM global	Potential of a world with 100% renewables		x		Decarbonisation targets (emission constraints and emission taxes)
Deane et al. (2015a)	Irish TIMES	Analysis of electrification of heating		x		Technology adoption scenarios
Labriet et al. (2015)	TIAM World	Decarbonisation scenarios with a soft-linking approach		x		Decarbonisation targets (emission constraints)
Blesl et al. (2007)	German TIMES	Energy efficiency on all sectors			x	energy use constraints and emission constraints
Shi et al. (2016)	China TIMES	Energy efficiency in building sector			x	forcing technology adoption, demand projection changes
Fais et al. (2016)	UKTM	Role of industry on decarbonisation			x	energy use constraints, share of renewables and emission constraints
Rosnes et al. (2017)	TIMES-Norway	Reduction of energy use for heating			x	Imposing energy conservation technologies

2.1 Studies that mention energy efficiency but do not assess it

TIMES-based analysis has been widely used to investigate decarbonisation scenarios, the effects of energy policies in different sectors and the impact of certain technologies. For instance, Weilong et al. (2014) use the China TIMES model to analyse the role of Carbon Capture and Storage (CCS) in China's power sector, and conclude that, under a rigorous carbon mitigation scenario, there should be a widespread deployment of CCS technologies, nuclear and renewable energy in China's power sector. In this study the authors implement decarbonisation scenarios based on emission constraints. Energy efficiency, understood as technological change is mentioned as part of the strategies to achieve the emission reduction objectives, but it is not actively measured or further discussed (see Section 3 for a brief description of TIMES and how energy efficiency is approached in the model).

Simoes et al. (2015) present their analysis of how specific assumptions influence the outcomes of climate policy scenarios. Using the TIMES_PT (Portugal) version, this study assesses the uncertainty of the results dependent on the exogenous assumptions made in TIMES. The study considers seven scenarios, including: Baseline, High technology efficiency, High demand, Low renewable electricity, Low hydro availability, High hydro availability and High oil price. The authors conclude that assumptions relating to socioeconomic development (macro-economic and population growth) had the greatest impact, with up to 9% change of the Baseline scenario emissions in 2020. Assumptions on end-use technology deployment presented a 2.5% change from the Baseline scenario, and the availability and price of energy resources (hydro availability and oil prices) did not represent important variations on GHG emissions (less than 2% of the Baseline scenario emissions in 2020).

Note that this study of Simoes et al. (2015) focuses mainly on changes to CO_2 emissions, so whilst final energy use and share of renewables are mentioned, efficiency gains (as a reduction of energy use) are not explicitly assessed. In addition, the energy efficiency scenario used in this study involved changes in the potential penetration of end-use efficient technologies. This scenario removes the limits on the degree of penetration of more efficient and renewable technologies (removing technology adoption constraints – see Section 3 for more details on energy efficiency modelling in TIMES). However, it is important to note that relaxing technology adoption constraints does not necessarily translate into the adoption of more efficient technologies as the most cost-effective options could be less efficient technologies that use cheaper input fuels. Moreover, the relaxation of these constraints could result in very abrupt or unrealistic technology changes.

A different modelling approach is presented in Cayla and Maïzi (2015), where the TIMES France model framework is modified to take household behaviour and heterogeneity into account (in the form of household daily energy consumption and equipment purchasing behaviour). The authors state that in current TIMES models this is not adequately modelled as they represent energy demand by a single mean or representative household. Results show that in the mean household model (original), only one technology is diffused at each time period. Therefore, the results obtained may seem unrealistic, as from one time period to the next we observe a 100% market share reversal of gas boilers to heat pumps. Alternatively, the proposed TIMES variant presents several technologies at each time period, responding to energy and technology prices in a more realistic way. Therefore, the authors conclude that the problem of unrealistic technology diffusion pathways could be avoided with the highly disaggregated representation of households and their behaviour in TIMES. This study from Cayla and Maïzi (2015) does not consider explicitly energy efficiency scenarios, which are therefore not assessed in the results.

There are many papers analysing climate change policies following a soft-linking[4] approach with TIMES and computable general equilibrium models (CGE)[5]. For example, in Dai and Mischke (2014) the global TIAM model is modified to introduce three sub-regions of China (East, Central, and West), and is linked to the global Asia-Pacific Integrated Modelling/Computable General Equilibrium (AIM/CGE) model. The analysis is mainly a soft-linking exercise, and explores different energy and economic development scenarios up to 2050. The authors conclude that, mainly due to changes in the economy, Chinese energy consumption and emissions will decrease during that period, while important regional differences within China continue to exist. The study mentions energy efficiency briefly but does not measure it.

A similar example is presented in Arndt et al. (2016). In this study, the South African TIMES model (SATIM) is coupled to the South African General Equilibrium (SAGE) model. The soft-linking process consisted of SATIM computing a power plant investment plan based on forecasted electricity demand and fossil fuel prices from SAGE. SAGE replicates the power plant mix and associated electricity price from SATIM, and then revises its electricity demand and fuel price forecasts. The three analysed scenarios are: a carbon tax, liberalization of import supply restrictions (to exploit regional hydropower potential), and a combined policy where both carbon taxes and import liberalization are implemented. The authors conclude that a hydropower based energy strategy could be a potentially inexpensive approach to decarbonizing the South African economy. In this case, energy efficiency is also mentioned in the strategy but is not measured.

Different energy policy scenarios in Portugal are analysed in Fortes et al., (2014), using a soft-linking platform with TIMES and GEM-E3 (General Equilibrium Model for Economy, Energy, Environment) models. Three policy scenarios for decarbonisation are considered and energy efficiency is mentioned as part of the strategies but it is not explicitly implemented in the scenarios or assessed as part of the results. The outcomes of this soft-linking exercise show that TIMES is very sensitive to energy service price changes, generating a wide range of results. On the contrary, the soft-linking framework partially offsets the increase or decrease in energy costs from the policy scenarios (reducing uncertainty).

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

In addition to the studies that mention energy efficiency but do not assess it, other studies allow indirect assessment of energy efficiency via other reported results (such as changes in final energy consumption). An example of this can be found in Føyn et al. (2011), presenting a global climate change analysis using the TIAM global energy system model. The focus of this study is to test if it is possible to reach a global 100% renewable energy system with the existing model database. Three decarbonisation scenarios are analysed, including emission constraints and carbon taxes, and final energy use is assessed, indirectly including energy efficiency in the results (measured as a resulting reduction on total energy use, which contributes in reaching the decarbonisation scenarios). The main conclusion is that the

[4] Soft-linking refers to the process in which two models communicate ‘off-line’. The two models run independently, and interact by passing some of the outputs of one model to the other. This process is usually iterative, and it is repeated until a convergence criterion is met.
[5] The modelling details of how do the reviewed papers perform the soft-linking between models falls outside the scope of this study. However, further discussion of soft-linking methodologies and examples can be found in Calvillo et al. (2017). Also, note that the studies reviewed in this section have been selected as they include or at least mention energy efficiency in their analyses, and not because they consider (or not) soft-linking approaches.

climate change target of 2ºC is feasible, but expensive. Also, in scenarios with high economic growth it will be hard to reach a 100% renewable system.

Soft-linking approaches, indirectly assessing energy efficiency, can also be found in the literature. For instance, Deane et al. (2015) explores the impacts of increased electrification of residential heating on the power system and associated emissions from the residential sector. In particular, the study assesses how many houses can be served with 1000MW of heat pumps (HP), and how the power system will be affected by this. The soft-linking setting uses the Irish-TIMES model to assess the full energy system of Ireland under the technology adoption scenario. Then, PLEXOS (a power system model) is used to examine the impact and technical appropriateness (of the technology mix produced with TIMES) for the electrification of heating requirement for the year 2020. Finally, the ArDEM (housing stock) model is used to accurately assess how many households can be served by the new technologies. The outcomes of this study suggest that electrification reaches a level of approximately 914 ktoe (10.6 TWh) by 2020, representing the heating requirements of approximately 817000 dwellings (according to TIMES) or between 270000 and 340000, depending on the energy efficiency performance of the households (according to ArDEM). The authors remark on the important difference in estimates between the models, concluding that relying solely on energy systems models may lead to an overestimation of the extent of electrification of residential heating. Even though energy efficiency improvement is not explicitly measured, it is indirectly assessed as part of the results.

In Labriet et al. (2015), the authors present a soft-linking methodology for TIAM-WORLD model and GEMINI-E3 (global multi-regional CGE model). The TIAM-WORLD receives sector economic production data (macro-drivers, such as GDP or industrial outputs) from GEMINI-E3 to recalculate energy service demands, while GEMINI-E3 model receives data from TIAM-WORLD on energy and CO_2 prices, energy mix and capital consumption. The study analyses 2 decarbonisation scenarios based on sectoral and regional emission constraints, and the authors conclude that the inter-sectoral effects of climate policies have little effect on overall aggregated sectoral emissions, as the sectoral emissions difference between TIAM-WORLD used in a standalone manner and the coupled models is smaller than 5%. Note that, similar to the abovementioned studies, energy efficiency is not explicitly implemented on the analysed decarbonisation scenarios. However, the sectoral energy efficiency improvements as a reduction of energy use are included in the reported results.

2.3 Studies that directly assess energy efficiency, implementing energy efficiency scenarios

Finally, we review examples of studies that implement energy efficiency scenarios as part of their analysis. Blesl et al. (2007) is an example of energy efficiency focused analysis, where TIMES is used to analyse the impacts of efficiency improvement measures on the German energy system, measuring energy savings, technological development, emissions and costs. Six energy efficiency scenarios are considered, five of them are modelled by limiting the fuel consumption of all technologies in a single sector: road transport, residential, service, industrial and power sectors, and the sixth scenario combines the measures for all sectors. Results of these energy efficiency scenarios show that the transport sector presents the most expensive CO_2 reduction, mainly using bio-fuels and methanol to achieve the efficiency targets. On the other hand, the residential sector offers the largest relative benefits of CO_2 reduction and cost savings, mainly through substitution of conventional gas or oil boilers by condensing gas boilers. An additional scenario is also considered, which assumes the CO_2 emissions in the combined efficiency measures scenario as the target. In other words, this case does not implement the sectoral input fuel constraints of the energy efficiency scenarios, but implements an emissions constraint instead. Results of this case show that transport and service sectors reduce their efficiency targets and other sectors like residential and industry present higher efficiencies (i.e. the total energy used to satisfy the energy service demands in these sectors is lower), relative to the previous energy efficiency scenarios. The authors conclude that the same amount of CO_2 reduction is possible at a lower cost, when there is higher flexibility on the sectoral efficiency targets. These results also suggest that the sectoral approach taken to modelling energy efficiency could significantly affect the model results and might lead to impractical solutions.

A TIMES modelling extension is presented in Fais et al. (2016), where the UK TIMES model is modified to incorporate a process-oriented modelling approach for the industrial sector. The scope of this analysis is to assess the potential contribution of UK industry to system wide targets on energy efficiency, renewable energy and emission reduction. The authors propose 5 scenarios: base case, emission reduction, emission reduction + minimum renewable shares, emission reduction + energy efficiency, and emission reductions + minimum renewable shares + energy efficiency. The energy efficiency scenarios implement a linear reduction of final energy use of 0.9% per year. However, due to lack of detail in the paper, it is not clear how these scenarios are modelled in TIMES; according to the authors' description, it could be assumed that it is something similar to the approach used in Blesl et al. (2007), that is limiting the fuel consumption of all technologies in a single sector. The authors conclude that with this new process-oriented modelling approach, the contribution of industry to decarbonisation of the energy system has clearly increased in comparison with previous reported outcomes.

Shi et al. (2016) present a different energy efficiency modelling approach. Using the China version of TIMES, the authors analyse the impact of technical progress (improving energy efficiency) and the use of renewable energy in the Chinese building sector. The study considers four scenarios with different levels of insulation improvement and domestic renewable technology penetration (such as solar heaters) in the building stock. Unlike the studies described above, these scenarios include energy efficiency measures implicitly in their demand projections, reducing directly the demand for heating services in TIMES, instead of using constraints. The authors conclude that renewable energy sources, such as PV, and ambitious energy efficiency standards will be necessary to maintain a low level of direct carbon emissions in China's building sector up to 2050.

Another study focusing on energy efficiency in the residential sector is proposed in Rosnes et al., (2017). The focus of the study is to implement an energy efficiency scenario where the residential heating service demand is reduced by 27% by 2030 (in comparison with 2010) using two different models – the TIMES-Norway and the CGE model SNoW (Statistics Norway World model). Then, the results of both models are analysed and compared. The energy efficiency scenario in TIMES is modelled by imposing the adoption of energy conservation technologies (such as thermal insulation and building retrofitting) in order to reduce by 27% the use of energy for heating. The authors remark that, as expected, the target reduction was achieved by the models in very different ways. In SNoW by reducing demand and by technology substitution in TIMES. Rosnes et al., (2017) also remark that energy service demands are exogenous in TIMES, precluding any potential demand changes, and the CGE model does not have the level of technology detail available in TIMES. The authors conclude that, considering the strengths, limitations and different model scopes, policy makers should not rely on a single tool to inform the energy policy making process.

2.4 Summary and discussion of findings

Table 1 summarises the studies presented in this literature review. There is a large quantity of energy related research using different versions of TIMES. However, it can be seen in Table 1 that energy efficiency is rarely assessed (directly or indirectly), and most studies only mention energy efficiency briefly as part of the required strategies to achieve other outcomes (mainly decarbonisation scenarios), but without measuring it.

From the studies reviewed that measure energy efficiency improvements, most cases report them as a by-product of other type of scenarios, such as emission reduction, renewable energy penetration or technology adoption cases. Only a few studies explicitly consider energy efficiency scenarios, in most cases in combination with other type of scenarios such as emission reduction targets.

Moreover, the studies that explicitly implement energy efficiency scenarios have taken significantly different approaches. Figure 1 shows how energy service demand is met in TIMES, and how different scenarios have been applied in the reviewed examples that explicitly consider energy efficiency. In TIMES, energy service demands can be met with 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[6] technology). Note that this a simple generic description, and not all demand can be met by energy conservation technologies.

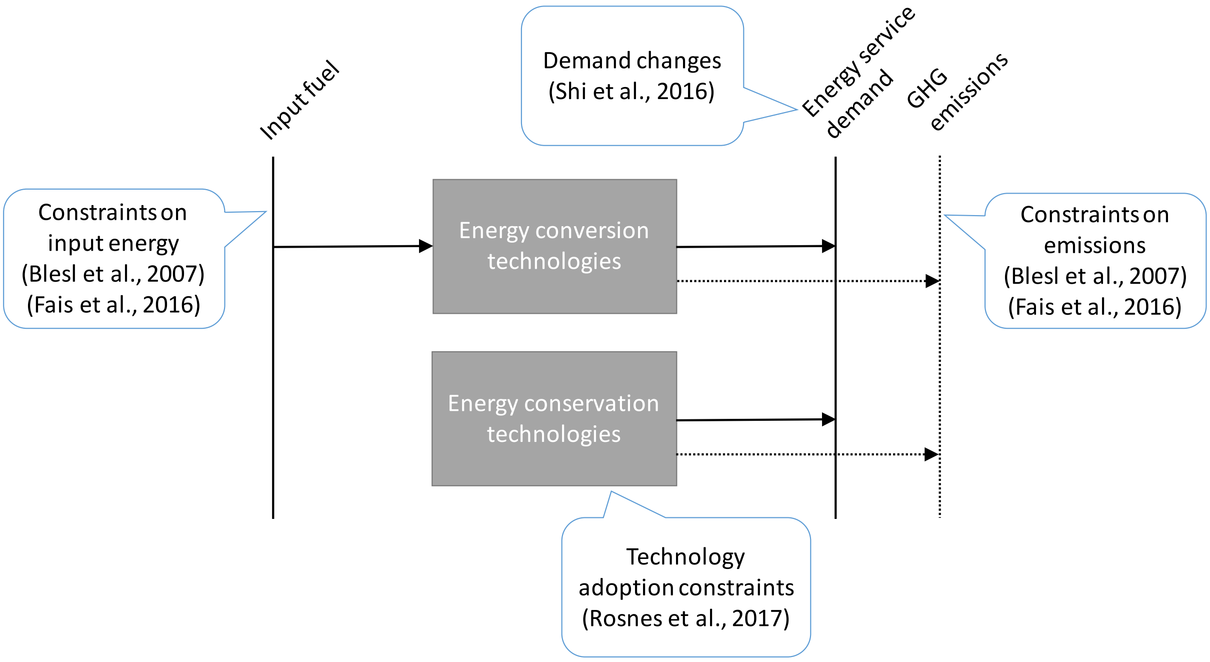


Figure 1. Energy efficiency scenario approach diagram of examples found in the literature.

The study presented in Blesl et al. (2007) approaches energy efficiency with total energy use constraints (reducing the energy input required to meet 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 in achieving 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

[6] Energy conservation is, by definition, not energy efficiency. However, due to the way energy efficiency improvements are measured in TIMES, energy conservation technologies are considered in this study as a proxy of energy efficiency investments.

energy efficiency improvements, or they might be over reliant 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. This suggests that by exogenously making demand adjustments, much of the impact on the energy system is taken out of the model, potentially leading to 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 can affect the results significantly, potentially affecting policy decisions. The work developed in this report 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.

3. The TIMES model - a brief 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 formal documentation can be found in Loulou et al. (2004, 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 limits on GHG emissions, levels of technology adoption, 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 (end-use service demand). The former is composed of 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 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 with the various conversion and energy transport 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.

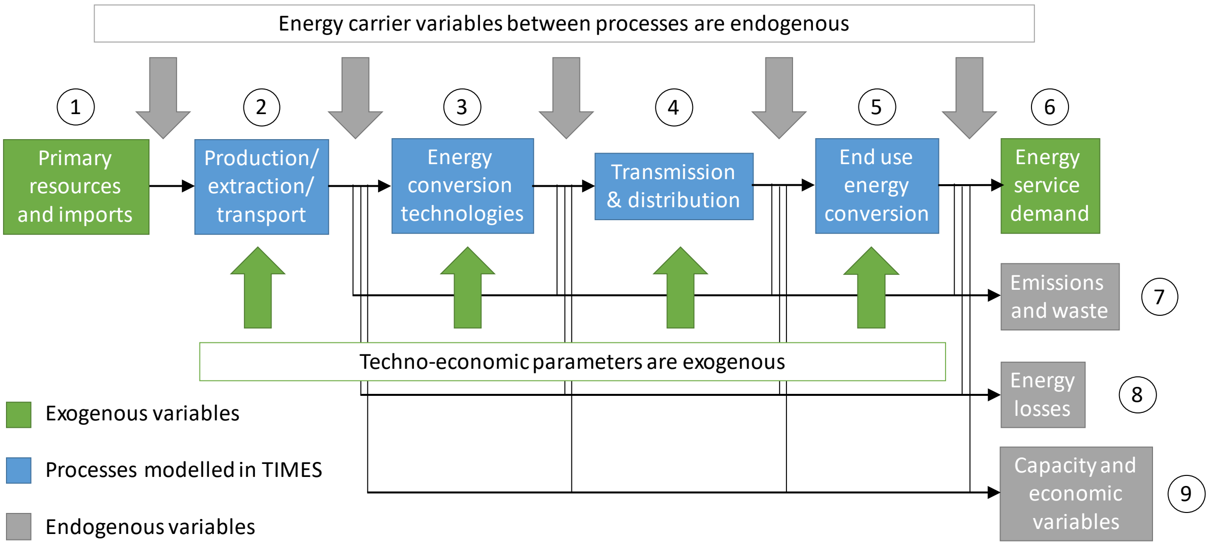


Figure 2. Modelling of the energy system in TIMES (Calvillo et al., 2017).

All the items depicted in Figure 2 are modelled in TIMES as three elements: Technologies (also called processes), Commodities, and Commodity flows. The commodities are all the energy carriers (e.g. electricity or coal), energy services (e.g. heating or transportation of heavy goods), materials, monetary flows (e.g. costs), and emissions (e.g. CO_2 or NO_x). The Technologies or processes are representations of physical devices that transform commodities into other commodities, including energy conversion technologies (e.g. a boiler or a light bulb) and other processes, such as: extraction, production, transport, and transmission and distribution of commodities. Lastly, commodity flows represent an input or an output of a process. Commodities could be used in different processes (e.g. electricity or gas). Commodity flows are attached to a particular process. For example, Gas is the commodity and the commodity flow is the amount of gas used in a gas boiler (see Figure 3).

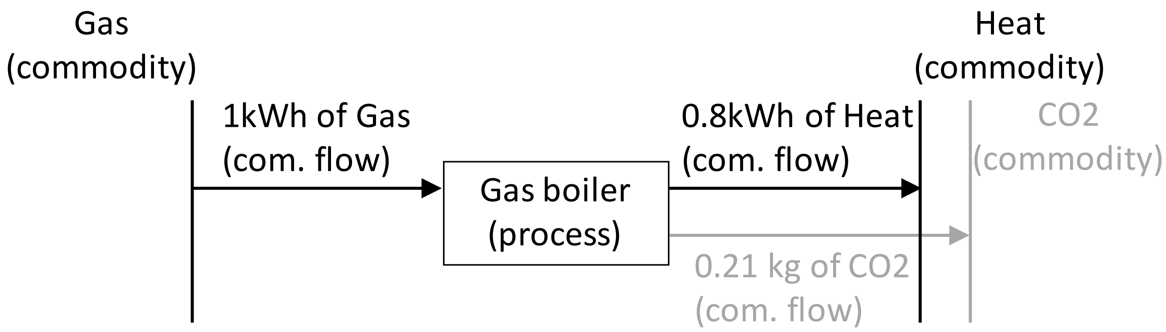


Figure 3. Example of processes, commodities and commodities flows in TIMES.

Note that the technologies and/or processes in TIMES are modelled using different exogenous techno-economic parameters. These parameters define the types of commodities used as inputs and outputs, the performance characteristics, and the costs of the process and/or technologies. Examples of these parameters include: technology investment costs per capacity unit, operation and maintenance costs, discount rates, operational efficiency, technology lifespan, and emissions per unit of production.

3.1 Residential heating modelling in TIMES

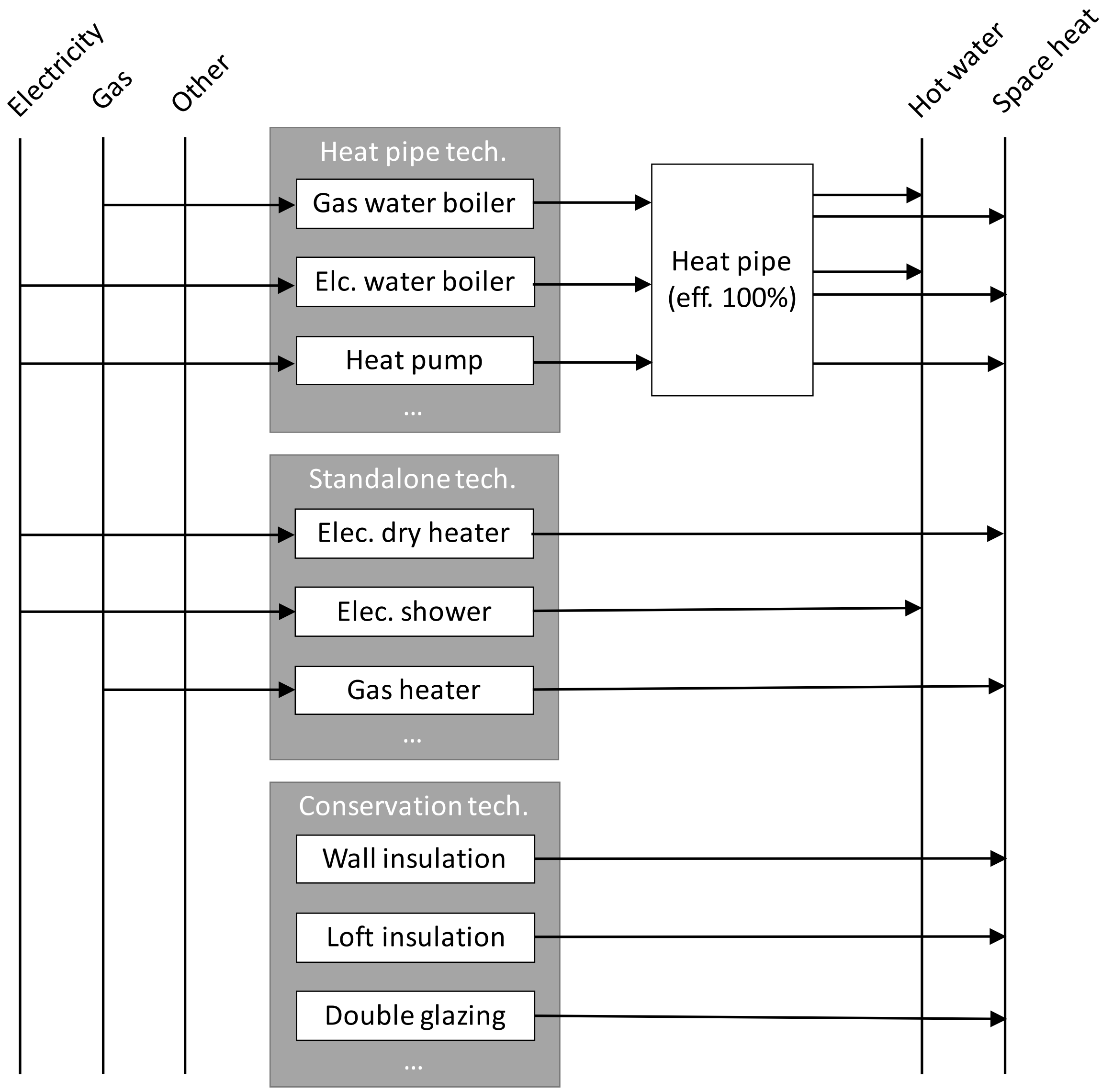
Figure 4 shows the residential heating modelling approach used in TIMES. Residential heating is an energy service demand modelled as two demand commodities: domestic hot water and domestic space heat (right-hand side of Figure 4). The domestic hot water demand in TIMES can be met with energy conversion technologies, such as water boilers, that transform energy carriers (e.g. electricity, gas, oil, etc.) into the required service. The domestic space heating demand in TIMES could use the same energy conversion technologies as used for the hot water demand, but it can also partly be met with energy conservation technologies, which are passive elements that reduce the need for 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 middle block of technologies in Figure 4).

Note that there is a distinction between energy conversion technologies in TIMES, based on how they deliver the energy services. They can be classified in two groups.

The first group is heat pipe technologies, which are those technologies that use pipes to transport hot water (or some other fluid) to its end use. For example, a gas boiler heats up water which then goes through the household pipes to the tap or shower for domestic hot water, or to the radiators for space heating.

The second group is formed by standalone technologies (second block of technologies in Figure 4). These technologies differ from the previous group because they do not need a residential pipe network to deliver the end user demand. For instance, dry electric heaters or electric showers.

For modelling purposes, the main difference between these two groups is that heat pipe technologies have an intermediate process before the service demand, transforming the output of the energy conversion technology into the two energy services (i.e. heat pipe technologies can be used to supply both domestic hot water and space heating), while the standalone technologies are normally used for one of the two services (i.e. one technology is used for space heating and a different one is used for domestic hot water). Note that these types of technologies could be used in a complementary fashion, as in many cases there could be a combination of both heat pipes and standalone technologies. For instance, having a gas boiler and an electric shower.



3.1.1 Figure 4. Residential heating modelling in TIMES.

4. 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.

4.1 The UKTM model and the base scenario

The UK TIMES model (UKTM) is used in this study to analyse the different energy efficiency scenarios[7], and the outputs are compared with a 'business-as-usual' base scenario. Note that this base scenario follows a least-cost pathway, according to the data and modelling constraints set in UKTM and this base scenario, and it does not consider emission reduction targets. So, this scenario does not intend to provide the most probable or practical picture of the UK energy system in 2050, but to serve as a benchmark to assess the different energy efficiency modelling approaches.

This model differs from other TIMES versions, especially in the input data used, which should reflect the characteristics of the country or region modelled. However, the general structure of different country models will be similar. Thus, the insights obtained here are very likely to be of general use and are likely to be applicable to 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 UCL, (2014) for more information on the UK TIMES model). Figure 5 shows the energy service demand projections for the residential sector in the UKTM base scenario. The residential service demands (in PJ) are: space heating for existing houses (RHEA), space heating for new houses (RHNA), hot water for existing houses (RWEA), hot water for new houses (RWNA), cooking hobs (RCH), cooking ovens (RCO), cooking other (RCE, including kettles, microwaves, etc.), wet appliances (REW, including washing machine, driers and dishwasher), consumer electronics (REA, including TV, hi-fi, game console, etc.), computers (RECP), refrigerators (RECR), freezers (RECF) and other demands (REO). Note heating related demands are separated into two types of residential houses: existing and new. New housing demands are projected to grow in time (new houses being built), whereas exiting housing demand has a decreasing projection (old houses are not used anymore and/or demolished). This differentiation is made as not all technologies apply to both types of housing. For instance, in UKTM energy conservation technologies can only be applied to existing houses as the new houses are assumed already to be more energy efficient, so no extra building envelope technologies are required. Also, some technologies might have special constraints and/or requirements according to the type of housing. An example of this is district heating which is considered to be cheaper to implement on new houses than on existing ones.

Figure 5 shows that the largest demand corresponds to space heating (RHEA in yellow with 'o' marker and RHNA in purple with '∗' marker), followed by domestic hot water demand (RWEA in green with '□' marker and RWNA in cyan with 'x' marker). Other energy service demands are considerably smaller.

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[7] The UKTM version used for this study is V.1.2.2, last update in January 2016.

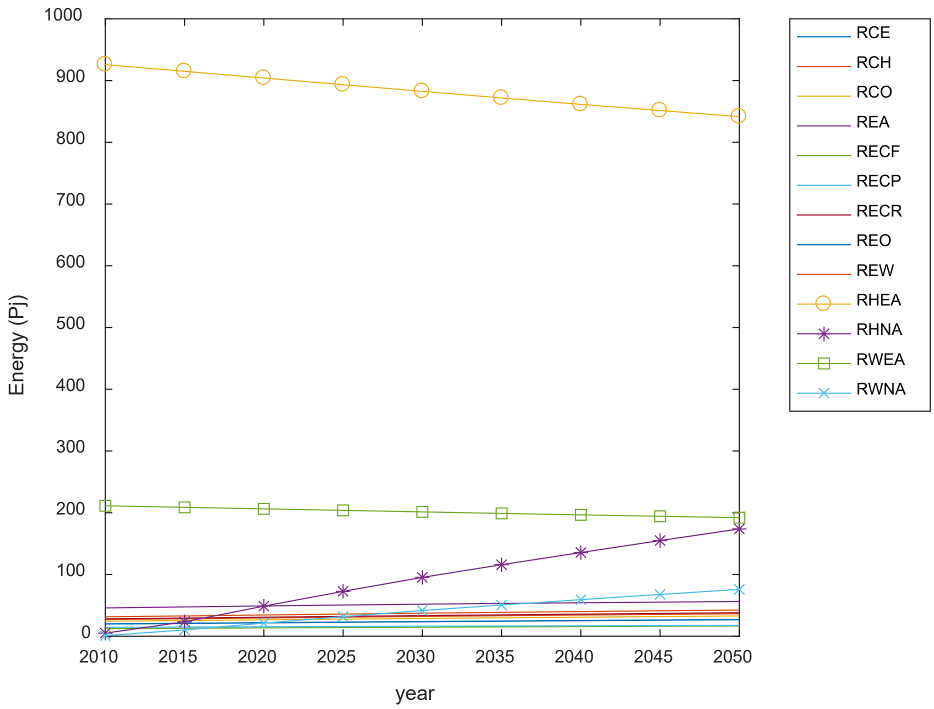

Figure 5. Residential energy service demand projections in UKTM – Base scenario.

Figure 6 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 6), 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 6). It can be seen that EA demand decreases in time (blue line with 'o' marker in Figure 6), 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 (solid yellow line).

The energy efficiency target applied in this study is expressed in terms of the total energy used for heat in the residential sector. It is illustrated with the pale purple dashed line in Figure 6, and it is applied for all scenarios (described in detail in Section 4.2). The resulting energy use value of this target is computed as 10% less than the total energy consumption value in 2010. Note that this target has been arbitrarily selected for this study and does not represent any particular policy target. However, this analysis could be adjusted to any other energy efficiency target.

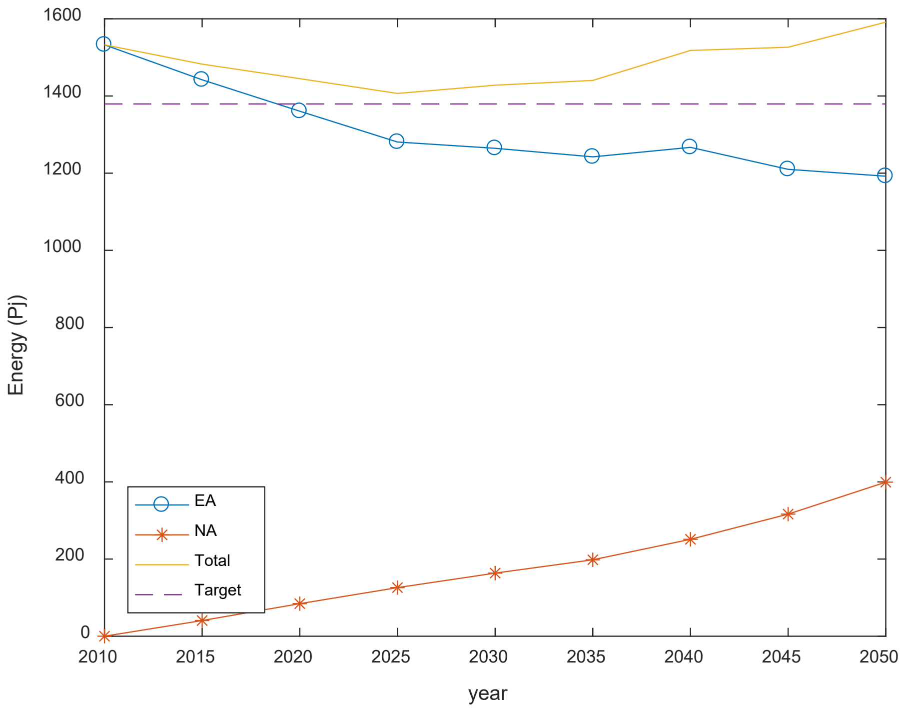

Figure 6. Aggregated residential heat energy use – Base scenario.

Figure 7 shows the fuel mix to meet the residential heating demand in the base scenario – which has the objective of meeting energy service demand at least cost with no emissions constraints – in 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 Figure 7.a) are oil (OIL 7.4%), electricity (ELC 5.3%) and small shares of coal (COA 1.7%) and biomass (BIO 0.4%). By 2030 (see Figure 7.b) oil and coal have disappeared and are mainly replaced by electricity (ELC 9.9%). Lastly, 2050 maintains a similar pattern of fuel mix to 2030 with very minor variations (see Figure 7.c).

As described in Section 3.1, heating and domestic hot water production technologies in TIMES can be grouped in two types: heat pipe and stand alone, and the stand alone normally produce one of the two services (i.e. heating or domestic hot water). Figure 8 shows the shares of each technology group in the base scenario. It can be seen that for the entire time horizon, most heating technologies are of the heat pipe type (around 90%, diagonal bars pattern in Figure 8) and just a small share are standalone (around 10%), which are mainly used for heating (vertical bars and solid patterns in Figure 8).

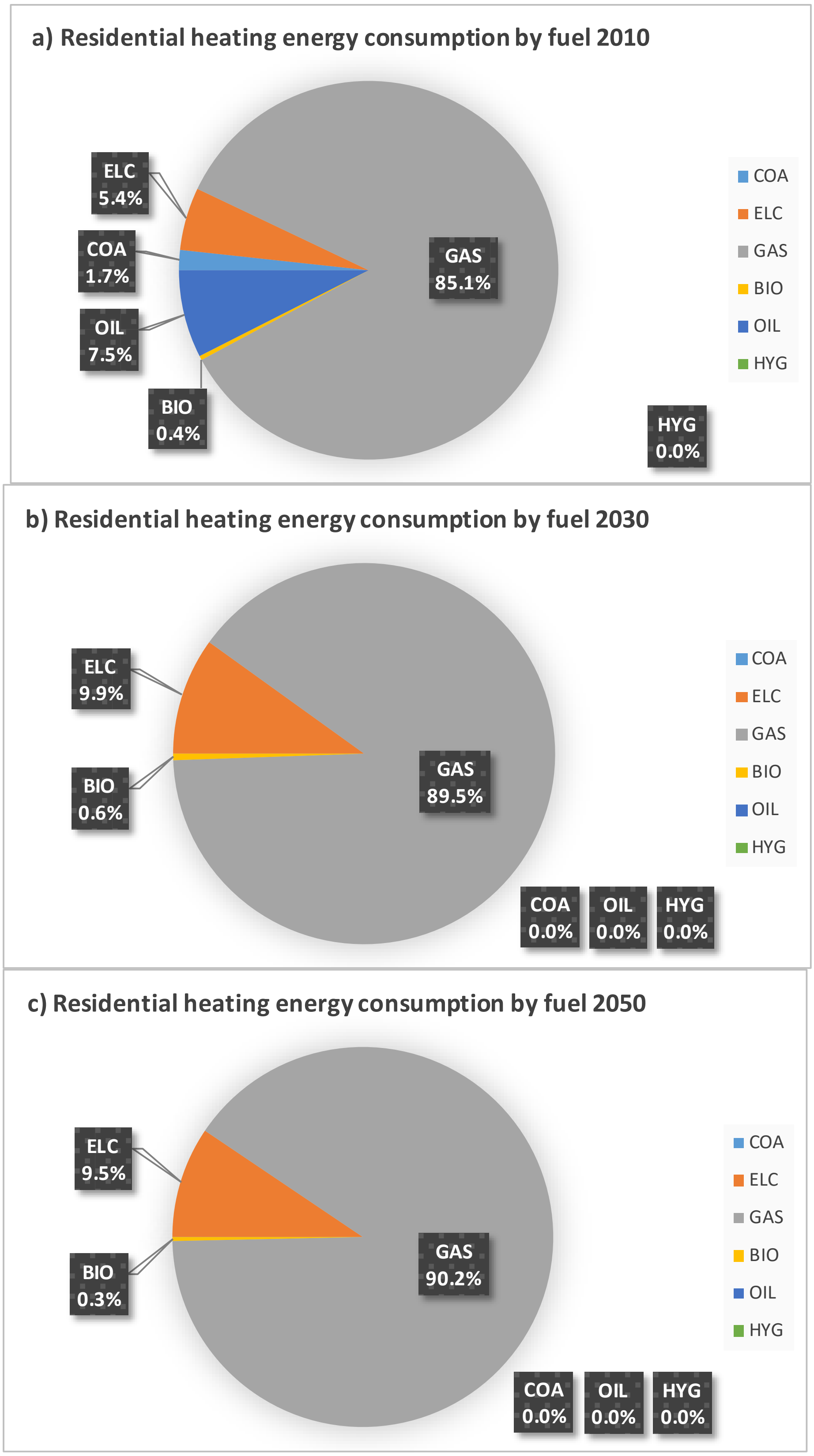

Figure 7. Residential heating energy consumption by fuel in 2010, 2030 and 2050 – Base scenario.

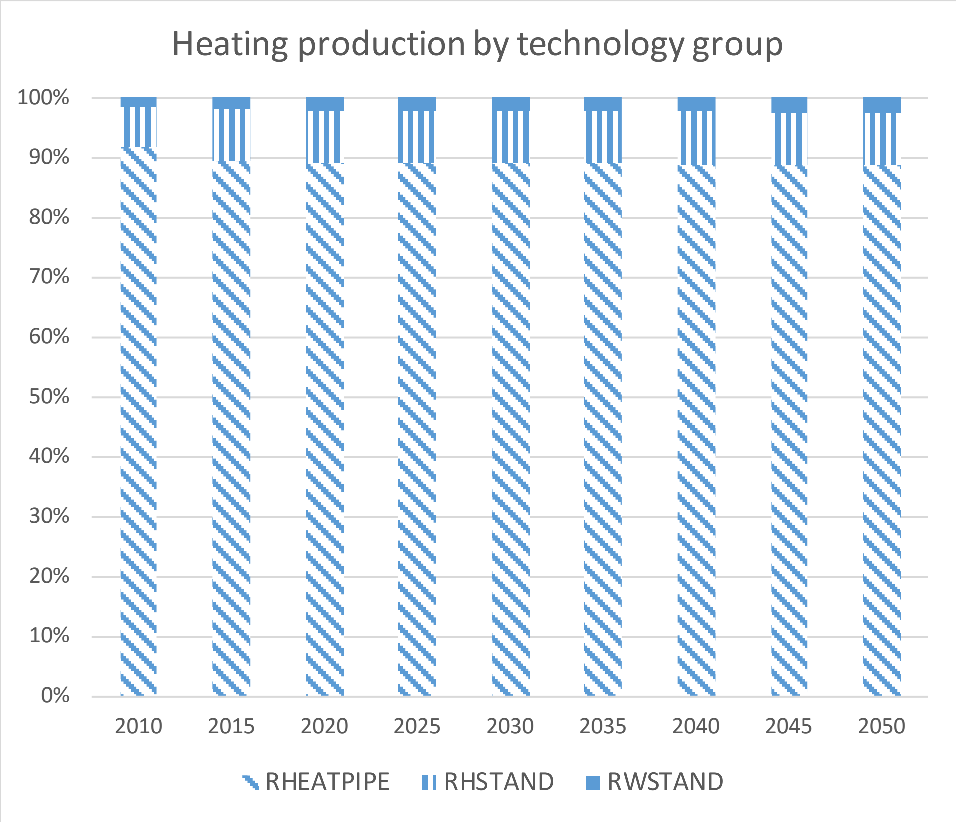

Figure 8. Residential heating energy production by technology group – Base scenario

Figure 9 shows the technology production mix. In 2010 (Figure 9), the technology with the largest penetration is the gas boiler (83.6%), with the oil boiler in second place (5.9%). Other technologies are also present but with considerably smaller penetration levels: electric night storage (labelled 'NT storage', 4.1%), standalone heater (labelled 'Standalone', 2.5%), standalone water heater (labelled 'Stand Water', 1.5%), coal boiler (1.1%), district heating (1.0%), electric boiler (0.2%) and heat pumps (HP, 0.1%). In 2030 (middle column in Figure 9) 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, 14.8%) but gas boilers remain the main technology with 73.1%. By 2050 (right column in Figure 9) the CHP increasing trend continued and it now fully replaces gas boilers, reaching 85.1% of technology penetration. The technology mix is complemented with electric boilers (2.1%) and district heating (1.5%).

These shares correspond to the fuel mix shown in Figure 7, where gas is the main input fuel, so the main technology used in this base scenario is the gas boiler and CHP (a heat pipe technology).

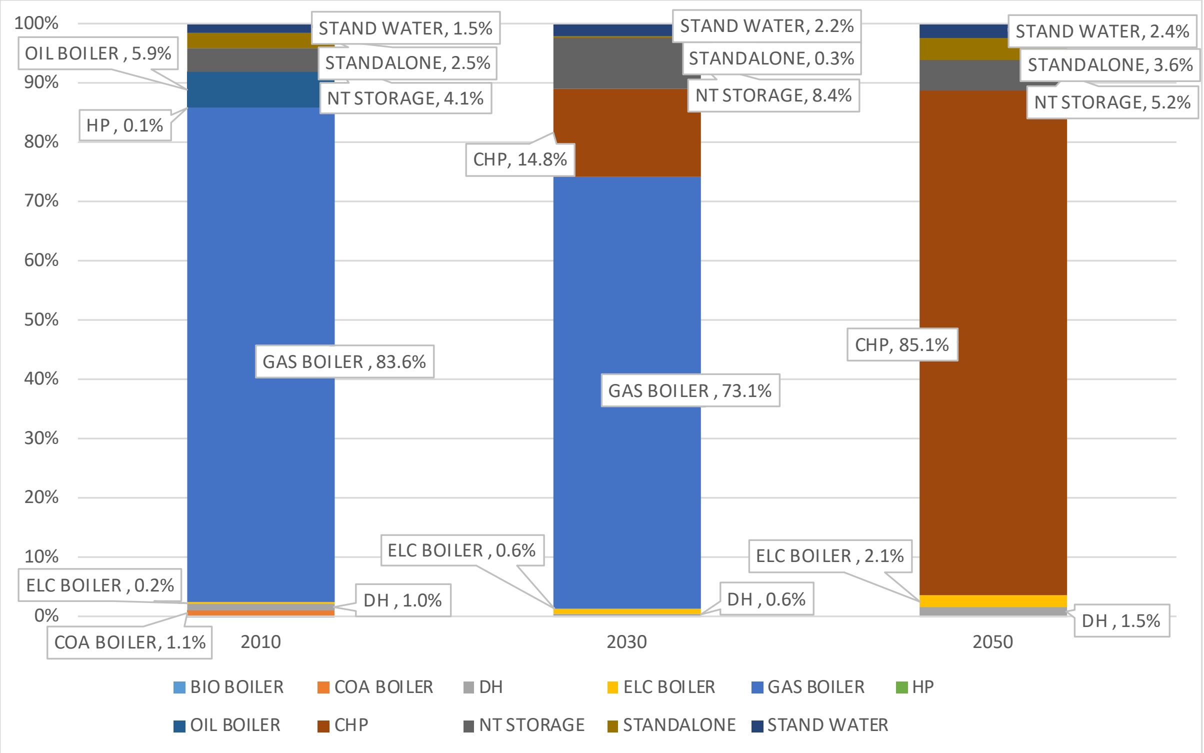

Figure 9. Residential heating production by technology in 2010, 2030 and 2050 – Base scenario.

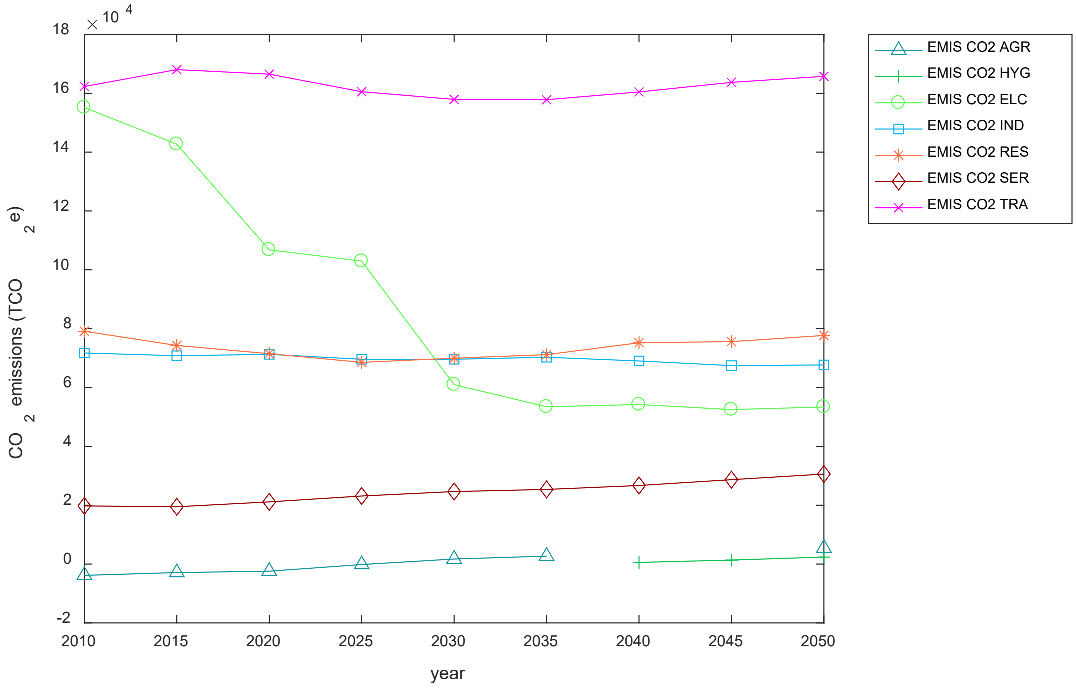

Figure 10. CO_2 emissions per sector – Base scenario.

Figure 10 shows the evolution of CO_2 emission production per sector in the base scenario. The figure shows that the transport sector (TRA, pink line with 'x' marker in Figure 10) is the largest generator of CO_2 emissions. In 2010, the second largest emission contributor is the electricity sector (ELC, light green line with 'o' marker), but this sector decarbonises gradually up to 2030, after which the emissions remain stable. The residential (orange line with '*' marker) and industrial (light blue line with '□' marker) sectors follow as the third and fourth largest producers of CO_2, with a mainly steady amount of emissions up to 2050. Other sectors also contribute on the total emissions, but their share is considerably smaller than the main four CO_2 producer sectors.

4.2 Energy efficiency scenarios

In TIMES, energy efficiency measures are mainly implemented by technology substitution, involving switching a process or technology for a more efficient one. Moreover, there are energy conservation technologies modelled in TIMES that would simulate energy efficiency measures. For the case of heating, energy conservation measures could be smart control systems or building envelope technologies, such as loft or wall insulation.

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 2, energy efficiency scenarios have been modelled in a variety of ways, the choice among which is likely to affect the outcomes.

In this study, six different energy efficiency scenarios for residential heating are proposed, with the objective of analysing the implications of the chosen modelling approach for TIMES outcomes. All scenarios are modelled with the objective of increasing energy efficiency in residential heating (space heat demand) by 10%, relative to 2010 levels, from 2030 and up to 2050, i.e. reducing the total energy required to meet residential space and water heat demand. So the TIMES model is run for the time horizon covering from 2010 to 2050, but the residential energy constraints only apply from the year 2030 onwards. Note that as the end-service demand is static in TIMES, simulating energy efficiency requires a reduction in the use of energy input in the model (commodities on the left-hand side of Figure 11) to produce the same service (on the right-hand side of the Figure). In TIMES, the reduction in energy use can be achieved by technology changes (see Section 3.1). Other types of changes in energy efficiency (such as those motivated by user behaviour or the wider economy) are not considered here.

The energy efficiency scenarios (for residential heating) are:

- Scenario 1 – the imposition of a constraint on all input fuels.
- Scenario 2 – the imposition of an input fuel constraint on gas alone.
- Scenario 3 – the imposition of a constraint on the production of heat pipe technologies.
- Scenario 4 – the imposition of a minimum energy conservation technology adoption level.
- Scenario 5 – exogenous demand reduction of space heat energy services.
- Scenario 6 – the imposition of a constraint on CO_2 emissions.

Figure 11 illustrates where the specific modelling constraints embodied in each Scenario are binding. Note that these scenarios have been selected as they represent similar approaches to those already found in the literature (see Section 2) or are alternative ways of capturing possible energy efficiency policy changes (e.g. reducing the consumption of one particular fuel, such as gas). More detailed descriptions of these scenarios are provided in the following subsections.

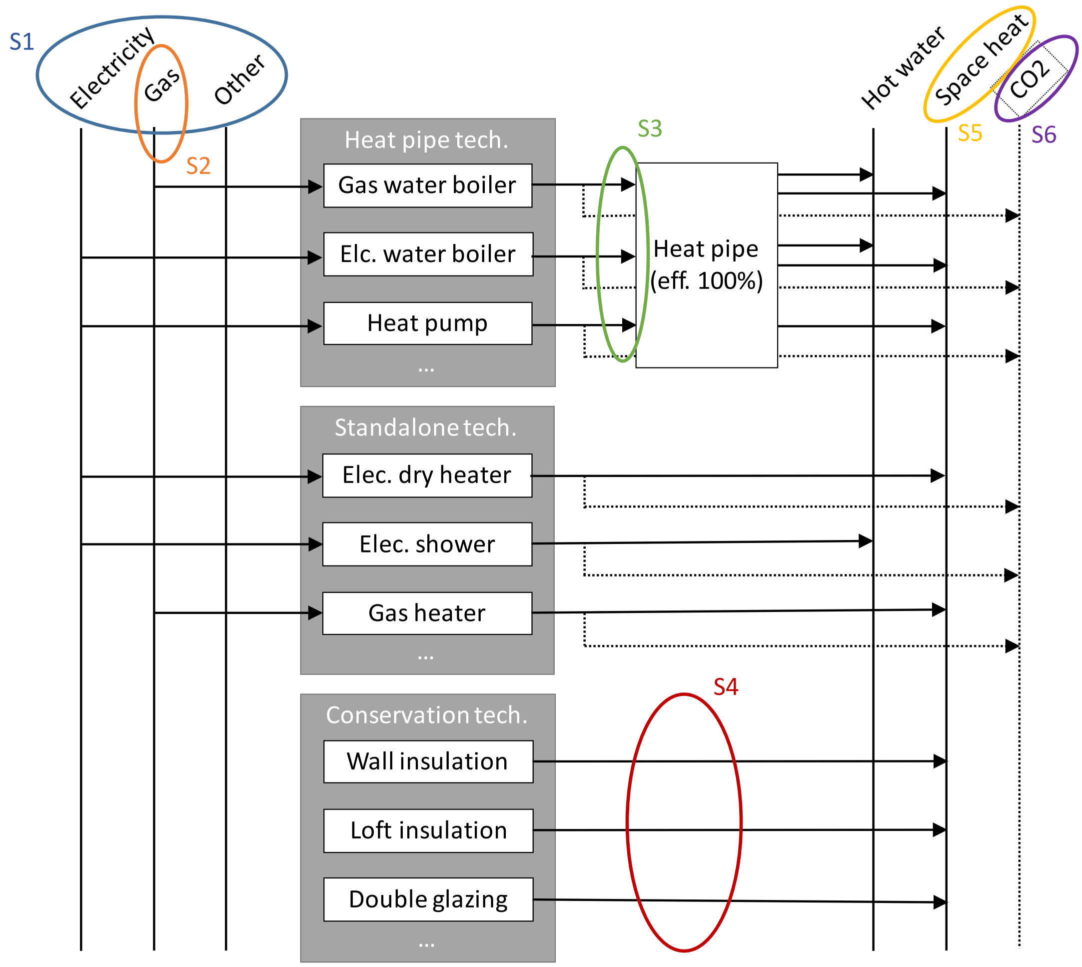

Figure 11. Summary of energy efficiency scenarios for this study.

Note that this study analyses these energy efficiency scenarios in isolation, without combining any other types of scenarios or changes (whether policy-induced or not). This is done to facilitate comparison between scenarios, so the simulation results can then be entirely attributed to the changes in energy efficiency modelling under consideration (subject to the existing configuration of UKTM).

The technical detail of the energy efficiency scenarios considered in this study can be found in Appendix A.

5. Results

TIMES produces a very large quantity of results for the whole 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. Appendix B extends the results of these scenarios, including other relevant metrics such as imports, exports, changes in electricity and gas shadow prices (marginal costs), etc.

5.1 Scenario 1 results - input fuels constraint

This section presents the results of scenario 1 (S1), which implements a constraint on total fuel consumption for residential heating from 2030. The input fuels constraint scenario is similar to the one presented by Blesl et al. (2007). In this scenario the maximum total amount of input energy for residential heating processes (in petajoules 'PJ') is set from 2030 onwards to be 10% less than that in the base case at 2010.

By reducing the use of fuels for heating technologies, the effects of this constraint are likely to include more implementation of energy conservation measures than in the base case, which reduce the need for input fuels. Also, the constraint set in this scenario limits the sum of all energy types, so that changes to more efficient technologies are likely to occur. That is, there are likely to be switches to technologies that produce more units of heating services per unit of input energy (e.g. heat pumps), regardless of the fuel type. (See Appendix A.1 for more details on this scenario).

Key results in S1:

- The technology mix for residential heating in 2050 includes gas boilers (54.1%), CHP (32.5%), standalone technologies (11.5%), HP (1.5%) and others (0.5%), which is significantly different from the base scenario (CHP 85.1%, standalone 11.2%, Elc boiler 2.1%, DH 1.5%).
- Energy conservation technology "production"[8] is 21.91% larger than the base scenario.
- Residential gas and electricity consumption is reduced and the overall fuel use for heating (accumulated total from 2010 to 2050) is reduced by 4.71% relative to the base scenario.
- The total CO2 emission production is reduced slightly (-0.15%) and the total system cost increases by 0.08%, relative to the base scenario.

Figures 12 and 13 show the heating technology production from 2010 to 2050 for existing and new houses, respectively. In both figures, the results for the base scenario are in solid lines and the results for S1 are in dashed lines. For existing houses, there is an important change in this scenario on the use of gas boilers (blue line with '□' marker in Figure 12) and combined heat and power systems (CHP, dark red lines with '△' marker in Figure 12). It can be seen in Figure 12 that in the base scenario there is a replacement between these two technologies, starting around 2025. However, in S1 the transition between these two technologies stops around year 2035, and gas boilers stay as the main heating technology with CHP remaining as the second most important technology.

[8] It may be recalled that 'energy conservation technology' is modelled as a source of energy that requires no input fuel.

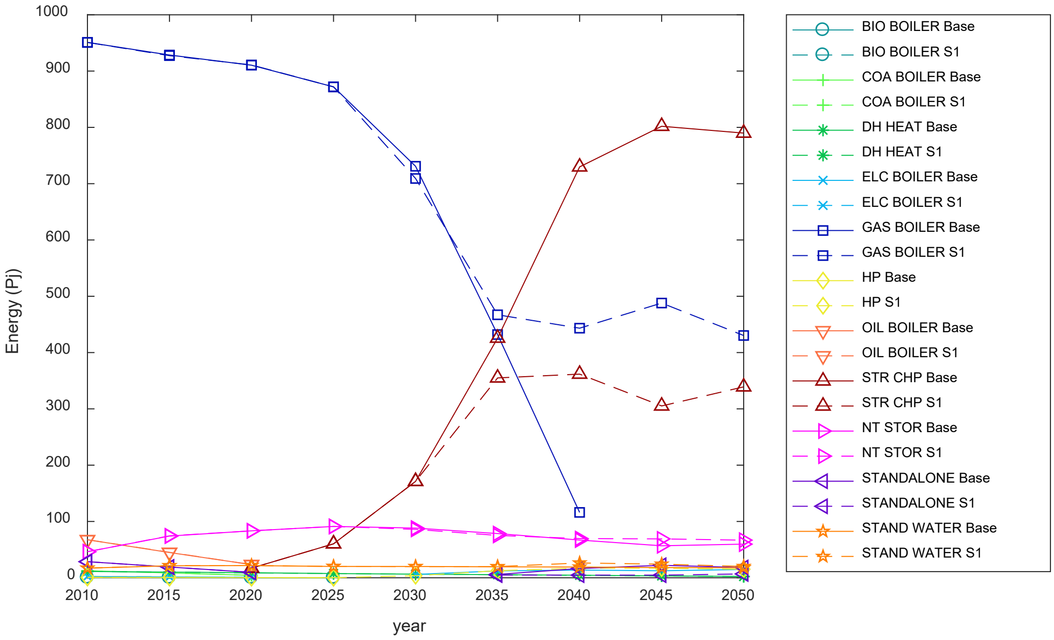

Figure 12. Production of residential heating technologies in existing houses for the base scenario and S1.

A similar pattern occurs for the heating technologies in new houses (Figure 13). In the base scenario, Gas boilers (blue line with '□' marker) production increases steadily, reaching a peak at 2035. Then gas boiler production is replaced by CHP and, to a lesser degree, with other technologies such as standalone heaters (purple line with '◁' marker) and district heating (dark green line with '*' marker). In S1, the gas boiler continues on an increasing trend up to 2045, replacing most of the CHP production in the base scenario. Other technologies complement heating production but to a considerably smaller degree.

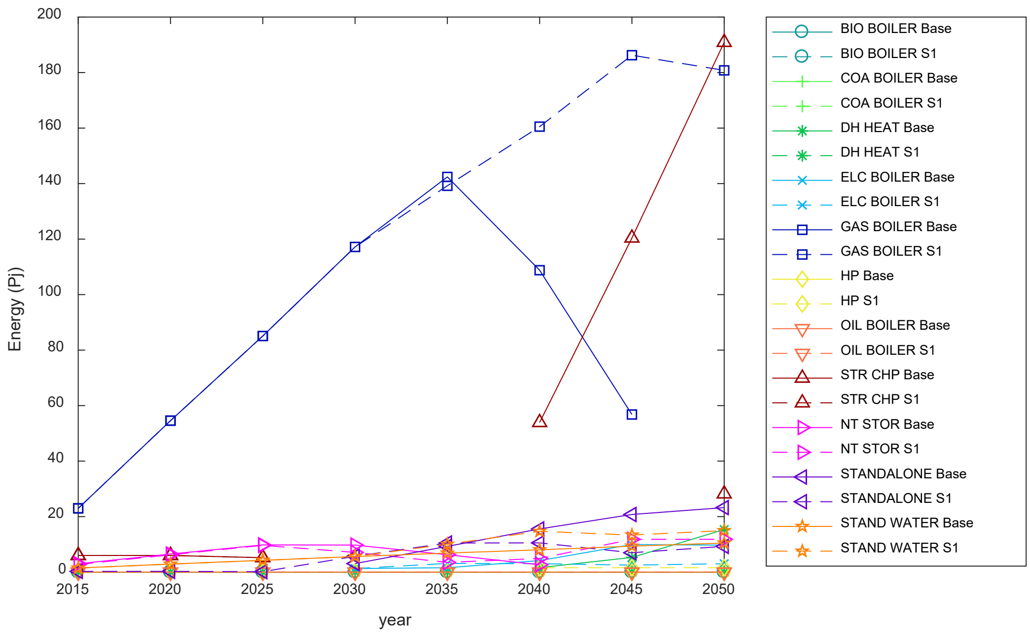

Figure 13. Production of residential heating technologies in new houses for the base scenario and S1.

Figure 14 shows the share of residential heating technologies in S1 at 2050. These shares are considerably different from those in the base scenario (see Figure 9 left-most column), where CHP exhibited the largest share. S1 presents a wider technology mix, where gas boilers are the main heating technology with 54.1%, and CHP is the second most important technology with 32.5%. Standalone technologies (including night storage and standalone water and space heaters) with 11.5% and heat pumps (HP, 1.5%) complement the heating production.

These figures show interesting changes on technology adoption. CHP is potentially more efficient than the gas boiler, producing more total output in two energy vectors (heat and electricity) from a single energy carrier (gas in this case). However, the implemented constraint applies to heating production only, so the results show that the CHP requires more input to produce heat than the gas boiler (not taking into account the electricity production for other demands).

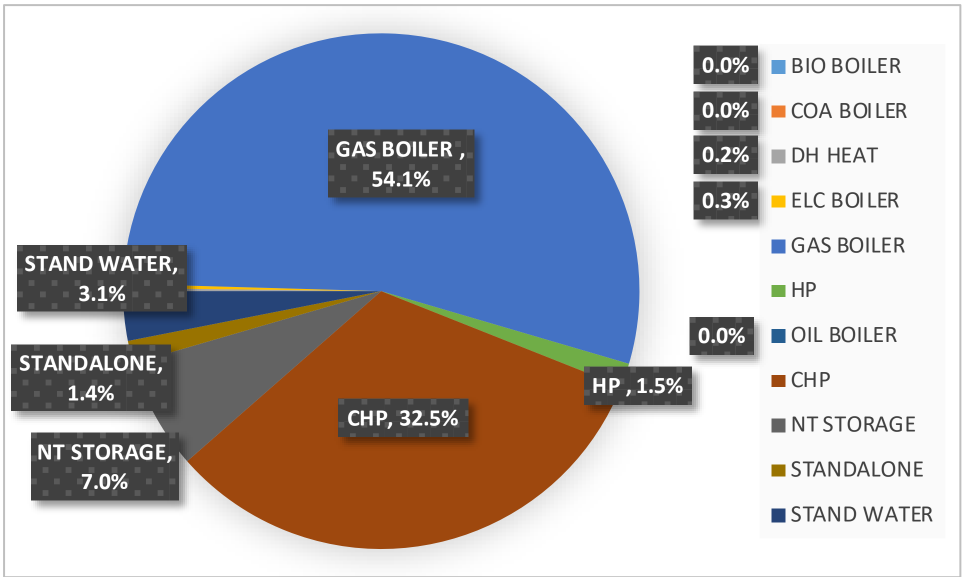

Figure 14. Residential heat production shares by technology type at 2050 – S1.

Figure 15 shows energy conservation technologies production from 2010 to 2050. These technologies include different types of cavity wall insulation (CAV), loft insulation (LOF), solid wall insulation (SOL) and floor insulation (FLR). In the base scenario, several energy conservation technologies, including CAV, LOF and SOL01, increase steadily up to 2030, and then remain constant. SOL02 (a second type of solid wall insulation, solid dark blue line with '□' marker) starts to be implemented in 2035 and reaches a maximum level in 2045. In S1, the CAV, LOF and SOL01 technologies remain unchanged. SOL02 (dashed dark blue line with '□' marker) implementation starts earlier than the base scenario and reaches the same maximum level by 2035. Lastly, SOL03 technology (third type of solid wall insulation, dashed yellow line with '◊' marker) appears in 2045 and increases in 2050. The total energy conservation production in S1 is 21.91% greater than in the base scenario.

Note that the SOL03 technology did not appear in the base scenario. This suggests that other cheaper energy conservation technologies (CAV, LOF, SOL01 and SOL02 technologies) have reached their maximum capacity set in TIMES[9]. So in order to get extra

[9] Most technologies modelled in TIMES present technology adoption constraints that limit the maximum or minimum capacity and/or production, and the adoption rate. These types of constraints are implemented to replicate to some extent the consumer adoption profiles or supply chain capacity, avoiding dramatic or unrealistic technology shifts (e.g. a 100% change from one technology to another in a single year).

energy conservation capacity SOL03 is implemented, despite being more expensive than other technologies.

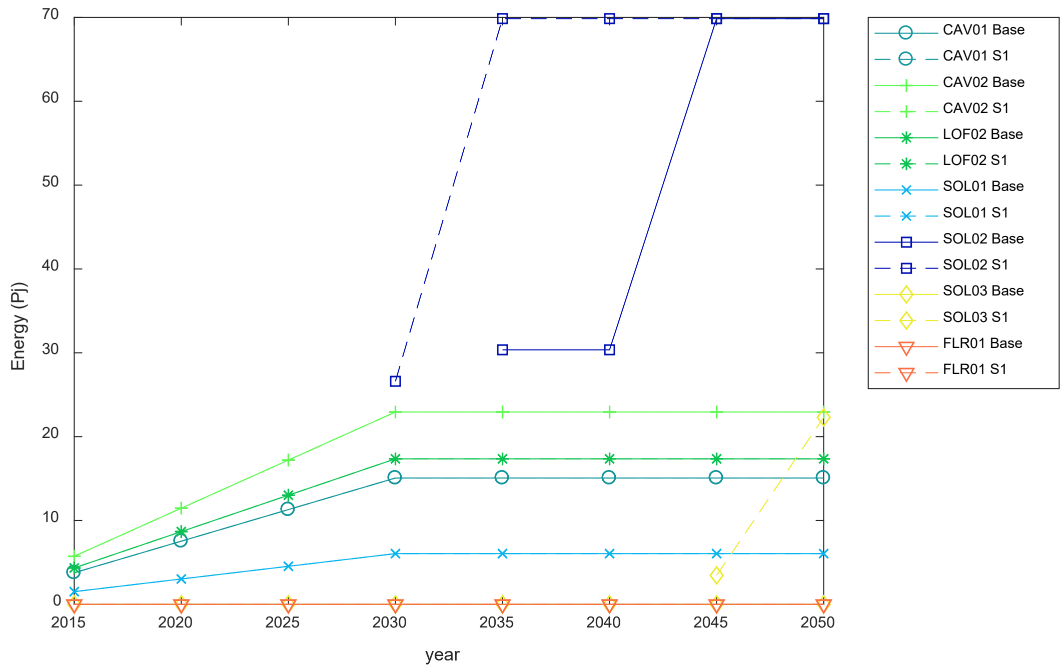

Figure 15. Production of energy conservation technologies for the base scenario and S1.

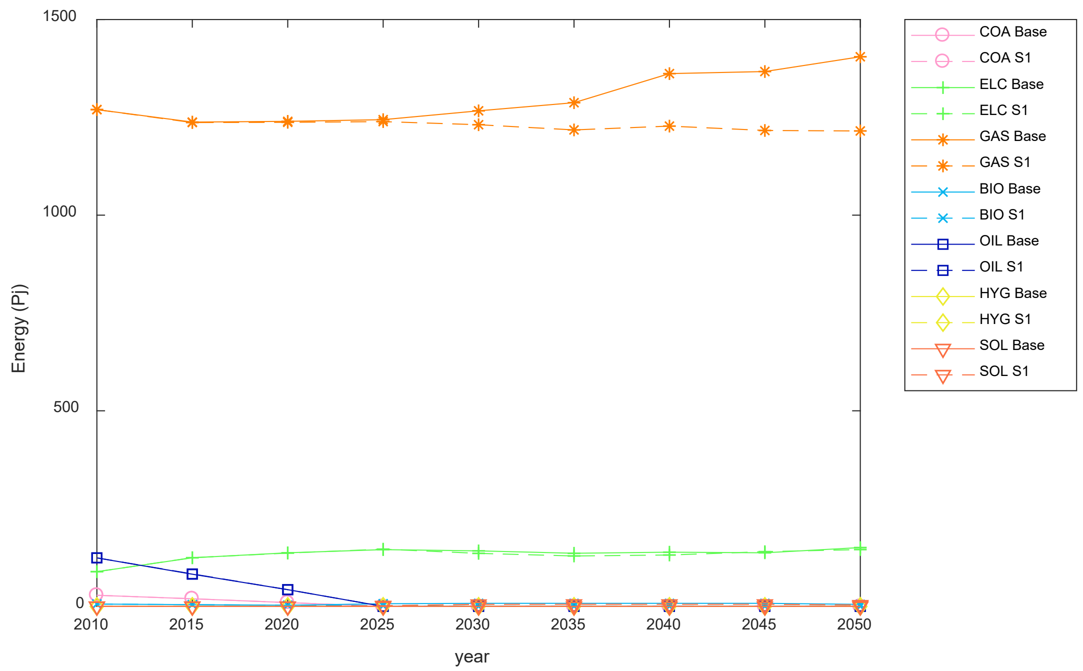

Figure 16. Fuel use for residential heating for the base scenario and S1.

Figure 16 shows the fuel use for residential heat from 2010 to 2050. Gas use presents the largest reduction in absolute values (orange lines with '∗' marker). The second largest fuel is electricity (light green lines with '+' marker), but the reduction for this fuel is negligible. The use of other fuels such as biomass also change, but their reduction in absolute values is considerably smaller. The total fuel use change in S1 is -4.71% (considering the total sum from 2010 to 2050), most of which relates to gas use.

Table 2 shows the cumulative sectoral CO_2 emission changes in S1. As expected, the residential sector presents the largest reduction (-3.69%) caused by the decrease in gas consumption. However, the power sector (ELC) increases its emissions by 2.66%. This increment is caused by the "extra" electricity coming from the distribution network for residential use, making up for the lower electricity production from the CHP technology (see Figures 12 and 13). Total CO_2 emissions are reduced very slightly (-0.15%).

Table 2. Cumulative sectorial CO2 emission changes in S1 relative to base scenario.

Sector	CO_2 emissions change (%)
EMIS CO2 AGR	0
EMIS CO2 ELC	2.66
EMIS CO2 HYG	-0.32
EMIS CO2 IND	-0.27
EMIS CO2 RES	-3.69
EMIS CO2 SER	-0.44
EMIS CO2 TRA	0
Total	-0.15

Lastly, the cost increase for S1 in comparison with the base scenario is 0.08%. This is caused by the more constrained problem, making the model invest in more expensive technologies and energy conservation measures. Note that the total cost refers to the whole system costs from 2010 to 2050, so even a very small relative change (e.g. 0.01%) can represent changes of several billion pounds.

5.2 Scenario 2 results - gas input constraint

This section presents the results of scenario 2 (S2), which implements a constraint on gas consumption for residential heating, starting from 2030. S2 is similar to S1, with the difference that the constraint only applies to the gas energy input for heating, rather than to all energy carriers (see S2 in Figure 11). This scenario is motivated by the heavy reliance on gas for heating in the UK (around 85% in the considered base scenario at 2010, see Figure 7a). Therefore a policy that tries to reduce gas consumption is likely to be easier to implement than a policy that affects all energy fuels.

Similar to S1, this scenario is likely to produce higher levels of energy conservation technology implementation and, as this constraint applies only to gas, a greater increase in electricity-based technologies seems likely to occur (see Appendix A.2 for more details on this scenario).

Key results in S2:

- The technology mix for residential heating in 2050 includes CHP (77.2%), standalone technologies (11.5%), electric boilers (7.3%), DH (2.8%) and gas boilers (1.3%). This technology mix is considerably different to the one in S1 (S1: gas boilers 54.1%, CHP 32.5%, standalone 11.5%, HP 1.5% and others 0.5%).
- Energy conservation technology "production" is 23.72% larger than the base scenario.
- The constraint on gas use in this scenario reduces the residential gas consumption, but electricity use increases. The overall fuel use for heating is reduced by 2.92% relative to the base scenario. Most of this reduction is attributed to gas.
- Total CO2 emission production is increased by 0.2% and the total system cost increases by 0.06%, relative to the base scenario. The solution of this scenario seems to be more cost effective than that of S1. However, it increases overall emissions, suggesting that just reducing gas use in the residential sector might not help in achieving CO2 emissions targets, as emissions are transferred to other sectors, especially the hydrogen and electricity sectors.

Figure 17 shows the heating technology production from 2010 to 2050 for existing houses. Once again, the results for the base scenario are represented in solid lines and the results for the current scenario, S2, are in dashed lines. In comparison with S1, the change in the use of gas boilers (dashed blue line with '□' marker) and CHP systems (dashed dark red line lines with '△' marker) is considerably smaller for S2. It can be seen in Figure 17 that the gas boiler and CHP production for S2 follow the same pattern as the base scenario, but with a small decrement in total production (around 2% for gas boilers and less than 1% for CHP), and an increment of around 7% on total production for night storage heaters (pink lines with '▷' marker).

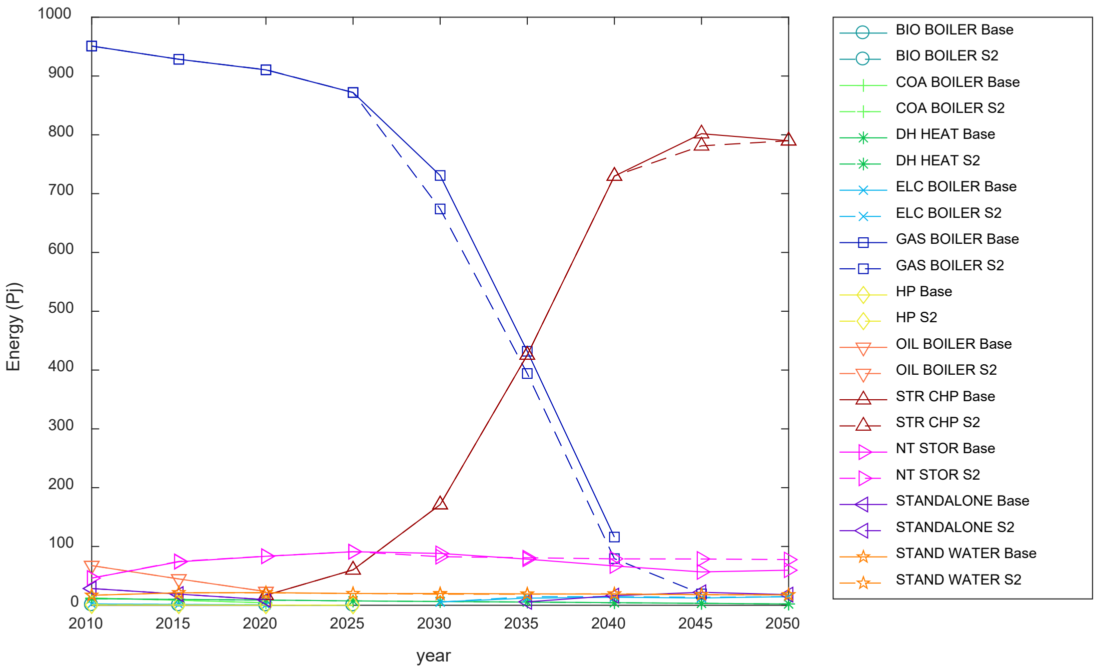

Figure 17. Production of residential heating technologies in existing houses for the base scenario and S2.

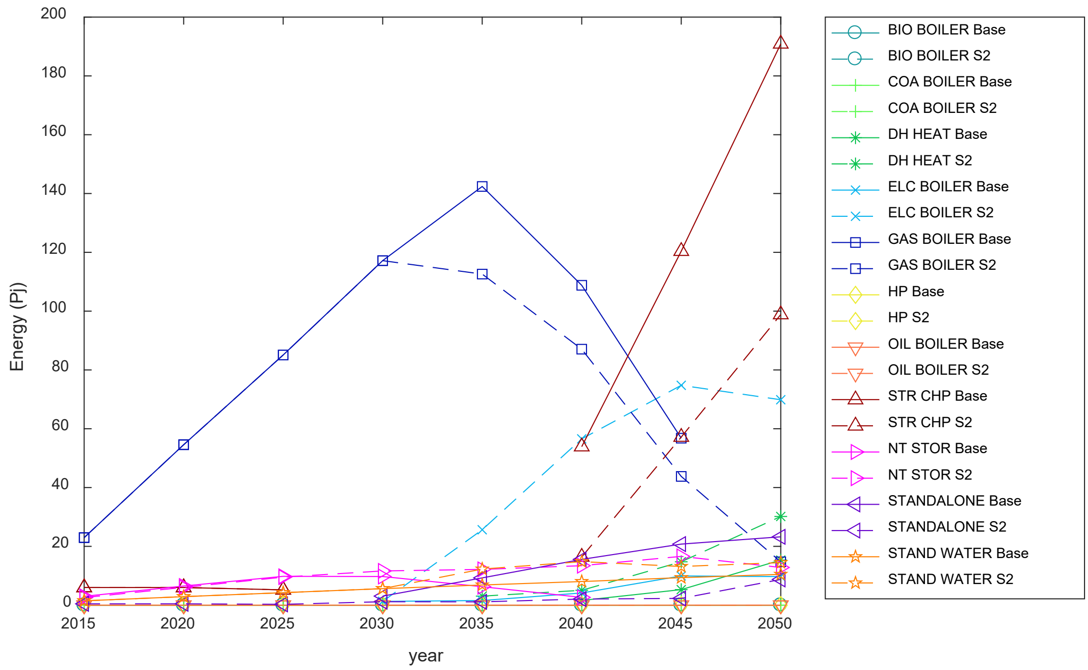

Figure 18. Production of residential heating technologies in new houses for the base scenario and S2.

New houses experience greater changes in heating technologies (see Figure 18) than existing houses. CHP and gas boiler production also follow the general patterns of the base scenario but with significantly smaller adoption, especially for CHP systems (around 50% less in total heat production). These gas fired systems are replaced mainly by electric technologies, such as electric boilers (dashed light blue line with 'x' marker), storage heaters (dashed pink line with '▷' marker) and district heating[10] (DH, dashed green line with '∗' marker).

The technology changes presented in Figure 18 show the effect of the constraint on gas use implemented in this scenario, limiting the use of CHP and gas boilers and making the model replace these systems with electricity-based technologies.

Figure 19 shows the share of residential heating technologies in S2 at year 2050. These shares are still quite different from those in the base scenario (see Figure 9 left-most column), but not as different as the shares in S1. For scenario S2, CHP presents the large majority of heating with 77.2%, complemented with other electric systems, and a small share of gas boilers (1.3%). In the base scenario: CHP 85.1%, standalone 11.2%, Elc boiler 2.1%, DH 1.5%.

These results show the importance of the type of energy efficiency scenario used, as even with relatively similar constraints in S1 and S2, the technology adoption patterns are quite different (see for example Figure 13 and Figure 18), leading to very different technology mixes (see Figure 19 in comparison with Figure 14).

[10] UKTM considers several types of district heating technologies, using a variety of fuels including gas, hydrogen, electricity, etc.

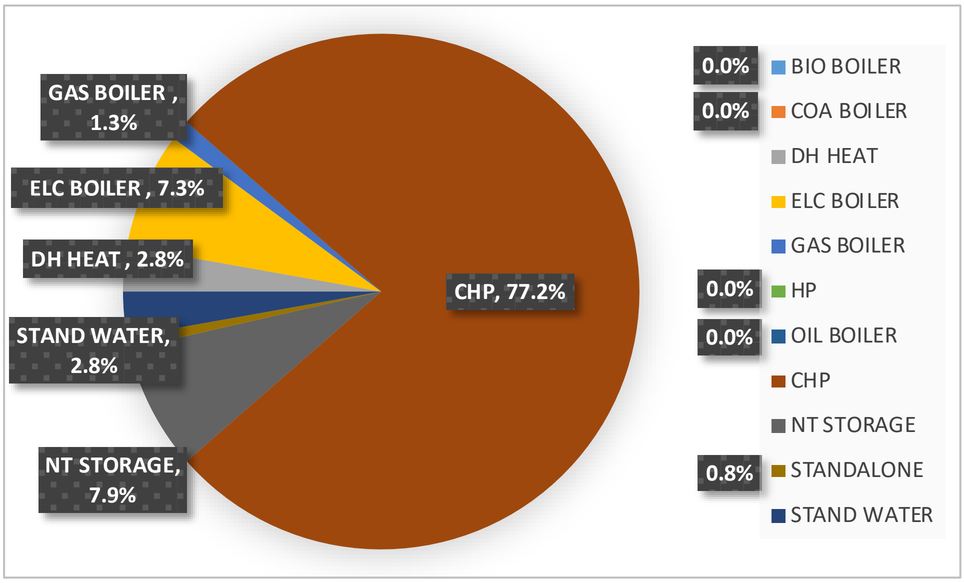

Figure 19. Residential heat production shares by technology type at 2050 – S2.

Figure 20 shows energy conservation technology production in S2. Similar to S1, in this scenario, the production of the solid wall insulation SOL02 (dashed dark blue line with '□' marker) increases significantly, relative to the base scenario, reaching the maximum possible capacity from year 2035. However, unlike S1, in S2 there is no production from SOL03. The total energy conservation technologies production in S2 is 23.72% more than the base scenario.

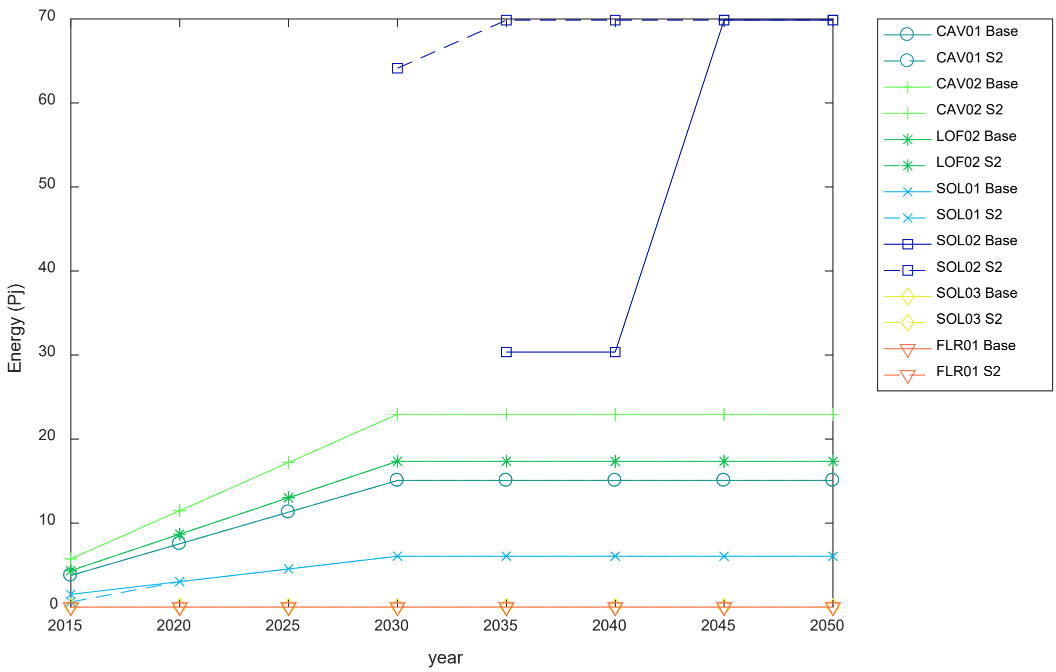

Figure 20. Production of energy conservation technologies for the base scenario and S2.

Figure 21 shows the total fuel use for residential heating in S2. The change of total gas use in this scenario is slightly larger than in S1 (5.53% total reduction in S2, and 5.04% in S1), which is also accompanied by an important increase in relative terms for hydrogen (dashed yellow line with '◊' marker). Note that hydrogen is also used as an alternative to gas in CHP and other domestic gas-fired technologies.

For electricity, unlike S1 that presented a small reduction (around 1% less than base scenario), S2 presents an important increase in electricity use for heating (15.36% more than the base case). These changes in fuel use follow the technology adoption changes shown in Figures 17 and 18, with less presence of gas-fired technologies and an increase in electricity-based heaters. The total change in fuel use for this scenario is -2.92% relative to the base case, most of it attributable to gas use reduction.

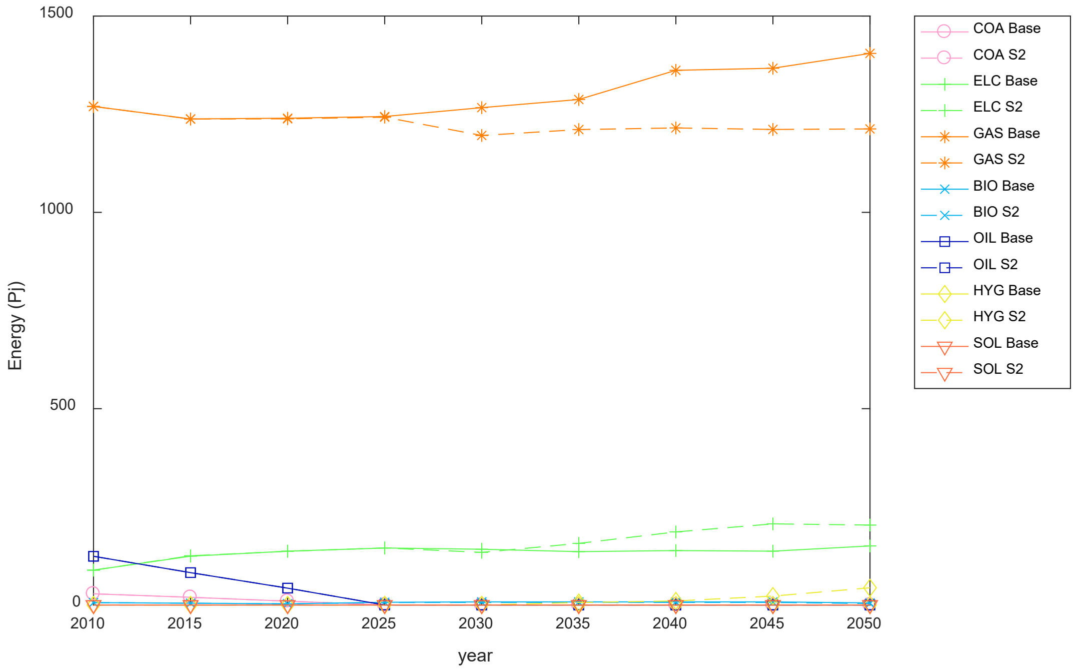

Figure 21. Fuel use for residential heating for the base scenario and S2.

Table 3 shows the sectoral CO_2 emission changes for S2. The residential sector generates a larger reduction (-5.11%) in this scenario than in S1 (-3.69%), but also the electricity sector is associated with a slightly larger increase (3.8% in S2 and 2.66% in S1), caused by the larger production from electricity-based heating and the reduction of CHP-produced electricity. The emissions due to hydrogen production have also increased considerably (nearly threefold) and overall, total CO_2 emissions have increased slightly by 0.2% in comparison with the base scenario. This shows that for this UK case, just reducing the use of gas in the residential sector might not help in achieving CO_2 emissions targets, as emissions are transferred to other sectors.

Table 3. Sectorial total CO2 emission changes in S2 relative to base scenario.

Sector	CO_2 emissions change (%)
EMIS CO2 AGR	-2.89
EMIS CO2 ELC	3.80
EMIS CO2 HYG	+100
EMIS CO2 IND	-0.06
EMIS CO2 RES	-5.11

EMIS CO2 SER	0.30
EMIS CO2 TRA	0
Total	0.20

The change in total cost for S2 is 0.06% which is slightly lower than the total cost in S1. These results show that the technology mix obtained in this scenario would be more cost effective than the one in S1. However, this approach increases the total amount of CO_2 emissions which should also be taken into account.

5.3 Scenario 3 results – Heat pipe production constraint

This section presents the results of scenario 3 (S3), implementing a constraint on the energy transferred using heat pipe technologies (technologies that use pipes and radiators to supply heating and domestic hot water services) for residential heating, starting from 2030. S3 represents an alternative to scenario 1 by constraining the energy carried by these technologies (the output of the technologies, see S3 in Figure 11), instead of limiting the input fuels as in S1 (see Appendix A.3 for more details on this scenario).

The constraint implemented in this scenario is similar to the one set in S1 as it produces a similar effect in limiting heating technologies, with the benefit that it is relatively easier to implement in TIMES. The potential drawback of this approach is that it does not take into account standalone technologies, so an increase in these types of technologies is likely to occur. However, in the UKTM base case this does not necessarily represent a drawback as most technologies are of the heat pipe group (see Figure 8).

Key results in S3:

- The technology mix for residential heating in 2050 includes CHP (84.9%), standalone technologies (13.2%), and DH (1.9%). This technology mix is different to previous scenarios and closer to the one in the base scenario (base scenario: CHP 85.1%, standalone 11.2%, Elc boiler 2.1%, DH 1.5%).
- The energy conservation technology “production” is 45.72% larger than in the base scenario. Also, considerably more than in S1 (21.91%) and S2 (23.72%).
- Gas and electricity use for residential heating is reduced. The overall fuel use for heating is reduced by 3.86% relative to the base scenario.
- Total CO_2 emissions are reduced by 0.76% and the total system cost increases by 0.27%, relative to the base scenario. This scenario generates higher costs than previous cases, but also a better CO_2 outcome.

Figure 22 and 23 show heating technology production in S3 for existing and new houses, respectively. Considering that the constraint implemented in this scenario has similar effects to S1, applying indirectly to all input energy types, the changes in technology for existing houses prove to be quite different for S3 (see Figure 12 in comparison with Figure 22). On the other hand, the changes in this scenario are similar to those in S2 (see Figure 17) for gas boilers and CHP, but differ significantly on electricity based heaters with an important decrease of electric boilers (0% in S3, in comparison with 2.1% in S1 and 6.7% in S2) and almost no change for storage heaters (pink lines with ‘▷’ marker), relative to the base scenario.

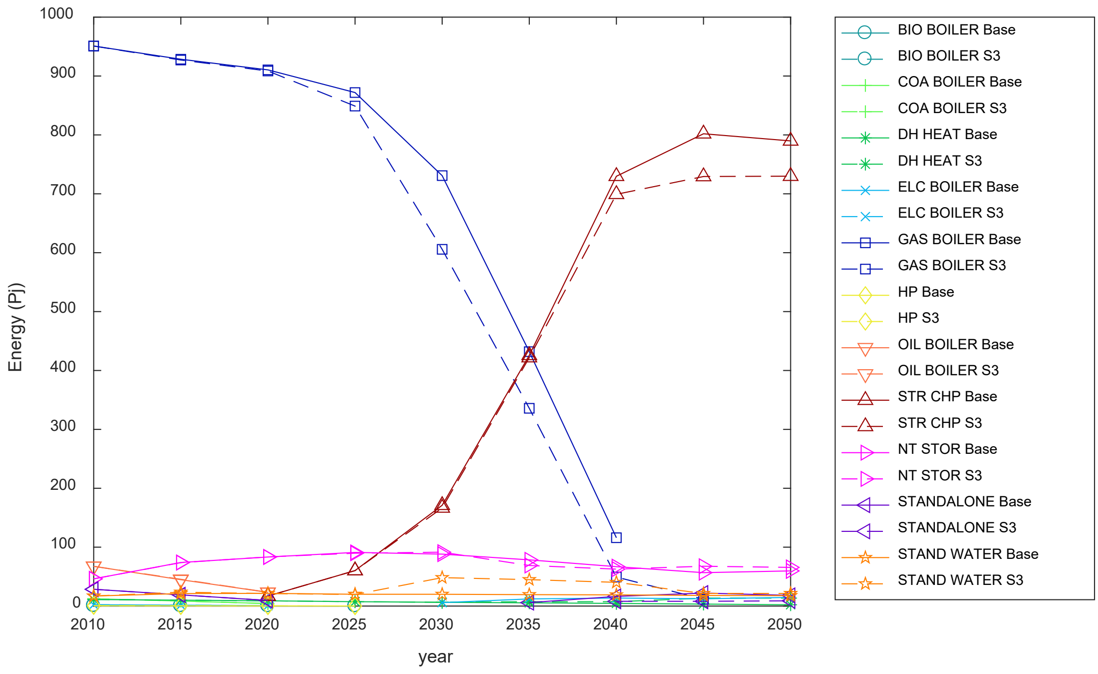

Figure 22. Production of residential heating technologies in existing houses for the base scenario and S3.

A similar effect can be seen for the heating technologies in new households (Figure 23), where CHP and gas boilers follow the patterns of the base scenario but with lower levels: -18.48% for gas boilers and -31.6% for CHP total production changes, and electric boiler use disappears. Conversely, some of the standalone technology production increase importantly, such as the standalone water heaters (dashed orange line with '☆' marker, 79.4% increase) or night storage heaters (dashed pink line with '▷' marker, 19.2% increase in total). As the constraint implemented in S3 applies to non-standalone technologies, it is expected that these standalone technologies would increase in importance.

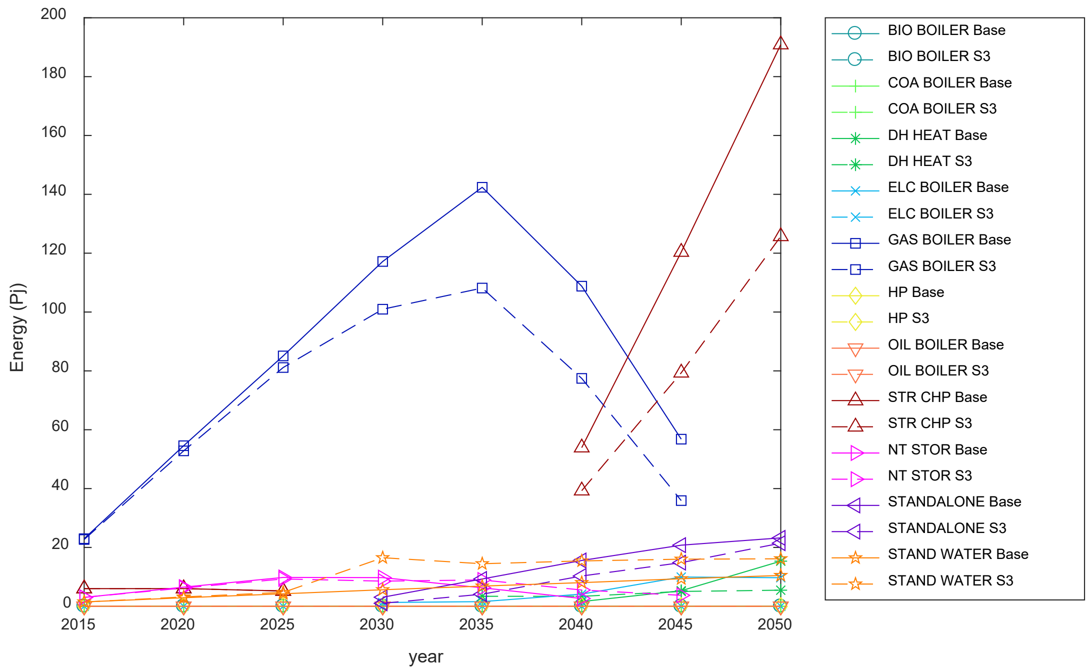

Figure 23. Production of residential heating technologies in new houses for the base scenario and S3.

Figure 24 shows the residential heating technology mix in S3 at year 2050. These shares are closer to those in the base scenario (see Figure 9 left-most column) than in S1 or S2, with CHP as the major technology (84.9%). Standalone technologies and district heating complete the mix.

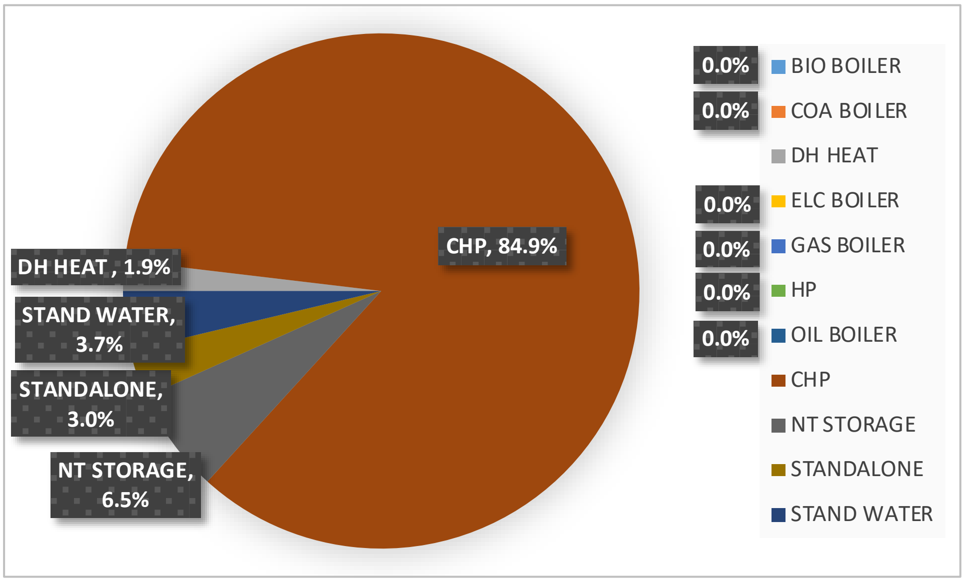

Figure 24. Residential heat production shares by technology type at 2050 – S3.

Figure 25 show the energy conservation technology production from 2010 to 2050 for S3. The increases in energy conservation production in this scenario are considerably larger than those observed in S1 and S2. In this case SOL02 (dashed dark blue line with '□' marker) and SOL03 (dashed yellow line with '◊' marker) reach a maximum value at 2030. So the increment in production for these technologies is 82% and +100%, respectively. The total production change in energy conservation for S3 is 45.72%, which is approximately double that in S1 (21.91%) and S2 (23.72%). This difference is attributed to the fact that in S1 and S2, even though the input fuel for heating technologies was constrained, the model could switch to more efficient technologies to maintain a similar production of heat without increasing energy conservation measures. However, in S3, more efficient technologies would be equally affected by the constraint on production, so in order to meet the demand, the model had to use more energy conservation measures.

As discussed before, the constraint implemented in this scenario is similar to the one used in S1 by constraining the production of all technologies (except for standalone ones, which represent around 10% of total production), so similar results would have been expected with some extra standalone technologies penetration. However, the results show that this scenario not only produces differences in the heating production technologies but also promotes higher energy conservation measures.

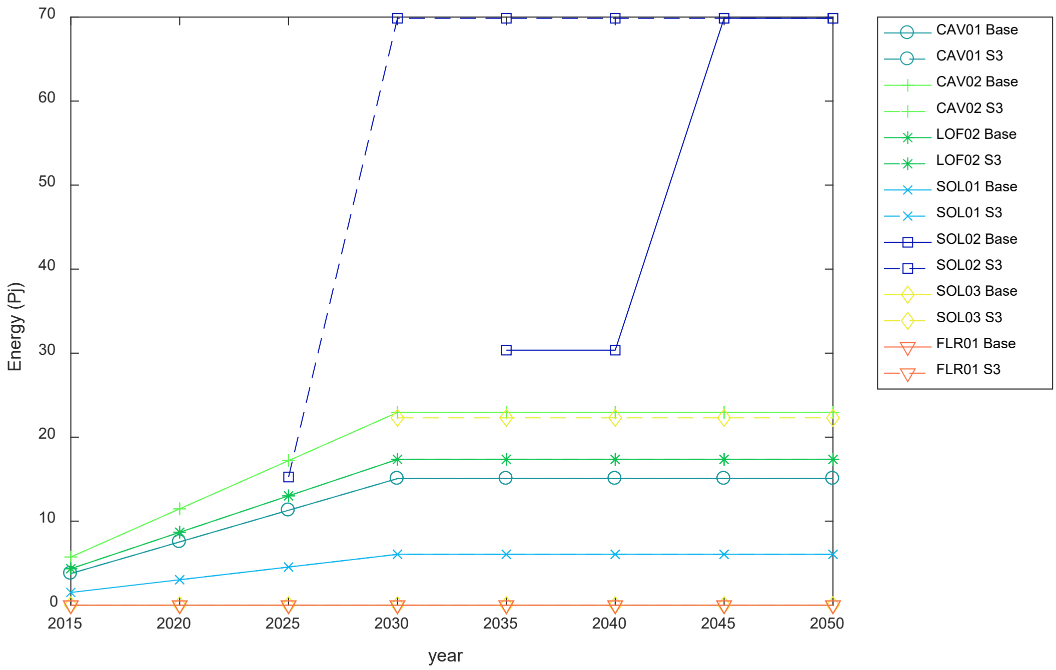

Figure 25. Production of energy conservation technologies for the base scenario and S3.

The residential heat fuel use in S3, shown in Figure 26, is similar to the one in S1, where gas use presents the largest reduction in absolute values (orange lines with '∗' marker, reduction of approximately 4%). However, total electricity consumption is barely modified (light green lines with '+' marker, -0.21%). Total fuel use change in S3 is -3.86%.

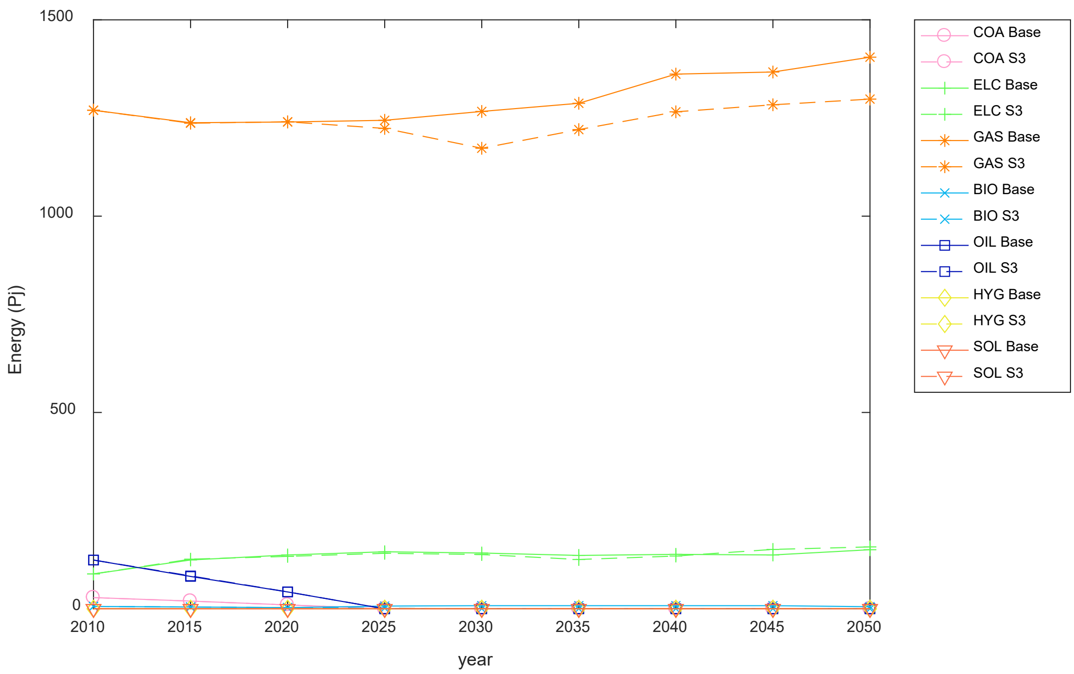

Figure 26. Fuel use for residential heating for the base scenario and S3.

Table 4 shows the sectoral CO_2 emission changes for S3. The residential sector presents a similar reduction to S1 (-3.69%) caused by the decrease in gas consumption. However, unlike S1 or S2 the power sector (ELC) presents a decrease of emissions in S3 (-0.59%). These decreases can be attributed to both the lower use of gas-based heating technologies and more importantly to the increment of energy conservation implementation. The total CO_2 emission production is also reduced more in S3 (-0.76%) than in previous scenarios. Also note that there is no sectoral substitution for emissions, as all sector changes are negative or zero.

Table 4. Cumulative sectorial CO2 emission changes in S3 relative to base scenario.

Sector	CO_2 emissions change (%)
EMIS CO2 AGR	0
EMIS CO2 ELC	-0.59
EMIS CO2 HYG	-0.32
EMIS CO2 IND	-0.25
EMIS CO2 RES	-3.69
EMIS CO2 SER	-0.51
EMIS CO2 TRA	0
Total	-0.76

Another important difference appears in the change in total cost. S3 generates an increase of 0.27%, which is considerably higher than in S1 (0.08%) or S2 (0.06%). In all these scenarios, the residential heating energy efficiency target has been achieved. However, these results show that the different technology mixes could be more (or less) effective in reducing CO_2 emissions and could vary in costs considerably.

5.4 Scenario 4 results – Minimum level of conservation technologies

This section presents the results of scenario 4 (S4) that sets a minimum level of energy conservation technology production. 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 S4 in Figure 11), so heating production technologies are not directly affected, but their role in meeting energy services demand is reduced.

The constraint used in S4 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. This contrasts with directly limiting the use of fuels (as in S1 through S3). Therefore, the outcomes of this scenario are likely to be similar to those of previous scenarios, with a potentially larger share of energy conservation technologies (see Appendix A.4 for more details on this scenario).

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. However, this constraint has proved to be problematic for the model as the total costs generated by this scenario is almost nine times higher (873%) than the costs in the base scenario. This is an enormous difference with previous scenarios where the change in total cost was between 0.06% and 0.27%, suggesting a problem in the implementation of this constraint[11].

Analysing the results, it was found that the constraint in S4 is infeasible, as the energy conservation technology imposes a technology cap (set by the UK TIMES modellers), and the total possible production of these technologies is 154.3 PJ[12] which is slightly below the desired target (-8.5%). The problem presented in this scenario is an example of potential issues caused by constraints and considerations set by TIMES modellers, which could unnecessarily limit or bias the solutions if they are not set based on adequate projections or assumptions (see Section 6 for further discussion on these issues).

To obtain reliable results, a new target has been set for this scenario (labelled S4*), adjusting the minimum level of annual energy conservation technology production to 154 PJ. The results for this adjusted scenario are presented in Section 5.4.1.

5.4.1. Scenario 4* results – adjusted target

Key results in S4*:

- The technology mix for residential heating in 2050 includes CHP (85.5%), standalone technologies (11.3%), electric boilers (1.9%) and DH (1.9%). The technology mix in this scenario is almost identical to the one in the base scenario (CHP 85.1%, standalone 11.2%, Elc. boiler 2.1%, DH 1.5%).
- The cumulative energy conservation technology production is 43.94% larger than the base scenario. Similar to the implementation level in S3.
- Similar to S1 or S3, gas and electricity use for residential heating is reduced. However, the overall fuel use for heating is only reduced by 2.53% relative to the base scenario. This suggests that a restrictive conservation technology constraint in UKTM seems to be ineffective to achieve energy efficiency targets, as the cost minimisation problem allows the system to shift to cheaper but less efficient technologies.
- Total CO_2 emissions are reduced by 0.29% and the total system cost increases by 0.04%, relative to the base scenario. This scenario performs better in CO_2 emissions reductions, and at a lower cost, than S1 and S2. So this approach could be useful if the objective is to reduce emissions, independently of the energy use targets.

Figure 27 shows heating technology production from 2010 to 2050 for existing houses. The changes in these technologies are similar to those presented in S2 or S3, with reductions on CHP and gas boiler production (-2.10% and -3.33%, respectively), but unlike previous scenarios the use of other technologies, including electric boilers and standalone technologies, also declines (e.g. electric boiler -12.94%, storage heater -2.46%, and standalone heater -5.88%). These results suggest that the implementation of energy

[11] TIMES implements "dummy" variables that help the model to find feasible solutions where otherwise this would not be possible, but at a considerably higher costs (so that their use should be avoided unless absolutely necessary). In case of an infeasible solution, the results obtained with the TIMES model are limited, and the source of infeasibility is not always evident. This approach allows the analyst to run the model, detect a problem, and still obtain results that could help them in the troubleshooting process.

[12] As described previously, technology adoption constraints are used in TIMES, among others, to replicate to some extent the consumer adoption profiles, avoiding dramatic or unrealistic technology shifts. It is assumed that this energy conservation technology limit used in UKTM follows realistic projections for the UK and it is not deliberately set to bias the solutions in any way.

conservation technology produces a reduction in energy use for all type of fuels, instead of a shift from a type of fuel/technology to another.

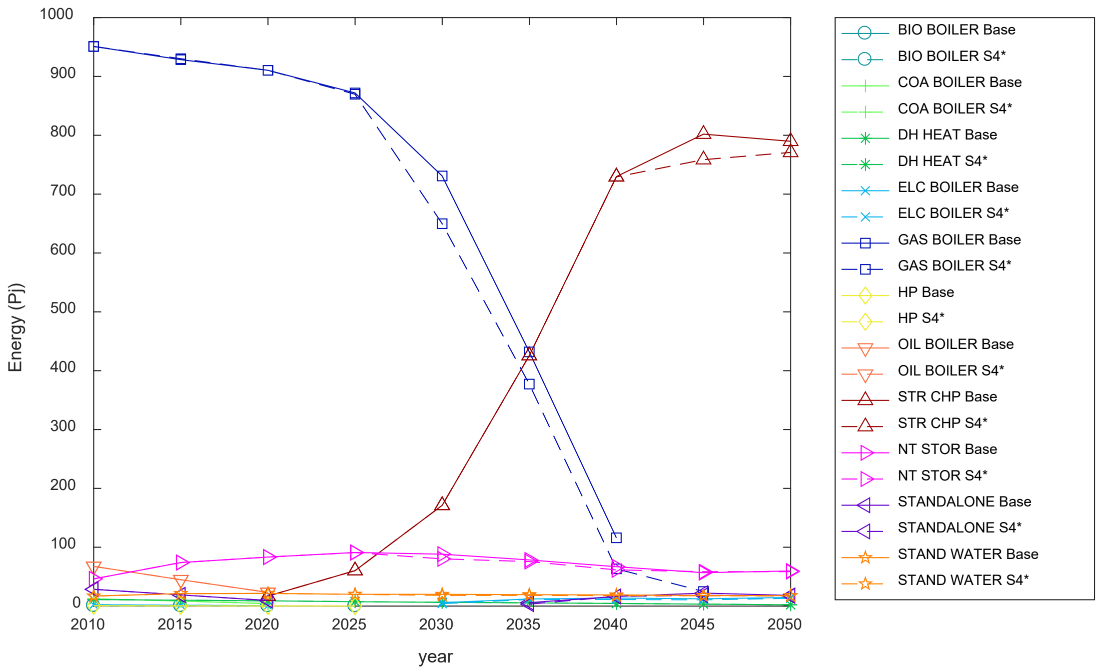

Figure 27. Production of residential heating technologies in existing houses for the base scenario and S4*.

A similar effect occurs on new houses (see Figure 28) with most technologies reducing their production slightly, relative to the base scenario. The exception here is CHP which actually increases total production by 3.02%. This small increase is motivated by the CHP system producing more electricity for residential demands.

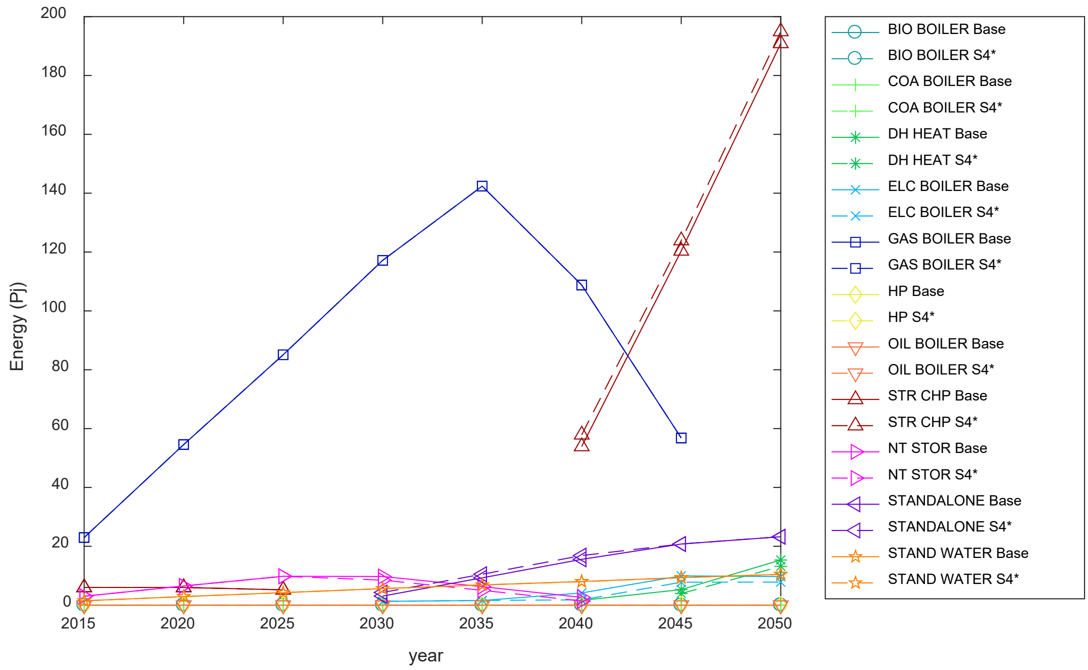

Figure 28. Production of residential heating technologies in new houses for the base scenario and S4*.

Figure 29 shows the share of residential heating technologies in S4* at year 2050. The technology mix in this scenario is almost identical to the one in the base scenario (see Figure 9 left-most column). In other words, these results suggest that the implementation of more energy conservation alternatives is less ‘intrusive’ to the overall heating technology adoption paths.

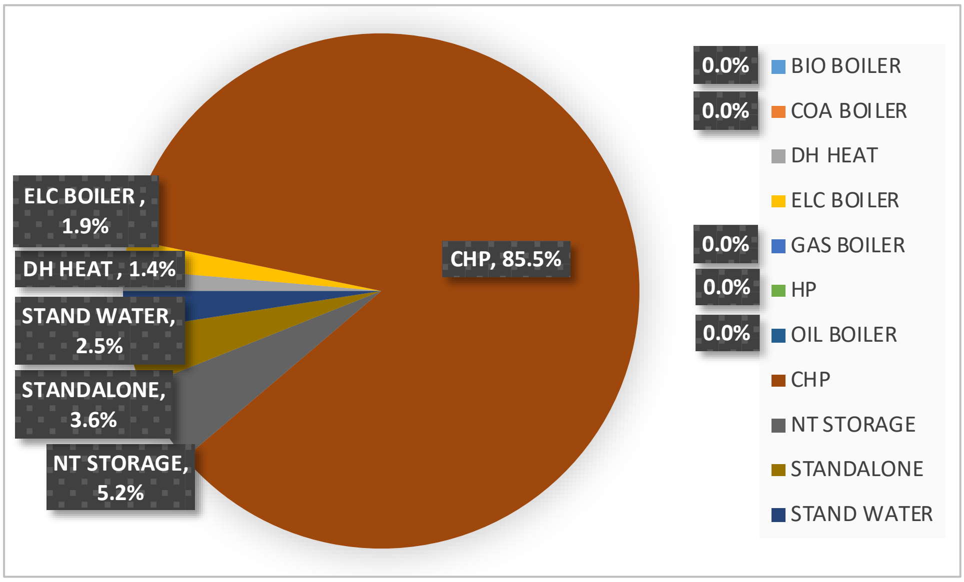

Figure 29. Residential heat production shares by technology type at 2050 – S4*.

Figure 30 shows energy conservation technology production in S4*. The constraint implemented in this scenario makes the system use all available energy conservation technologies, reaching their maximum capacity from 2030. The most apparent change in this scenario is the implementation of floor insulation FLR01 (dashed orange line with ‘▽ ’marker), a technology that has not been used in previous scenarios due to its higher cost.

Total energy conservation technologies production in S4* is 43.94% more than the base scenario. This value is larger than in S1 and S2, but it is very similar to the total energy conservation implementation in S3, showing that the use of this type of energy conservation technology could be promoted by different constraints.

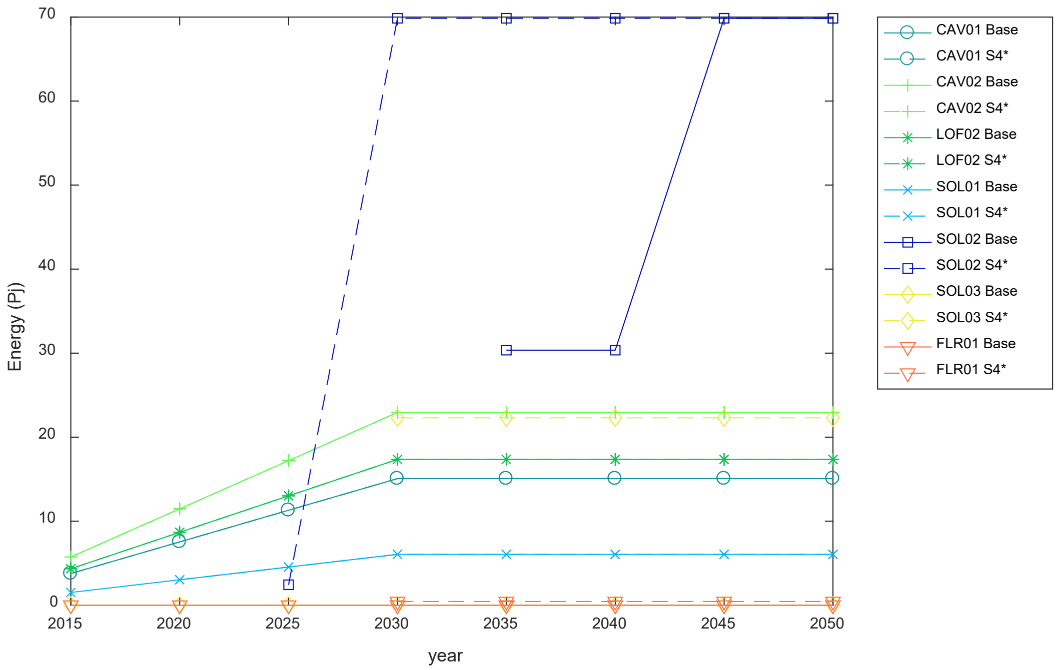

Figure 30. Production of energy conservation technologies for the base scenario and S4*.

Figure 31 shows the total fuel use for residential heating in S4*. This scenario also presents a reduction in gas use, but it is not a ‘flat’ reduction as in S1 or S2 (see orange lines with ‘∗’ marker in Figure 16 and Figure 21) or a more constant one as in S3 (see Figure 26). In S4* the gas use reduction is larger at 2030 and then the reduction decreases steadily up to 2050. So the total gas use change is -2.53%, which is lower than the values of previous scenarios. Electricity use also registers a small reduction (-3.65%) and the other fuels remain mainly unaffected.

Note that the total fuel use change for this scenario is -2.53%, which contrasts importantly with S1 or S3 where savings reached -4.71% and -3.86%, respectively. In other words, forcing the implementation of energy conservation technologies in UKTM (some of which might not be cost-effective) seems to be less effective in achieving energy efficiency target as the cost minimisation problem allow the system to shift to less efficient technologies (minimising any potential savings from energy conservation alternatives) if that represents lower overall costs.

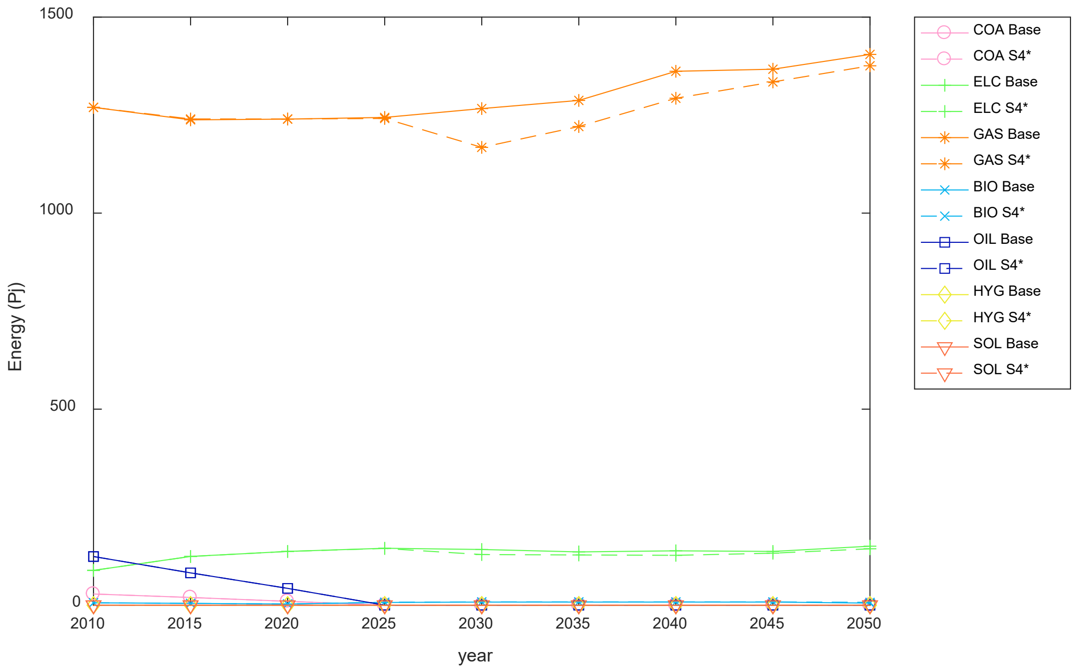

Figure 31. Fuel use for residential heating for the base scenario and S4*.

Table 5 shows the sectoral CO_2 emission changes for S4. The residential sector presents a reduction of -2.34%, but this is smaller than in S1 (-3.69%), S2 (-5.11%) or S3 (-3.69%). Also, unlike in previous scenarios, the electricity sector also generates a reduction in emissions (-0.28%). Other sectors are mainly unaffected. The overall CO_2 emissions change in this scenario is -0.29% which is smaller than in S3 (-0.76%), but better than in S1 (-0.15%) or S2 (0.2%).

Table 5. Cumulative sectorial CO2 emission changes in S4* relative to base scenario.

Sector	CO_2 emissions change (%)
EMIS CO2 AGR	0
EMIS CO2 ELC	-0.28
EMIS CO2 HYG	0
EMIS CO2 IND	0.05
EMIS CO2 RES	-2.34
EMIS CO2 SER	0.42
EMIS CO2 TRA	-0.01
Total	-0.29

Total cost in S4* (relative to the base scenario) increases by 0.04%, which is smaller than in previous scenarios. However, this scenario does not achieve the desired energy efficiency target for residential heating, which is an important outcome to take into account, especially for researchers and policy makers who have used this approach in their energy efficiency scenarios (see Section 2.4). On the other hand, the solution obtained performs better in terms of CO_2 emissions reductions, and at a lower cost, than S1 and S2. So this approach could be useful if the objective is to reduce emissions, independently of the energy use.

5.5 Scenario 5 results – Demand reduction

This section presents the results of scenario 5 (S5), implementing a demand shock, consisting of a reduction of 10% on residential heating services demand from 2030. This demand reduction scenario is similar to the one used in Shi et al. (2016).

This scenario, unlike previous ones, only reduces the heating demand (a model input) and does not implement any constraint that could affect technology implementation, 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 (see Appendix A.5 for more details on this scenario).

Note that this scenario implies a change in consumer behaviour which occurs outside of the model, and this demand reduction does not represent an improvement in energy efficiency within TIMES using the energy efficiency and conservation technologies available to it. 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'.

Key results in S5:

- The technology mix for residential heating in 2050 includes CHP (86.8%), standalone technologies (11.2%), electric boilers (1.6%) and DH (0.4%). These technology shares do not change significantly relative to those in the base scenario (CHP 85.1%, standalone 11.2%, elc. boiler 2.1%, DH 1.5%).
- The energy conservation technology "production" is 10.63% lower than the base scenario. This scenario is the first one that is associated with a reduction in total energy conservation production, in this case linked to a reduction in demand.
- The overall fuel use for heating is reduced by 5.53% relative to the base scenario. This reduction is slightly greater than previous scenarios, caused mainly by the reduction in final energy demand.
- The total CO_2 emission production is reduced by 0.69% and the total system cost is reduced by 0.48%, relative to the base scenario. This is the first case where the total system costs are reduced, so this would represent an 'ideal' scenario where the end user decides to use less energy for heating, a 'free' solution for the energy efficiency problem. However, this is not necessarily a good proxy for energy efficiency improvements.

Figure 32 and Figure 33 show heating technology production in S5 for existing and new houses, respectively. With the reduction in demand in S5, most technologies have decreased their production accordingly (average of -4.93% for existing houses and -8.24% for new houses). A similar effect occurs in S4*, but the heating production reductions of S5 are larger than in S4*.

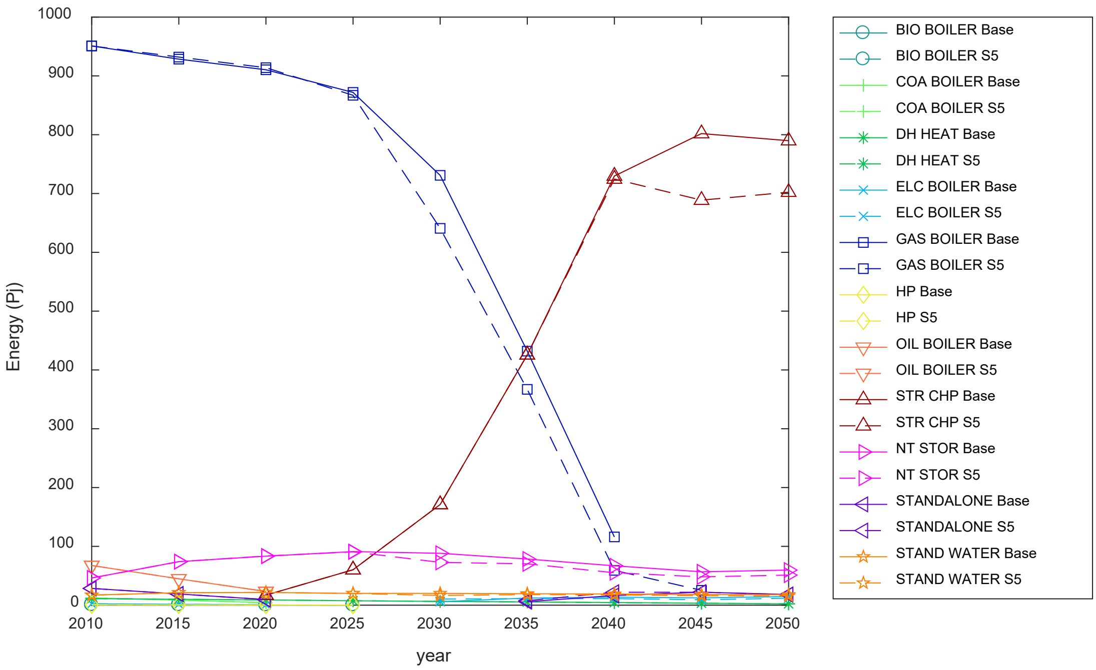

Figure 32. Production of residential heating technologies in existing houses for the base scenario and S5.

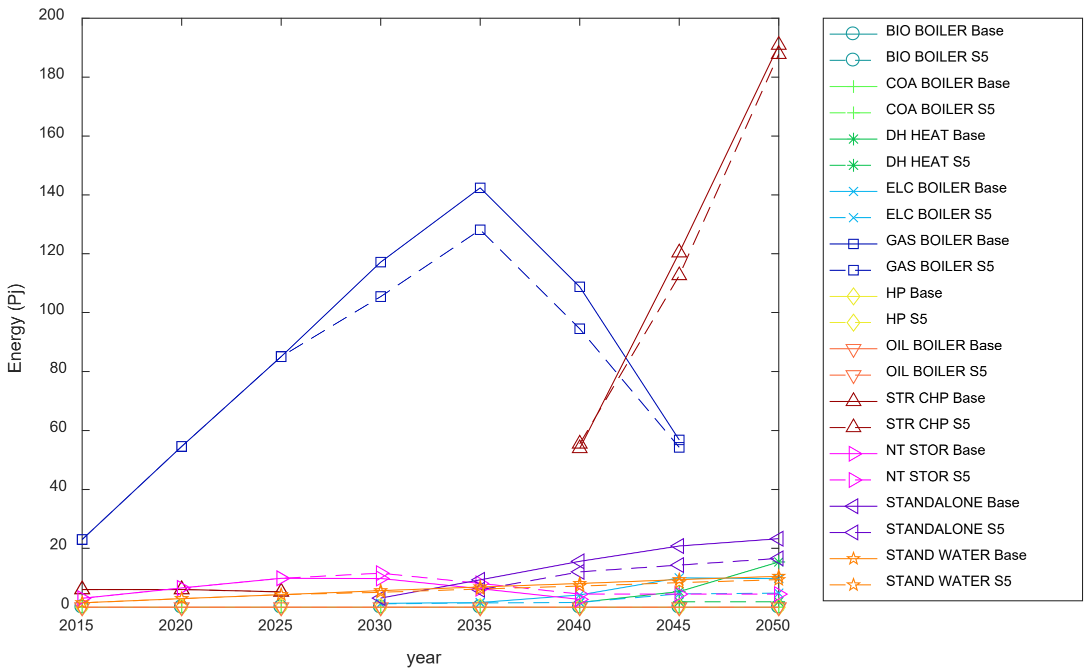

Figure 33. Production of residential heating technologies in new houses for the base scenario and S5.

Figure 34 shows the residential heating technology mix for S5 (year 2050). The shares are not significantly different from those in the base scenario (see Figure 9 left-most column), which suggests a relatively even fall in production across all technologies.

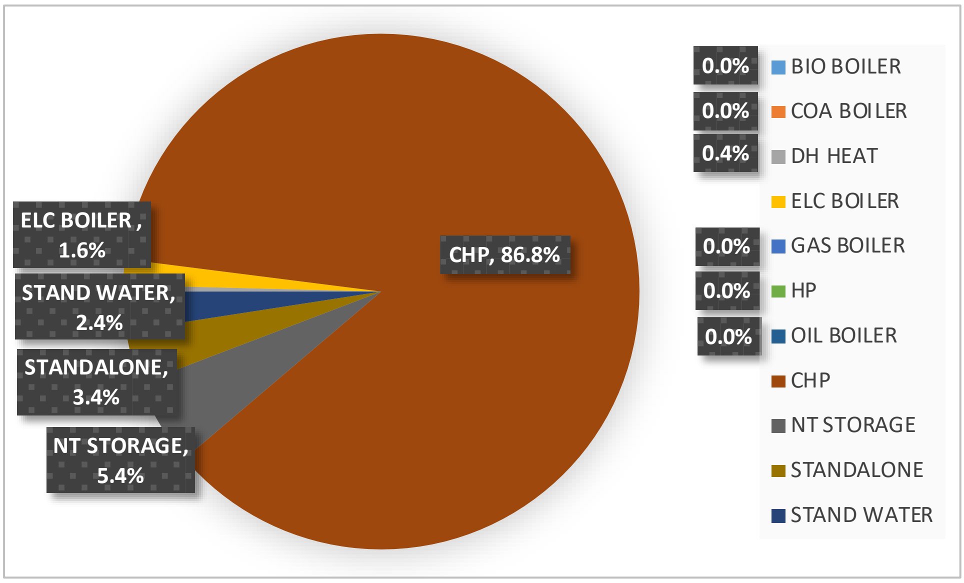

Figure 34. Residential heat production shares by technology type at 2050 – S5.

Figure 35 shows the energy conservation technology production for S5. This scenario is the first one associated with a reduction in total energy conservation production, caused by the reduction in demand. In particular, solid wall insulation SOL01 and SOL02 have reduced total production by -7.69% and -30.29%, respectively. Also, SOL03 and FLR01 have not been implemented and other energy conservation technologies have not been changed. The total change in energy conservation production for this scenario is -10.63%, suggesting that conservation measures were a relatively expensive way of meeting demand.

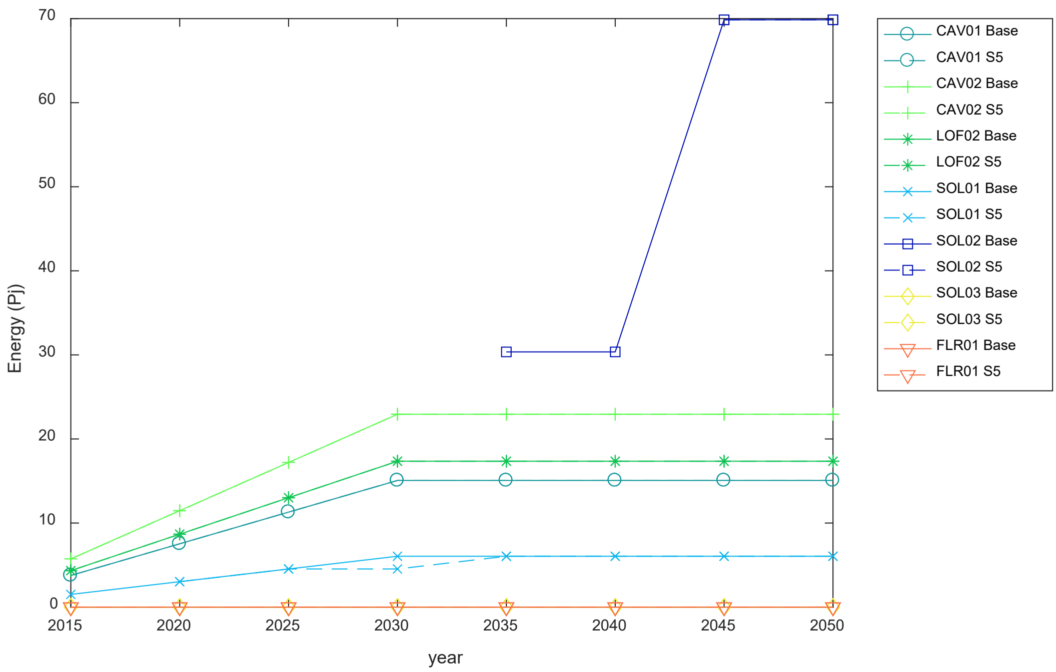

Figure 35. Production of energy conservation technologies for the base scenario and S5.

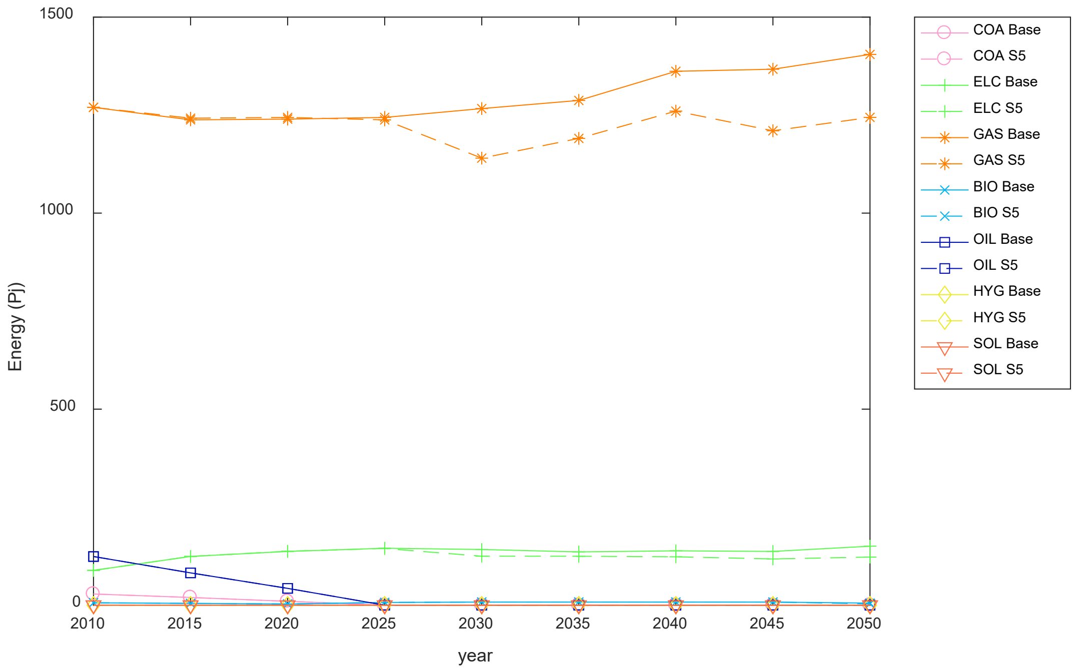

Figure 36. Fuel use for residential heating for the base scenario and S5.

The residential heat fuel use in S5, shown in Figure 36, differs from previous scenarios in that it generates net reductions in all fuel types. In particular, gas and electricity present the largest relative reductions (-5.48% and -7.53%, respectively). The cumulative total fuel use change in this scenario is -5.53%.

Table 6 shows the sectoral CO_2 emission changes for S5. In this scenario, most sectors reduce emissions, with the residential sector showing the largest falls (-5.07%). The power sector is also associated with a small reduction (-0.31%), and total CO_2 emissions fall by -0.69% which is larger than in S1, S2 or S4*, but slightly lower than S3 (-0.76%).

Table 6. Cumulative sectorial CO2 emission changes in S5 relative to base scenario.

Sector	CO_2 emissions change (%)
EMIS CO2 AGR	3.59
EMIS CO2 ELC	-0.31
EMIS CO2 HYG	-0.32
EMIS CO2 IND	0.03
EMIS CO2 RES	-5.07
EMIS CO2 SER	-0.35
EMIS CO2 TRA	-0.05
Total	-0.69

The total cost change in S5 also represents an important difference with previous scenarios, as this is the first case where the total system costs are reduced (change of -0.48% relative to base scenario). Certainly, this would represent an ideal scenario where the end user decides to use less energy for heating, a 'free' solution for the energy efficiency problem. However, even if such a change in consumer behaviour is possible, policies would need to be put in place to motivate it and the costs of such policies are not considered in this study. Even though this scenario does not truly represent energy efficiency, it could still be relevant for policy makers to assess potential impacts on the energy system due to changes in behaviour.

5.6 Scenario 6 results – CO2 emission constraint

This section presents the results of scenario 6 (S6), which implements a constraint on residential CO_2 emissions (from 2030 to 2050), replicating the emissions obtained in S1. Note that this scenario does not really represent an energy efficiency scenario. However, it represents an approach that has been used in the literature for energy efficiency analysis (see for example Fais et al. (2016) or Blesl et al. (2007)), and thus, it is considered in this study (see Appendix A.6 for more details on this scenario).

The constraint set in this scenario does not target any type of technologies or fuels directly, but those technologies that use fossil fuels are likely to be more affected. So it is expected that oil-, carbon- and gas-based technologies experience a reduction in production, and 'cleaner' options should expand.

Key results in S6:

- The technology mix for residential heating in 2050 includes CHP (74%), standalone technologies (11.2%), gas boilers (7.7%), electric boilers (4.2%) and DH (2.9%). Despite achieving the same residential CO2 performance as S1, the technology mix exhibits considerable differences (S1: gas boilers 54.1%, CHP 32.5%, standalone 11.5%, HP 1.5% and others 0.5%).
- The energy conservation technology "production" is 18.81% larger than the base scenario. Slightly lower than S1 levels (21.91%).
- The overall fuel use for heating is reduced by 2.24% relative to the base scenario. The change in total gas use is similar to that in S1. However, unlike in S1, which generated a small reduction in electric energy use, this scenario is associated with an increase, limiting the overall energy use reduction.
- This scenario reaches the same CO_2 emission reduction for residential heating as S1. However, the total CO_2 emission increases by 0.17% and the total system cost increases by 0.03%, relative to the base scenario. The technology mix obtained in S6 is more cost effective than that in S1. However, this sectoral approach increases the total amount of CO_2 emissions.

Figure 37 and 38 present the residential heating production by technology for existing and new houses, respectively. In the existing houses, the changes are relatively minor (e.g. gas boiler reduction of 1.9%, or night storage increment of 3.19%). However, new houses show important changes. Gas boiler production decreases from 2035 but it continues its production for longer than in the base scenario (production change of 28.63%). CHP production also decreases importantly (-67.73%), which is replaced mainly by district heating, electric boilers and storage heaters.

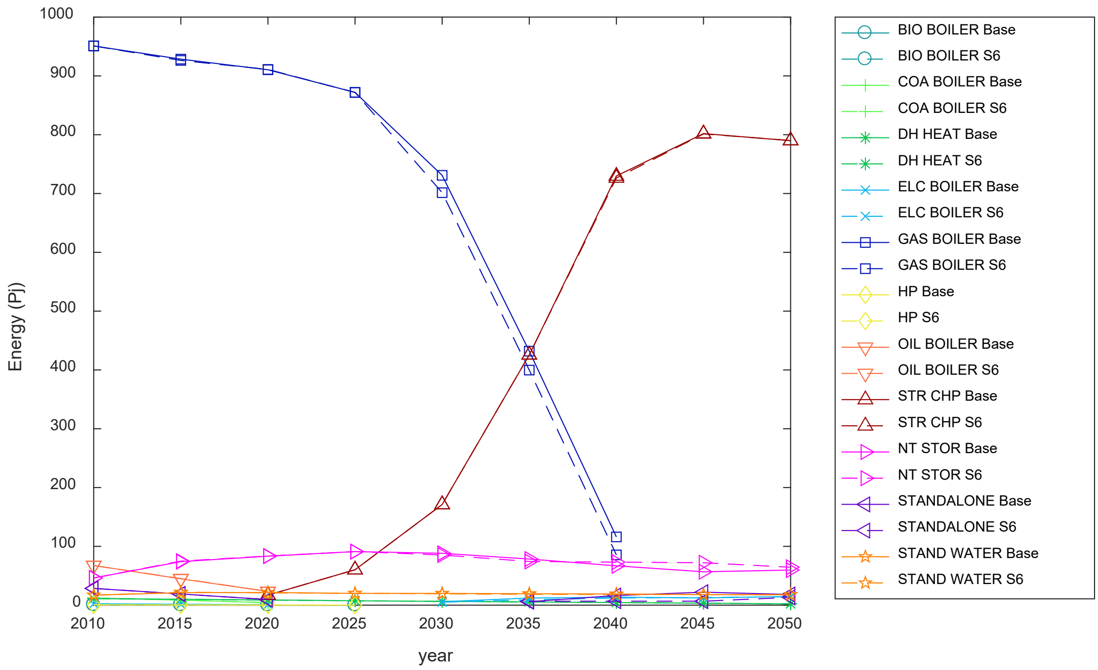

Figure 37. Production of residential heating technologies in existing houses for the base scenario and S6.

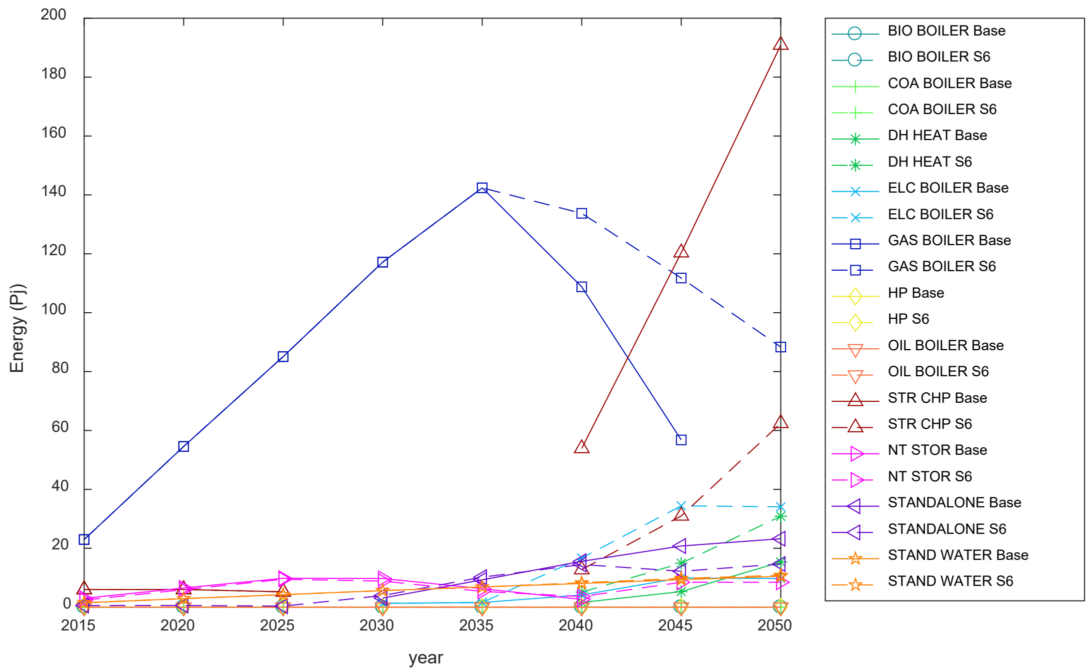

Figure 38. Production of residential heating technologies in new houses for the base scenario and S6.

Figure 39 shows the share of residential heating technologies in S6 at year 2050. The figure shows CHP technologies as the main heating system, followed by gas and electric boilers with 7.7% and 4.2%, respectively. Considering that this scenario achieves the same residential CO_2 emissions performance of S1, the technology mix in Figure 39 is quite different (see Figure 14 for comparison). On the other hand, the technology mix of S2 (see

Figure 19) is closer to the one in S6, suggesting that the CO_2 emission reductions has been achieved by using less gas as a heating fuel (the constraint implemented in S2).

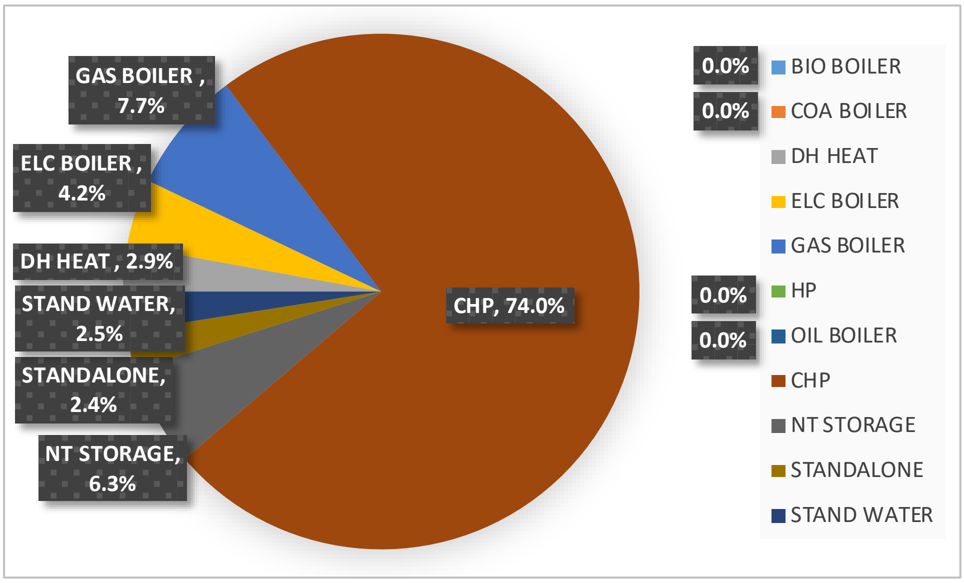

Figure 39. Residential heat production shares by technology type at 2050 – S6.

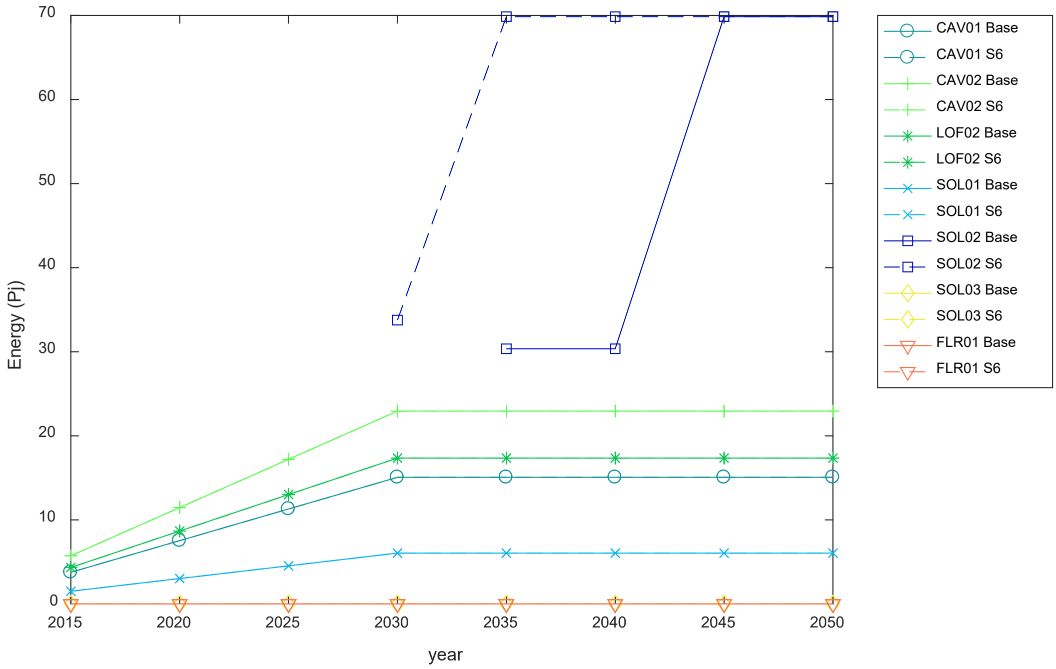

Figure 40. Production of energy conservation technologies for the base scenario and S6.

Figure 40 shows the energy conservation technology production in S6. Similar to S1 and S2, in this scenario, the production of the solid wall insulation SOL02 (dashed dark blue line with '□' marker) increases (total production change 56.26%), but the other technologies do not experience changes. Also, the technologies SOL03 and FLR01 are not adopted. Total energy conservation technologies production is 18.81% more than the base scenario.

Figure 41 shows the total fuel use for residential heating in S6. The change of total gas use in this scenario is similar to that in S1 and S2. For electricity, this scenario represents an increase in electric energy use (4.15%) as in S2, unlike S1 that presented a small reduction.

Also, S6 shows an important (relative) increase in the use of hydrogen (dashed yellow line with '◊' marker, increase over 100%). As in previous scenarios, hydrogen is used as an alternative to gas in CHP production. The total fuel use change in S6 is -2.24%.

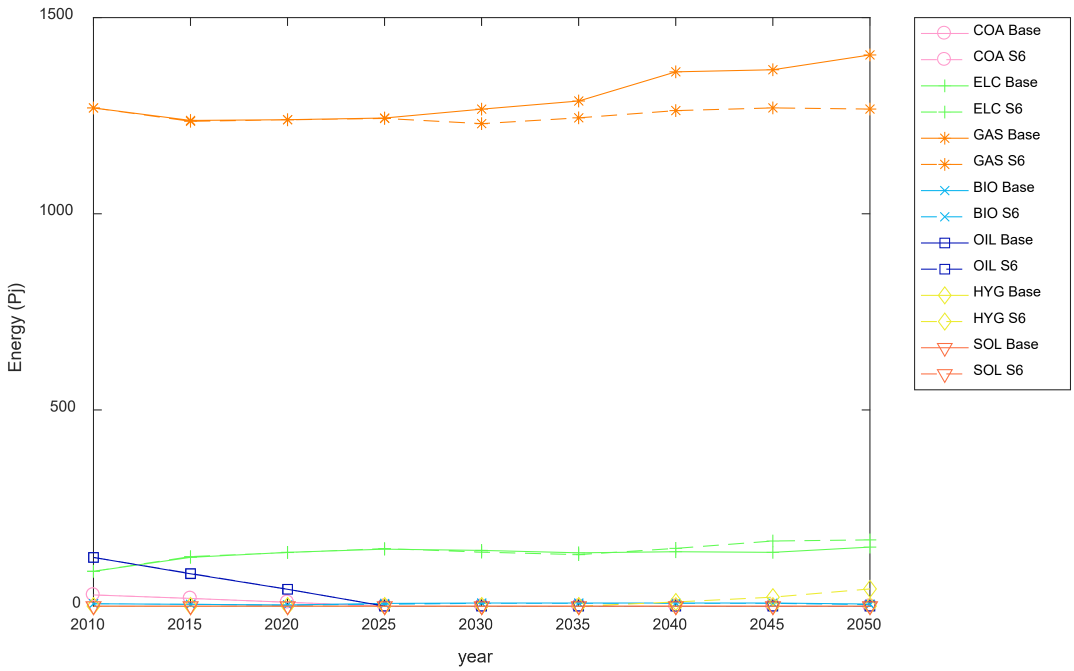

Figure 41. Fuel use for residential heating for the base scenario and S6.

Table 7 shows the sectoral CO_2 emission changes for S6. As expected, this scenario reaches the same CO_2 emission reduction than S1 for residential heating from year 2030 to 2050 and very similar total reductions for this sector (-3.7% in S6 and -3.69% in S1). However, the electricity sector exhibits a smaller increase in S6 (1.79% in comparison with 3.8% in S1). Also, the emissions due to hydrogen production have also increased considerably (+100%), and the overall total CO_2 emissions have increased slightly by 0.17% in comparison with the base scenario. Note that this increase in total CO_2 emissions contrast with the reduction associated with S1 (-0.15%), which shows that the constraint set in the residential sector has shifted those emissions to other areas, eliminating any potential benefits to tackle climate change.

The change in total cost for S6 is 0.03% which is lower than the total cost in S1 (0.08%), which shows that, if only the residential sector's CO_2 emissions target is considered, the technology mix obtained in S6 is more cost effective than that in S1. However, the setting of a sectoral-specific target for CO_2 actually increases the total amount of CO_2 emissions (see Table 7). Clearly this should not be overlooked when analysing policy alternatives.

Table 7. Cumulative sectorial CO2 emission changes in S6 relative to base scenario.

Sector	CO_2 emissions change total (%)
EMIS CO2 AGR	0
EMIS CO2 ELC	1.79
EMIS CO2 HYG	+100

EMIS CO2 IND	-0.21
EMIS CO2 RES	-3.70
EMIS CO2 SER	0.36
EMIS CO2 TRA	0
Total	0.17

6. Results discussion and policy implications

The results of the different scenarios illustrate the wide range of solutions that could be obtained with TIMES when simulating notionally equivalent energy efficiency scenarios. To facilitate the comparison of scenarios, their main outcomes are summarised in this section, and a discussion of their potential policy implications is provided, in terms of common energy policy goals and indicators. The considered energy policy indicators include: CO_2 emissions, costs, changes on energy use and technology change.

Note that 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), S4 follows the same approach used in Rosnes et al. (2017), S5 resembles the scenario analysed in Shi et al. (2016), and S6 type of scenarios have been used widely (for example Fais et al. (2016) and Blesl et al. (2007)). Also note that none of these approaches is ‘wrong’ in principle, but as clearly seen in these results, the scenarios impact the solution found by TIMES 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, since these are likely to be of considerable concern from a policy perspective.

Table 8 and Figure 42 show the overall changes in technology adoption for all scenarios. Relative to the base case, the total amount of residential heating technology production decreases in all cases and does not vary significantly across scenarios. Energy conservation technologies exhibit larger changes and higher variability among scenarios (see the second column in Table 8). For instance, S3, implementing a constraint to heat pipe production technologies (all heating technologies except standalone ones), and S4*, implementing a given level of energy conservation technologies, show the largest increase in energy conservation (around 45%). S1, S2 and S6, implementing input fuel and CO_2 emission constraints also show increases, but of a lower magnitude (around 21%). Conversely, the demand reduction implemented in S5 produced a decrease in energy conservation (-10.63%). Note that, as described in section 5.5, the demand reduction in S5 is exogenously applied, implying a change in consumer behaviour which occurs outside of the model. This demand reduction does not represent an improvement in energy efficiency utilised within TIMES and the potential costs or feasibility of such change is not assessed.

Table 8. Residential heating and energy conservation technology production changes for all scenarios (relative to base scenario).

Scenario	Heating technology production change (%)	Energy conservation tech. production change (%)
S1 – constraint on all input fuels	-1.26	21.91
S2 – constraint on gas input fuel	-1.36	23.72
S3 – constraint on heat pipe tech. production	-6.67	45.72
S4* – min. level of energy conservation tech.	-2.55	43.94
S5 – exogenous demand reduction	-5.31	-10.63
S6 – constraint on CO_2 emissions	-1.09	18.81

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 into which technologies could be supported and which ones should be analysed further. However, as shown in Figure 42 (the technology mix for all scenarios), the implications of decisions could be very different depending on the precise way in which energy efficiency is modelled within TIMES. For example, S1 presents a radically different technology mix than the other scenarios, even though they achieve very similar reductions on total energy use. The technology mixes presented in the other scenarios are similar to one another, with some very similar to the base case (see for example S4* in Figure 42), but they still exhibit some differences especially in the use of gas and electric boilers and district heating.

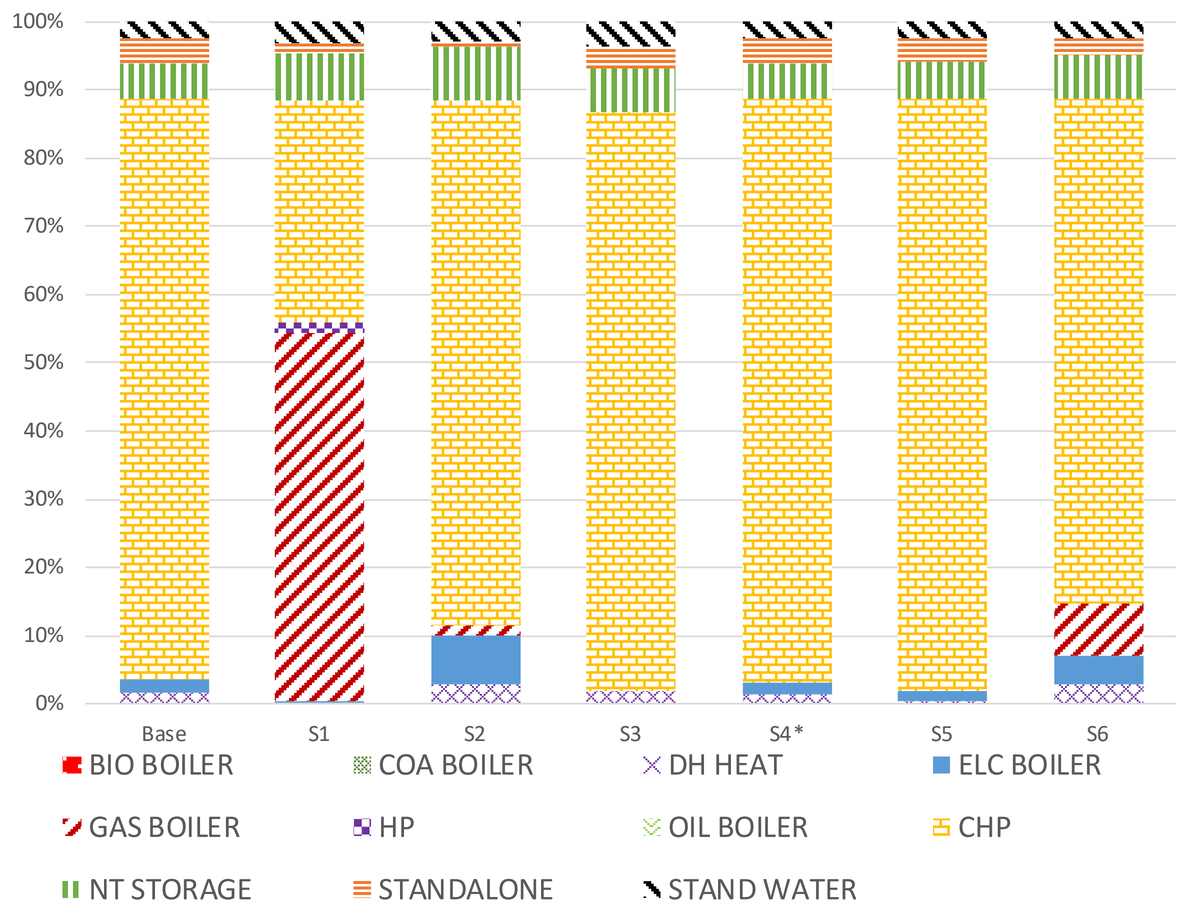

Figure 42. Comparison of heating technology shares across scenarios – technology mix in 2050.

Table 9 summarises other main results of the analysed scenarios, including the associated changes in: CO_2 emissions; total fuel use for residential heating (what we take to be the energy efficiency improvement), and changes in total system costs. With the exception of S4*, the CO_2 emission reductions in the residential sector in 2050 is between 3.7% and 5.1%. However, this reduction in the residential sector's emissions does not necessarily manifest itself in equivalent reductions in total system emissions. For example, scenario S2, implementing a constraint in gas use, exhibits the biggest own-sector reduction in emissions, but it is associated with the worst overall result in terms of total CO_2 emissions. Conversely, S4*, setting a minimum level of energy conservation technologies, shows the worst performance in terms of own-sector emissions, but a better overall CO_2 emission reduction than several other scenarios. This shows that sectoral targets alone might be misleading and – at least in terms of the TIMES model – could be counterproductive: they could be met at the expense of substituting more emissions-intensive technologies in other sectors, frustrating the potential overall objective of energy policy.

The total energy efficiency improvements (accumulated reductions in fuel use for residential heating, see third column in Table 9) varies across scenarios, most of them ranging between 3 to 5%, relative to the base scenario. However, S4* presents a total fuel use reduction of 2.53%. It should be noted that this scenario was 'relaxed' from its original target as it was creating an infeasible solution due to modelling constraints in UKTM. (See Section 5.4 for a more detailed description of this). Nevertheless, the target adjustment was small so such a difference in energy efficiency performance with the other scenarios was not expected[13]. Especially when compared with S3 (total energy reduction of 3.86%) that implemented a similar amount of energy conservation technologies (see Table 8). 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 case 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 identify and analyse in detail such model constraints, making sure they follow realistic and sensible considerations and projections.

The total system costs (see fourth column in Table 9) increase for all scenarios with the exception of S5. 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 S5 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 effect, this scenario explores the impact of easing one of the 'constraints' in the base scenario (in effect, an equality constraint set for the demand for heat services) whereas all the other scenarios impose further constraints. In the case of S5, the impact on estimated system costs within TIMES is exactly what would be expected. The benefits obtained in this scenario should be contrasted with the potential costs of 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.

After S5, the scenario that exhibits the lowest costs is S6, which achieves the same residential emission reduction as S1 but a lower cost (see the first and last column in Table 9). Certainly S6 does not perform as well as other scenarios in fuel use reduction and total emission reductions, but if the objective is solely to reduce residential emissions, S6 could be the preferred scenario as it achieves this target at the lowest possible costs. However, it does this at the cost of an increase in total system emissions.

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[13] In S4*, the energy conservation target forced the model to invest in more expensive energy conservation technologies, which does not contribute significantly in the total energy conservation 'production' but increase 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.

Table 9. 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 - constraint on all input fuels	-3.69	-0.15	-4.71	0.08
S2 – constraint on gas input fuel	-5.11	0.20	-2.92	0.06
S3 – constraint on heat pipe tech. prod.	-3.69	-0.76	-3.86	0.27
S4* – min. level of energy conservation	-2.34	-0.29	-2.53	0.04
S5 – exogenous demand reduction	-5.07	-0.69	-5.53	-0.48
S6 – constraint on CO_2 emissions	-3.70	0.17	-2.24	0.03

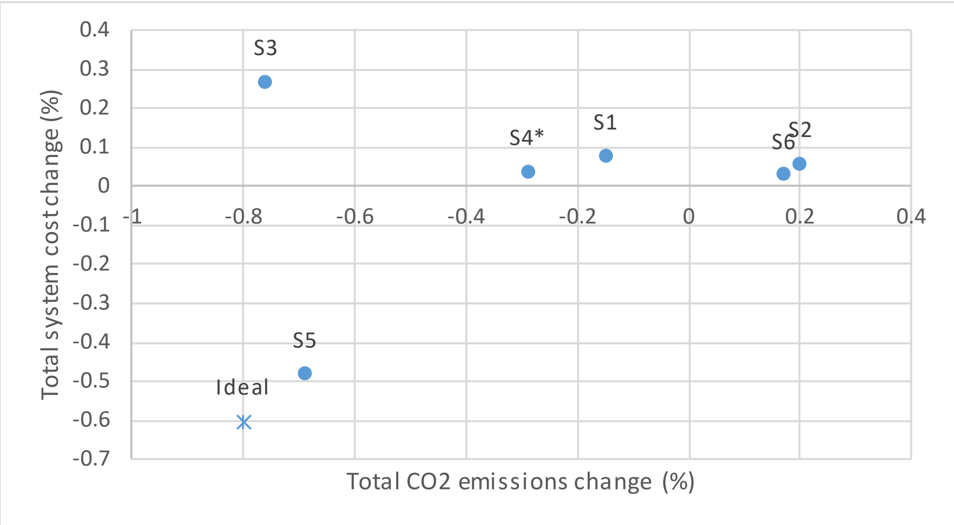

Figure 43. Summary of scenario results: total system costs vs total CO2 emissions.

Figure 43 shows a scatter plot of the scenario results in terms of CO_2 emissions and total costs changes, summarising the conflicting policy targets of the solutions. Ideally, the best scenario is that which achieves reductions in energy use, emissions and costs (bottom left corner in Figure 43). However, and not considering S5 which would create an unfair comparison with the other scenarios, all results fall far from this ideal point and compromises have to be made. For instance, S6 presents the lower costs but the worst overall emission reduction. Conversely, S3 presents the best emission reductions but at the higher costs. S4* could be seen as the best compromise, but it presents the second worst residential energy use reduction. It is therefore important for analysts and policy makers to be clear about their priorities, in order to find meaningful and useful results.

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.

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 (see Section 5.4). However, completely relaxing certain constraints is likely to lead to results that many observers would regard as impossible to achieve in practice even with an ideal set of policies or market frameworks.

Lastly, this study analyses energy efficiency scenarios in isolation, without combining any other changes (whether policy-induced or not). This is done because the simulation results can then be entirely attributed to the changes in energy efficiency scenarios under consideration (subject to the precise configuration of the UK TIMES model). However, many 'real' TIMES applications[14] consider several scenarios, including constraints affecting all sectors, run simultaneously. An example of this could be an analysis including a sectoral 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.

[14] Referring to TIMES analyses commissioned for or used directly by policy makers to inform their policies, and not just academic exercises.

7. Concluding remarks

The TIMES modelling framework has been widely used to analyse and inform policy, by creating and contrasting future energy system scenarios. TIMES applications vary not only in terms of the regions or countries to which they are applied, but also in terms of the objectives of the modelling exercise. Decarbonisation scenarios are the most commonly encountered in the literature, but other types of scenarios can be found as well. Energy efficiency in the residential sector is one example of such applications, with several studies available. However, the approach taken to modelling changes to energy efficiency varies considerably among them.

This study analysed six energy efficiency scenarios for residential heating using UK TIMES, reflecting a number of approaches described in the literature. The results obtained exhibit important differences across scenarios. While almost all of them achieved the desired change in energy efficiency, i.e. a reduction in energy use, no scenario showed an overall best performance in terms of emissions reduction, energy efficiency improvements and total costs. So the decision on which modelling approach to use to inform policy development in the context of energy efficiency improvements is not straightforward. Therefore, it is important to:

- Analyse different ways of modelling energy efficiency changes within the TIMES model and perform sensitivity analysis whenever possible. By analysing the outcomes of a wider range of modelling approaches and alternative scenarios, common technology adoption paths could be found, potentially leading to more robust conclusions. In this study, for example, domestic CHP is the main residential heating technology in most scenarios, so policy makers might more reliably assume that policies supporting this technology should reduce potential future ‘regret’.
- 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 or supply chain capacity 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. While this is not necessarily an erroneous outcome, it is important to analyse the motivation for these modelling constraints and whether they are based on reliable/sensible considerations and projections.
- Consider other (secondary) outcomes of the policies besides the main energy efficiency improvement objective. When the technology mix does not differ much between scenarios, looking into other results that could assist policy makers in choosing the best roadmap. 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 total system costs.
- Analyse the appropriateness of the energy efficiency modelling scenarios to emulate the notion of energy efficiency improvements in real life. For instance, it is not clear that reducing demand is a good proxy for an improvement in energy efficiency. Reducing demand in TIMES is effectively just easing the set of constraints, so it is not surprising that the results of that scenario are overall better. However, in practice, response of demand to an energy efficiency change depends on responses to relative prices, which could even produce an increase in demand. It is, therefore, important to analyse which scenarios can provide better insight for policy.
- Take into account external factors that might not be considered in TIMES. Whole energy system models such as TIMES are very useful tools to analyse future energy scenarios. However, neither the wider impacts of energy policies nor the final

operability of the energy system are always well captured in this type of model. In the case of energy efficiency, many benefits go beyond the energy system, including benefits to 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 CGE[15] model could be used to assess economy wide impacts of changes in the energy system.

The analysis in this study provides insight into some of the modelling challenges for energy efficiency analysis within TIMES. Given the ubiquitous use of TIMES to inform policy, this insight could be relevant for policy makers and wider stakeholders, increasing knowledge about potential conflicting targets, such as decarbonisation of heat versus 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.

[15] Computable General Equilibrium (CGE) models are large numerical models which combine economic theory with real economic data in order to derive computationally the impacts of policies or shocks in the economy (Scottish Government, 2016).

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Appendix A – Formulation and detailed description of the energy efficiency scenarios

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 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.

$$\sum_{e,t} energyInputHeat_{S1,y,e,t} \leq 0.9 * \sum_{e,t} energyInputHeat_{SB,2010,e,t} \qquad (1)$$
$$\forall y = [2030, \ldots, 2050]$$

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.

Scenario 2: gas input constraint

Scenario 2 is similar to scenario 1, with the difference that only applies to gas energy input for heating, instead to all energy carriers (see S2 in Figure 11). The gas input constraint is implemented as shown in eq. (2). This scenario is motivated by the heavy reliance on gas for heating in the UK (around 85% in the considered base scenario at 2010, see Figure 7a). Also, thinking in practical terms, a policy that tries to reduce gas consumption is likely to be easier to implement than a policy that affects all energy fuels.

Note that the target in (2) is adjusted to reflect the share of total heating energy use for gas. In other words, gas use constraint has to be lower than the value set in right-hand side of equation (1) to achieve the same overall energy efficiency target. This adjusted value is computed by multiplying the original target by the coefficient 0.85, which represent the share of gas from the total heating energy use.

$$\sum_{t} energyInputHeat_{S2,y,Gas,t} \leq 0.9 * 0.85 * \sum_{e,t} energyInputHeat_{SB,2010,e,t} \qquad (2)$$
$$\forall y = [2030, \ldots, 2050]$$

Similar to S1, this scenario is likely to produce higher levels of energy conservation technology implementation, and as this constraint applies only to gas, a higher change to electricity based technologies is also likely to occur.

Scenario 3: Heat pipe production constraint

The scenario 3 represents an alternative to scenario 1 by constraining the production of heating technologies (the output of the technologies, see S3 in Figure 11), instead of limiting the input fuels (as in S1). Eq. (3) shows this constraint, where *energyOutputHeat* represents the production of heating for all heat pipe technologies '*thp'* at year '*y*'. So the sum of all heat pipe technologies production should be lower or equal to the equivalent total heating production to achieve the set target for energy efficiency. Therefore, similar to (2), this equation is adjusted to consider the share of heat pipe technologies in the technology mix, which in the base scenario is 93% in 2010 (see Figure 8).

$$\sum_{thp} energyOutputHeat_{S3,y,thp} \leq 0.9 * 0.93 * \sum_{t} energyOutputHeat_{SB,2010,t} \quad \forall y = [2030, \dots, 2050] \tag{3}$$

This constraint is similar to the one set in S1 as it produces a similar effect on limiting heating technologies, with the benefit that is relatively easier to implement in TIMES. The potential drawback of this approach is that it does not take into account standalone technologies, so an increment in this type of technologies is likely to occur. However, in the UKTM base case does not necessarily represent an important drawback as most technologies are of the heat pipe group (see Figure 8).

Scenario 4: 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 S4 in Figure 11), so heating production technologies are not directly affected, but their participation to meet the energy services demand is reduced. Eq. (4) 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).

$$\sum_{tcs} energyOutputHeat_{S3,y,tcs} \geq 0.1 * \sum_{t} energyInputHeat_{SB,2010,e,t} + \sum_{tcs} energyOutputHeat_{SB,2010,tcs} \quad \forall y = [2030, \dots, 2050] \tag{4}$$

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 to S3). 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.

Scenario 5: 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 44 shows the change in demand for this scenario, where all four types of heating service demands modelled in UKTM are reduced by 10% from 2030 (see the dotted lines in the Figure 44). This is demand change is implemented in TIMES by modifying directly the demand projection values of these commodities.

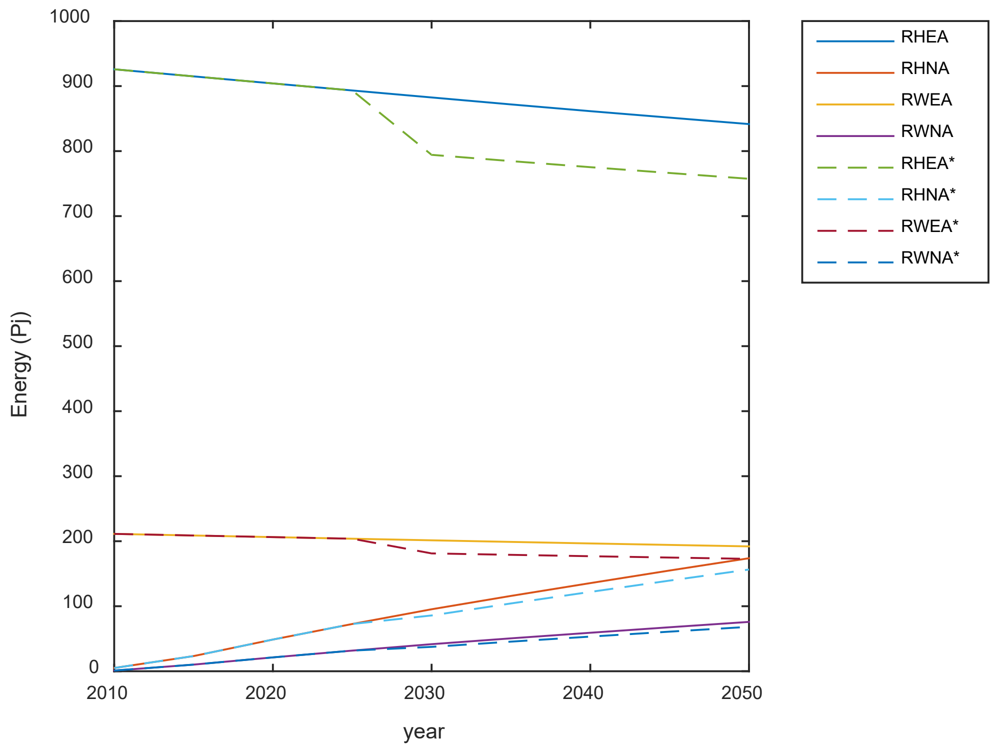

Figure 44. Residential heating – Demand reduction scenario.

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.

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'.

Scenario 6: CO2 emission constraint

As discussed in the literature review, many authors analyse energy efficiency improvements by imposing emissions constraints (see Section 2.2). This scenario implements a CO_2 emissions constraint, replicating the approach presented in Blesl et al. (2007), where the reduction on CO_2 emissions obtained from an energy efficiency scenario constraining energy input (similar to S1) is set as the target for this new scenario. The authors in Blesl et al.

(2007) claim that the same CO_2 emission reduction of the energy efficiency scenario could be achieved but a reduced cost by implementing a CO_2 emission constraint instead.

Eq. (5) shows the constraint implemented for this scenario, where the sum of CO_2 output for heat technologies (*CO2outputResHeat*) for all technologies '*t*' in scenario '*S6'*, is lower or equal to the sum of CO_2 output from residential heating technologies in 'S1'. This constraint applies for every year from 2030 to 2050.

$$\sum_t CO2outputResHeat_{S6,y,t} \leq \sum_t CO2outputResHeat_{S1,y,t} \quad \forall y = [2030, \ldots, 2050] \tag{5}$$

The constraint set in this scenario does not target any type of technologies or fuels directly, but those technologies that use fossil fuels are likely to be more affected. In other words, oil, carbon and gas based technologies should reduce their production for this scenario, and 'cleaner' options should increase their participation.

Appendix B – Complementary results

B.1 Scenario 1 results – input fuels constraint

Table 10. Residential heating technology production changes for existing and new houses in S1 relative to base scenario.

Heat technologies	Exist. Houses (%)	New Houses (%)
BIO BOILER	0	0
COA BOILER	-0.01	0
DH HEAT	-1.65	-100
ELC BOILER	0	-51.23
GAS BOILER	25.47	61.04
HP	0	+100
OIL BOILER	0.24	0
STR CHP	-46.28	-88.13
NT STORAGE	2.59	52.18
STANDALONE	-34.96	-39.29
STAND WATER	9.13	37.49
Total	-1.43	0.04

Table 11. Residential energy conservation technology changes in S1 relative to base scenario.

Conservation technologies	Total change (%)
CAV01	0
CAV02	0
LOF02	0
SOL01	0
SOL02	52.69
SOL03	+100
FLR01	0
Total	21.91

Table 12. Residential heating fuel use changes in S1 relative to base scenario.

Fuel use for residential heat	Total change (%)
COA	-0.01
ELC	-1.83
GAS	-5.04
BIO	-73.67
OIL	0.25
HYG	-100
SOL	+100
Total	-13.58

Table 13. Energy carrier import and export changes in S1 relative to base scenario.

RES conservation technologies	Imports change (%)	Exports change (%)
BDL	0	0
BIOMASS	0	0
COAL	-0.25	0
COKE	0	0
DST	0	0
ELC	0	0
ETHANOL	0	0
GSL	0	-0.03
HFO	-55.19	-14.98
JET	-7.25	-33.19
KER	0	0
LFO	-2.02	0.30
LPG	0	0
MOIL	-0.02	0
NGA	0.10	0.54
OIL	0	0
URN	1.34	0

Table 14. Electricity and gas average price changes (cost marginal) for the residential sector in S1 relative to base scenario.

Residential energy prices	Average change (%)
Electricity	6.50
Gas	-4.37

B.2 Scenario 2 results – gas input constraint

Table 15. Residential heating technology production changes for existing and new houses in S2 relative to base scenario.

Heat technologies	Exist. Houses (%)	New Houses (%)
BIO BOILER	0	0
COA BOILER	-0.17	0
DH HEAT	-0.72	138.63
ELC BOILER	6.66	755.56
GAS BOILER	-2.26	-8.47
HP	0	0
OIL BOILER	0.09	0
STR CHP	-0.68	-50.42
NT STORAGE	7.70	123.24
STANDALONE	-52.29	-76.86
STAND WATER	-0.60	40.76
Total	-1.55	0.10

Table 16. Residential energy conservation technology changes in S2 relative to base scenario.

RES conservation technologies	Total change (%)
CAV01	0
CAV02	0
LOF02	0
SOL01	-2.31
SOL02	71.42
SOL03	0
FLR01	0
Total	23.72

Table 17. Residential heating fuel use changes in S2 relative to base scenario.

Fuel use for residential heat	Total change (%)
COA	-0.17
ELC	15.36
GAS	-5.53
BIO	-12.96
OIL	0.09
HYG	+100
SOL	0
Total	-12.92

Table 18. Energy carrier import and export changes in S2 relative to base scenario.

RES conservation technologies	Imports change (%)	Exports change (%)
BDL	0	0
BIOMASS	0	0
COAL	1.63	0
COKE	0	0
DST	0	0
ELC	0	0
ETHANOL	0	0
GSL	0	-0.03
HFO	+100	37.63
JET	7.23	33.19
KER	0	0
LFO	0.59	0.03
LPG	0	0.77
MOIL	-0.05	0

NGA	0.20	0.75
OIL	0	0
URN	0	0

Table 19. Electricity and gas average price changes (cost marginal) for the residential sector in S2 relative to base scenario.

Residential energy prices	Average change (%)
Electricity	6.70
Gas	-4.37

B.3 Scenario 3 results – Heat pipe production constraint

Table 20. Residential heating technology production changes for existing and new houses in S3 relative to base scenario.

Heat technologies	Exist. Houses (%)	New Houses (%)
BIO BOILER	-0.01	0
COA BOILER	-0.09	0
DH HEAT	44.23	-22.20
ELC BOILER	-92.88	-100
GAS BOILER	-6.12	-18.48
HP	0	0
OIL BOILER	0.59	0
STR CHP	-5.72	-31.60
NT STORAGE	0.78	19.24
STANDALONE	-31.30	-28.14
STAND WATER	48.11	79.42
Total	-4.96	-19.96

Table 21. Residential energy conservation technology changes in S3 relative to base scenario.

RES conservation technologies	Total change (%)
CAV01	0
CAV02	0
LOF02	0
SOL01	-3.85
SOL02	81.88
SOL03	+100
FLR01	0
Total	45.72

Table 22. Residential heating fuel use changes in S3 relative to base scenario.

Fuel use for residential heat	Total change (%)
COA	-0.09
ELC	-0.21
GAS	-4.01
BIO	-73.67
OIL	0.59
HYG	-100
SOL	0
Total	-13.58

Table 23. Energy carrier import and export changes in S3 relative to base scenario.

RES conservation technologies	Imports change (%)	Exports change (%)
BDL	0	0
BIOMASS	0	0
COAL	-0.25	0
COKE	0	0
DST	0	0
ELC	0	0
ETHANOL	0	0
GSL	0	-0.07
HFO	+100	37.97
JET	8.02	33.19
KER	14.94	36.09
LFO	-0.75	0.17
LPG	0	0
MOIL	-0.03	0

NGA	-0.97	1.23
OIL	0	0.01
URN	0.81	0

Table 24. Electricity and gas average price changes (cost marginal) for the residential sector in S3 relative to base scenario.

Residential energy prices	Average change (%)
Electricity	2.38
Gas	-3.90

B.4 Scenario 4* results – Minimum level of conservation technologies (adjusted target)

Table 25. Residential heating technology production changes for existing and new houses in S4* relative to base scenario.

Heat technologies	Exist. Houses (%)	New Houses (%)
BIO BOILER	-0.01	0
COA BOILER	0	0
DH HEAT	0.13	-22.97
ELC BOILER	-12.94	-23.80
GAS BOILER	-3.33	-0.01
HP	0	0
OIL BOILER	0.03	0
STR CHP	-2.10	3.02
NT STORAGE	-2.46	-9.71
STANDALONE	-5.88	5.24
STAND WATER	-3.11	-0.29
Total	-2.88	-0.01

Table 26. Residential energy conservation technology changes in S4* relative to base scenario.

RES conservation technologies	Total change (%)
CAV01	0
CAV02	0
LOF02	0
SOL01	-3.85
SOL02	75.48
SOL03	+100
FLR01	+100
Total	43.94

Table 27. Residential heating fuel use changes in S4* relative to base scenario.

Fuel use for residential heat	Total change (%)
COA	0
ELC	-3.65
GAS	-2.53
BIO	7.14
OIL	0.03
HYG	0
SOL	0
Total	-0.82

Table 28. Energy carrier import and export changes in S4* relative to base scenario.

RES conservation technologies	Imports change (%)	Exports change (%)
BDL	0	0
BIOMASS	0	0
COAL	0.04	0
COKE	0	0
DST	0	0
ELC	0	0
ETHANOL	0	0
GSL	0	-0.01
HFO	84.14	22.84
JET	7.24	33.19
KER	0	0
LFO	18.52	0.53
LPG	0	0
MOIL	-0.04	0

NGA	-0.34	1.15
OIL	0	0
URN	0	0

Table 29. Electricity and gas average price changes (cost marginal) for the residential sector in S4* relative to base scenario.

Residential energy prices	Average change (%)
Electricity	0.81
Gas	0

B.5 Scenario 5 results – Demand reduction

Table 30. Residential heating technology production changes for existing and new houses in S5 relative to base scenario.

Heat technologies	Exist. Houses (%)	New Houses (%)
BIO BOILER	-0.01	0
COA BOILER	0	0
DH HEAT	-0.11	-83.55
ELC BOILER	-7.93	-49.48
GAS BOILER	-3.74	-7.27
HP	0	0
OIL BOILER	0.01	0
STR CHP	-6.87	-2.44
NT STORAGE	-8.17	37.58
STANDALONE	5.86	-32.22
STAND WATER	-6.07	-8.75
Total	-4.93	-8.24

Table 31. Residential energy conservation technology changes in S5 relative to base scenario.

RES conservation technologies	Total change (%)
CAV01	0
CAV02	0
LOF02	0
SOL01	-7.69
SOL02	-30.29
SOL03	0
FLR01	0
Total	-10.63

Table 32. Residential heating fuel use changes in S5 relative to base scenario.

Fuel use for residential heat	Total change (%)
COA	0
ELC	-7.53
GAS	-5.48
BIO	-2.82
OIL	0.01
HYG	-100
SOL	0
Total	-10.37

Table 33. Energy carrier import and export changes in S5 relative to base scenario.

RES conservation technologies	Imports change (%)	Exports change (%)
BDL	0	0
BIOMASS	0	0
COAL	0.08	0
COKE	0	0
DST	0	0
ELC	0	0
ETHANOL	0	0
GSL	0	0.11
HFO	+100	37.96
JET	7.22	33.19
KER	0	0
LFO	-2.46	0.38
LPG	0	-0.03
MOIL	-0.15	0

NGA	-1.20	1.51
OIL	0.01	0
URN	0	0

Table 34. Electricity and gas average price changes (cost marginal) for the residential sector in S5 relative to base scenario.

Residential energy prices	Average change (%)
Electricity	-0.45
Gas	-4.37

B.6 Scenario 6 results – CO2 emissions constraint

Table 35. Residential heating technology production changes for existing and new houses in S6 relative to base scenario.

Heat technologies	Exist. Houses (%)	New Houses (%)
BIO BOILER	0	0
COA BOILER	-0.08	0
DH HEAT	-0.26	129.07
ELC BOILER	-7.97	230.30
GAS BOILER	-1.90	28.63
HP	0	0
OIL BOILER	0.39	0
STR CHP	-0.12	-67.73
NT STORAGE	3.19	38.30
STANDALONE	-24.28	-20.85
STAND WATER	-1.25	2.20
Total	-1.23	0.01

Table 36. Residential energy conservation technology changes in S6 relative to base scenario.

RES conservation technologies	Total change (%)
CAV01	0
CAV02	0
LOF02	0
SOL01	0
SOL02	56.26
SOL03	0
FLR01	0
Total	18.81

Table 37. Residential heating fuel use changes in S6 relative to base scenario.

Fuel use for residential heat	Total change (%)
COA	-0.08
ELC	4.15
GAS	-3.57
BIO	-11.77
OIL	0.39
HYG	+100
SOL	0
Total	-9.99

Table 38. Energy carrier import and export changes in S6 relative to base scenario.

RES conservation technologies	Imports change (%)	Exports change (%)
BDL	0	0
BIOMASS	0	0
COAL	2.22	0
COKE	0	0
DST	0	0
ELC	0	0
ETHANOL	0	0
GSL	0	-0.04
HFO	0	-0.58
JET	-0.01	0
KER	0	0
LFO	-0.51	0.15
LPG	0	0
MOIL	-0.05	0
NGA	-0.41	0.34

OIL	0	0
URN	0.77	0

Table 39. Electricity and gas average price changes (cost marginal) for the residential sector in S6 relative to base scenario.

Residential energy prices	Average change (%)
Electricity	3.27
Gas	-2.69

Appendix C - List of acronyms and nomenclature

Acronyms and abbreviations

AGR	Agriculture sector
BIO	Biomass and derivatives
CAV	Cavity wall insulation energy conservation technologies
CCS	Carbon Capture and Storage
CGE	Computable General Equilibrium model
CHP	Combined heat and power heating technologies
COA	Coal and derivatives
DH	District heating technologies
ELC	Electricity
FLR	Floor insulation energy conservation technologies
GHG	Green House Gas
HP	Heat pump heating technologies
HYG	Hydrogen
IND	Industrial sector
LOF	Loft insulation energy conservation technologies
NT	Night thermal storage (electricity based) technologies
OIL	Oil energy carrier
RCE	Residential cooking other demand
RCH	Residential cooking hobs demand
RCO	Residential cooking ovens demand
REA	Residential consumer electronics demand
RECF	Residential freezers demand
RECP	Residential computers demand
RECR	Residential refrigerators demand
REO	Residential other demands demand

RES	Residential sector
REW	Residential wet appliances demand
RHEA	Residential space heating for existing houses demand
RHNA	Residential space heating for new houses demand
RWEA	Residential hot water for existing houses demand
RWNA	Residential hot water for new houses demand
SEEP	Scotland's Energy Efficiency Programme
SER	Service sector
SOL	Solid wall insulation energy conservation technologies (and solar input energy)
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System model
TRA	Transport sector
UKTM	UK TIMES

Nomenclature

Sets (subscripts)

s	Scenarios (S1, S2 … S6).
y	Years (2010, 2015 … 2050).
e	Energy carriers (electricity, gas, oil, biomass, etc.).
t	Heating technologies = gas boilers, electric boilers, heat pumps, etc.
thp	Subset of heating technologies *'t'* – heat pipe type (non-standalone)
tcs	Subset of heating technologies *'t'* – energy conservation type (wall insulation, loft insulation, etc.).

Variables

$energyInputHeat_{s,y,e,t}$	Input of the energy carrier '*e*' for the residential heat technology '*t*', at the year '*y*' and in scenario '*s'* (Pj)
$energyOutputHeat_{s,y,t}$	Production of heating for technology *'t'* at year *'y'* and in scenario *'s'* (Pj)
$CO2outputResHeat_{s,y,t}$	CO_2 output for technology '*t*' at year *'y'* and in scenario '*S6'* (kTCO2e)