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Potential for the use of TIMES in assessing energy system impacts of improved energy efficiency

Chistian Calvillo, Karen Turner, Keith Bell, Peter McGregor, Graeme Hawker

University of Strathclyde;

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Table of Contents

Table of Figures

Executive summary

The Scottish Government has set very ambitious targets and policies in its Climate Change Plan to decarbonise the energy system. The Scottish TIMES model is as a key tool informing these new climate change policies. TIMES is a well-known, widely used model. However, the adequacy of TIMES for energy efficiency policy analysis has not been assessed in the literature. This report sets out the potential for using TIMES to understand the system impacts of energy efficiency improvements, based upon work by ClimateXChange Fellow Christian Calvillo at Strathclyde University.

This report describes the generic structure of the TIMES modelling framework to help a wider audience to understand the capabilities of this type of model. The report reviews energy efficiency related work in TIMES, and assesses the main strengths and limitations of TIMES. The main challenges identified in the specific context of using TIMES for energy efficiency analysis are:

- Energy efficiency implementation in TIMES is not straightforward. Several approaches could be followed, delivering potentially different results.
- Decisions are cost driven. The cost minimisation algorithm would lead to outcomes involving extreme specialisation (corner solutions), if not prevented by user determined constraints (e.g. imposing maximum shares for different technologies).
- Energy demands and actions and reactions across the wider economy impacts are not modelled within TIMES. More generally, market “problems” and other drivers for consumer behaviour are not captured.

The report outlines several options to address or mitigate these modelling issues, and proposes ways forward in using TIMES for energy efficiency analysis. The three main possibilities are:

1. Use TIMES as it is. This should be considered as the first step in energy efficiency analysis. The current versions of TIMES can deliver reasonable outputs and useful insight. However, any limitations of TIMES should be taken into account when interpreting the results.
2. Develop TIMES improvements. Implementing improvements in the specification of the TIMES model to deal with issues such as those outlined above is potentially a second step in the analysis of energy efficiency changes, one that is likely only to be feasible in the medium term. Some of these developments might require relatively little time and resources to implement, while others will require important changes on the model structure and data. Hence, an assessment of the potential benefits in relation to the required resources for a TIMES improvement must be done beforehand, as it might be more convenient to rely on soft-linking with other models.
3. Soft-linking with other models. That is, modelling the type of behaviours and sectors not captured in TIMES in other models and using the outputs to inform and/or interact with TIMES. This solution can potentially give relevant and/or more accurate information that could be very difficult to get from TIMES alone. In particular, the soft-linking with a multiple sector economy-wide ‘computable general equilibrium (CGE) model approach is very relevant for energy efficiency policy analysis (and such a modelling framework is currently available to Scottish Government), as many of the expected outcomes go beyond the energy system (e.g. reducing energy poverty, job creation, economy boosts, etc.). In addition, this setup better represents consumer behaviour, which translates to more realistic technology adoption scenarios.

1. Introduction

For several years, the Scottish Government has shown its commitment to tackling climate change, with ambitious targets and policies to reduce GHG emissions, and transform the energy system into a largely decarbonised one. Recently, several documents have been released by the Scottish Government, updating their decarbonisation targets.

The Scottish TIMES model is a key tool informing the new climate change policies (Scottish Government, 2017a), which at the same time, drives other policies such as the Scottish Energy Strategy (Scottish Government, 2017b) and the Scottish Energy Efficiency Programme (Scottish Government, 2017c).

TIMES is a well-known, widely used model, with over 100 country versions and considerably more related studies (Connolly et al., 2010). However, the adequacy of TIMES for energy efficiency policy analysis has not been assessed in the literature. The main objectives for this report are:

1. Provide an assessment of strengths and limitations of the TIMES model, to analyse the impacts of energy efficiency changes in the Scottish energy system and on the wider economy.
2. Give recommendations on how TIMES can be used to assess the impacts of energy efficiency changes, and how can it be complemented with existing and potential new modelling approaches.

Therefore, this report seeks to assist Scottish policy makers to design the best energy efficiency policy measures, by using TIMES and other models judiciously.

The report is organised in 10 sections:

- A brief definition of energy efficiency is provided in section 1.1, to understand the differences with energy conservation.
- Section 2 presents an overview of the current state of Scotland's energy mix.
- Section 3 reviews briefly the most relevant energy efficiency policies in Scotland, the UK and the EU.
- Section 4 provides a general description of the energy system.
- Section 5 gives an overview of the TIMES model and how it represents the energy system.
- Section 6 presents a brief literature review of TIMES research work related to energy efficiency and further developments of the model.
- Section 7 continues with the literature review, but presenting cases where TIMES is soft-linked with other models, and remarking on the most common soft-linking challenges.
- Section 8 comments on the strengths and limitations of TIMES in energy efficiency analysis, also providing some of the typically suggested solutions.
- Section 9 presents recommendations on how the Scottish government could proceed in energy efficiency analysis, using TIMES.
- Lastly, section 10 presents concluding remarks, and makes some suggestions for research activity going forward.

1.1 Energy Efficiency Definition

According to the International Energy Agency (IEA) ("Energy efficiency," n.d.), energy efficiency is a way of managing and restraining the growth in energy consumption. "Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input" ("Energy efficiency," n.d.).

However, and as remarked in ("What's Energy Efficiency?," n.d.), energy efficiency is not energy conservation. Energy conservation refers to reducing or not using a service to save energy. For example: Turning off a light is energy conservation. Replacing an incandescent lamp with a compact fluorescent lamp (which uses much less energy to produce the same amount of light) is an example of energy efficiency.

This differentiation is relevant as many energy "efficiency" measures found in policy strategies actually concern energy conservation, and thus, they might need to be analysed separately as they impact the economic system in different ways (Turner et al., 2016), and the models required for these analyses could be different.

2. The Scottish Energy Mix

The short overview of the Scottish energy mix presented in this section is based on the report "Energy in Scotland 2016" (Scottish Government, 2016) and the "Draft Scottish Energy Strategy" (Scottish Government, 2017b).

The following figure, taken from (Scottish Government, 2017b), summarizes the energy mix and energy usage in Scotland. It can be seen that petroleum and gas are the main primary energy sources (84% together), and that the largest share of the total energy production goes to exports and losses (84%) and only a small share (16%) is consumed locally.

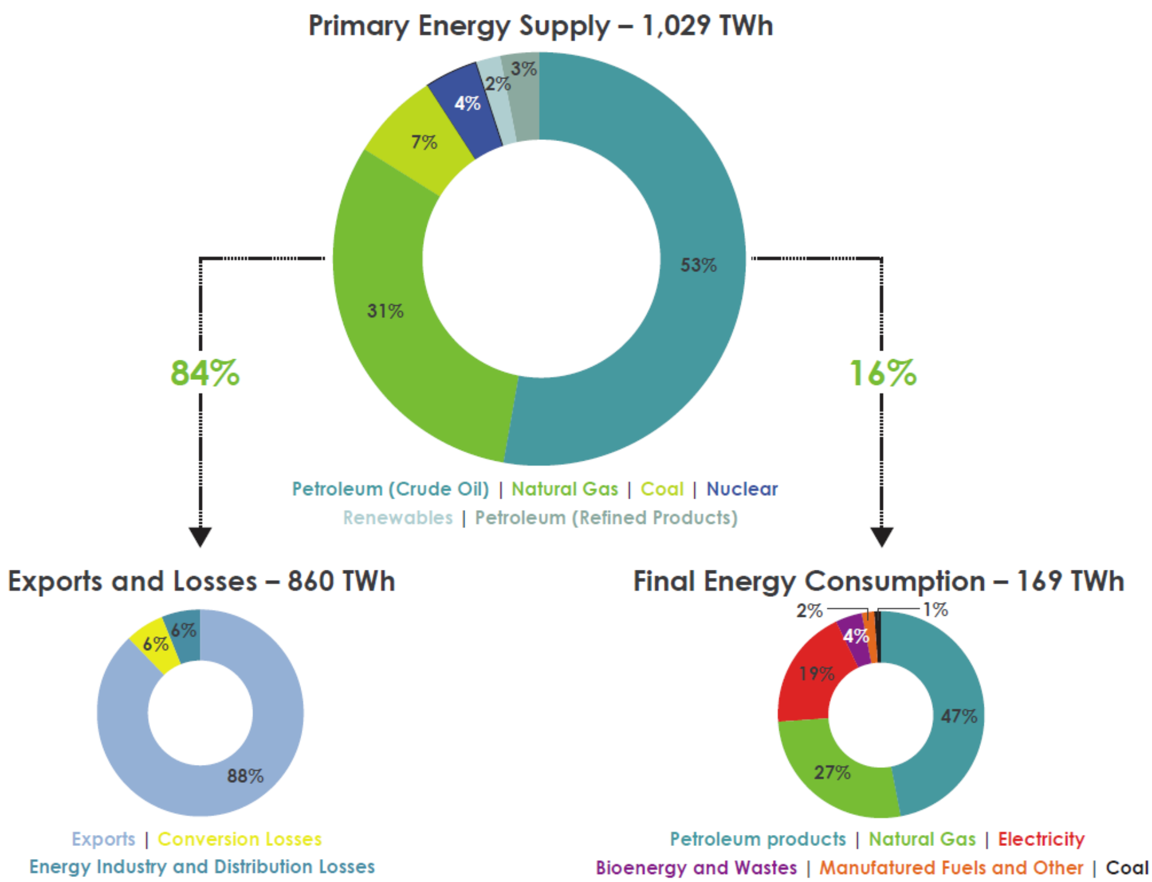

Figure 1. Scotland's Primary and Final Energy, 2014 (Scottish Government, 2017b).

2.1 Energy consumption in Scotland

Energy consumption in Scotland can be divided into three main consumption sectors: electricity with 21% of total consumption, heat with 54%, and transport with 25% (Scottish Government, 2016). Hence, the efforts towards energy efficiency on heat have the potential to be extremely significant (see section 3). Furthermore, the total heat and electricity consumption (excluding transport) is split between domestic consumption with a 41% share, and industrial/commercial with 59% (Scottish Government, 2016).

Actions taken on energy efficiency seem to be paying off across Scotland. For instance, there is a slow but constant improvement on average energy efficiency rating of the housing stock (Scottish Government, 2016). Also, Scotland is performing better on reducing energy consumption relative to the 2005-2007 base line (14.1% at 2013) in comparison with the UK (8.4%) and the EU (6.4%) (Scottish Government, 2016). Note that the average quarterly GDP growth of Scotland, the UK and other small EU countries, for the period 2004 – 2016, is 1.0%, 1.4% and 1.5%, respectively (Scottish

Government, 2017d). This suggests that the Scottish lower energy consumption is not necessarily related to slower economic growth but to other factors, which may include the implementation of energy conservation and/or efficiency measures.

The energy reduction in Scotland can be broken down for different energy uses:

- Domestic 17% reduction
- Non-domestic 17% reduction
- Transport 9% reduction

2.2 Electricity in Scotland

As mentioned before, electricity makes up 21% of total energy consumption in Scotland. In the year 2015, the electricity generation mix (energy production) was:

- gas with a 4% contribution to the total;
- coal with 17%;
- oil with 2%;
- pumped hydro with 1%;
- nuclear with 35%; and
- renewables with 42% (Scottish Government, 2017b).

This mix shows that low carbon technologies (nuclear and renewables) account for two thirds of total generation.

Renewables are taking an important role in the electricity mix. The share of gross consumption[1] provided by renewables has been gradually incremented from 10% in 2001 to almost 59% in 2015 (Scottish Government, 2017b). Also, it is interesting to note that from the renewable technologies, the two bigger components are wind power (62% at 2014) and hydro (29% at 2014) (Scottish Government, 2016). Additionally, more off-shore wind projects are expected for the coming years.

The use of electrical energy falls mainly in the domestic sector with 41%, industry uses 28%, transport only uses 1% of the total electricity, and 29% is used by other sectors (Scottish Government, 2016). Another important characteristic to consider is that Scotland has traditionally been a net exporter of electricity (mainly to the rest of the GB). In 2015, Scotland exported 29% of the electricity generated (Scottish Government, 2017b).

2.3 Heat in Scotland

54% of total energy consumption in Scotland is heat (non-electrical). From this energy, 41% is consumed domestically and 59% in the commercial and industrial sectors (Scottish Government, 2016). Overall, the heat production is done with gas and oil but renewable sources are slowly gaining presence. For instance, in 2013, 2.7% of the total heat demand was supplied by renewables (Scottish Government, 2016).

Indeed, the most used heating fuel in Scotland is gas, of which 57% is used in the domestic sector (Scottish Government, 2016). From all the Scottish households, in 2014, 78% use mains gas as their primary heating fuel, 13% use electricity, 6% oil, 1% communal heating, and 2% others. Note that, in 2014, the total domestic and non-domestic gas consumption has shown a decrement of 31% and 20%, respectively, in comparison with the consumption of year 2005 (Scottish Government, 2016).

Regarding renewable heat, since 2008 – 2009, generation has more than tripled, from 845GWh to 3,031GWh in 2014 (Scottish Government, 2016). The most commonly used renewable heat technologies are biomass with 89% (57% of it is used directly for heat production, and 32% is used as combined heat and power CHP), followed by heat pumps with 5%[2,] and energy from waste 6%. Solar thermal technologies have a very small share of less than 1%. Also, it may be noted that most of the renewable heat installations are micro in size (less than 45kWth) with 89% of the total (Scottish Government, 2016).

[1] Scotland's annual electricity demand

[2] Assuming that the input electricity was obtained from a renewable sources.

2.4 Transport

The transport sector is estimated to account for 25% of Scotland's total energy use. From this energy, the share to transport people is about 60% and to transport goods is about 40%. The main fuel input for transport is still petroleum with a share of biofuels of 3.3% in year 2015 (Scottish Government, 2016). The petroleum fuel used in 2013 is divided among buses 6%, diesel cars 24%, petrol cars 32%, heavy goods vehicles 23%, motor-cycles 0.4%, diesel large goods vehicles 15%, and petrol large goods vehicles 1% (Scottish Government, 2016).

There has been a change in road and rail energy consumption from 2005 to 2013, with a reduction of 8% in road transport, an increment of 6% in rail transport, and an overall reduction of 7% (Scottish Government, 2016). It is also noted in (Scottish Government, 2016) that car traffic (in number of road miles) has not changed significantly from 2009 to 2014, while the distance cycled is estimated to have increased by 18.1%. In addition, the number of bus and ferry passengers has decreased by 9.8%, and 4.7% respectively, while air and rail passenger numbers have increased by 7% and 20.5%, respectively, in the same period.

The total transport energy demand has been steadily decreasing from 2007 (mainly due technology efficiency improvements and high fuel costs) and it is expected to continue to do so (Scottish Government, 2016).

3. Overview of energy efficiency policy in Scotland

Several documents addressing Scottish energy efficiency policy have been produced by the Scottish Government, since the Climate Change (Scotland) Act 2009 and the plan "Conserve and Save: The Energy Efficiency Action Plan for Scotland" (Scottish Government, 2010).

For the sake of brevity, this section reviews only the latest documents released on energy efficiency related policies: the Draft Climate Change Plan - the draft Third Report on Policies and Proposals 2017-2032 (Scottish Government, 2017a), the Draft Scottish Energy Strategy: The Future of Energy in Scotland (Scottish Government, 2017b), and National Infrastructure Priority for Energy Efficiency - Scotland's Energy Efficiency Programme (Scottish Government, 2017c). Additionally, for the purpose of comparison, this overview includes a brief look into the UK's energy efficiency policy (from ("Energy efficiency | Energy UK," n.d.) and ("Energy Company Obligation," 2016)) and the EU energy policy (from ("2030 Energy Strategy - Energy - European Commission," n.d.)).

3.1 The Draft Climate Change Plan

The draft Climate Change Plan (Scottish Government, 2017a) includes the Scottish Government's third report on policies and proposals for meeting its greenhouse gas emission reduction targets from 2017 to 2032. This document was presented in the Scottish Parliament on 19 January 2017, and was subject to a 60-day period for Parliamentary consideration.

The development of the draft Climate Change Plan draws significantly on outputs of the Scottish TIMES model (Scottish Government, 2017a). The Scottish TIMES model is a high level strategic model, that covers the entire Scottish energy system, and contains thousands of variables capturing existing and future technologies and processes. Models such as TIMES aim to capture the main characteristics of an energy system and the interlinkages within it. While this is the first time a model like this has been available for Scotland, they are widely used internationally in modelling climate and energy policy choices. A more detailed description of the TIMES model is provided in section 5.

By constraining TIMES with the annual emissions reductions targets, the model helps in understanding the least-cost ways of achieving those emission reductions, while also assessing how the effort is best shared across the economy. In principle, this approach allows for the identification of an optimal pathway for meeting Scotland's statutory climate change targets. The pathway contains a carbon envelope, or budget, for each sector along with suggested policy outcomes needed to live within the carbon envelope. Examples of policy outcomes include the introduction of new energy technologies or the penetration of electric vehicles. Policies and proposals are then developed to realise the outcomes.

3.1.1 The Decarbonisation Pathway

The Scottish Parliament passed legislation in October 2016, setting the third batch of annual targets for the years 2028 to 2032. The targets set an emission reduction pathway to 2032 and in doing so establish a **2032 target that represents a 66% emission reduction below 1990 levels**[3] (Scottish Government, 2017a). This section summarises the proposed decarbonisation pathway out to 2032 as suggested by TIMES, organized by sector (see Figure 2, taken from (Scottish Government, 2017a)).

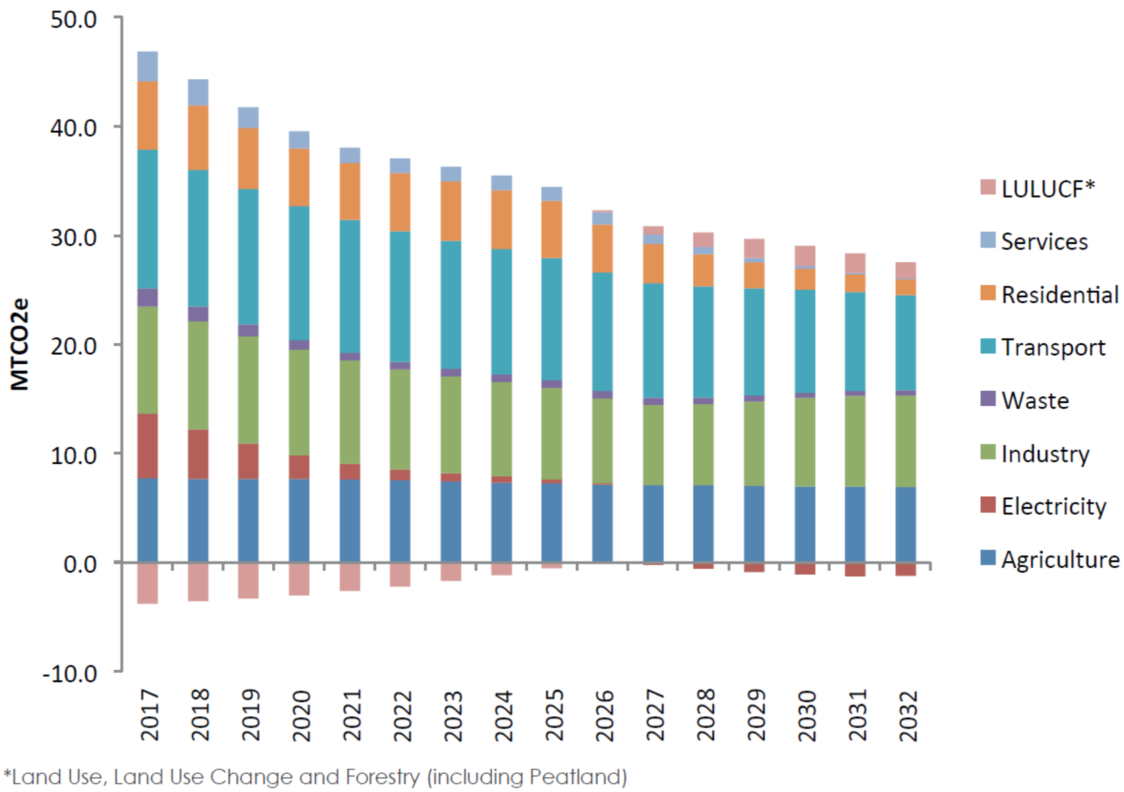

Figure 2. decarbonisation pathway to 2032 (Scottish Government, 2017a).

The main points of the pathway set out in the draft Climate Change Plan (Scottish Government, 2017a) include:

- The electricity system will be wholly decarbonised by 2032, and its share of total energy supply is expected to grow. Electricity will be increasingly important as a power source for heat and transport, and it will also be used for carbon capture and storage (which, through use of biomass fuel, explains the negative values in Figure 2).
- All the non-domestic buildings (service sector) will be near zero carbon emissions by 2032.
  - Energy efficiency improvements will be the main focus of the efforts up to 2025.
  - After 2025, the priority will be low carbon heat, with virtually all natural gas boilers being replaced by low carbon heat technologies by 2032.
- The residential sector will follow a similar approach to the services sector, although the rate of emissions reduction is slower particularly until 2025 (focus during this period is on energy efficiency measures, such as building envelope).
- Transport will experience a significant decarbonisation as well, with emissions reducing by 32% in 2032 compared to 2014. This will be mainly achieved by changing towards more efficient low emissions vehicles and transport systems.

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[3] The 1990 base year uses 1990 for carbon dioxide, methane and nitrous oxide and 1995 for hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride, and is measured in $MtCO_2e$ (million tonnes carbon dioxide equivalent) (Scottish Government, 2012).

- The decarbonisation plans for the industrial sector are broadly consistent with existing EU and UK regulatory frameworks for industrial emissions with a fall of around 19% by 2032.
    - This will be achieved through a combination of fuel diversification, cost saving energy efficiency and heat recovery, and participation in the EU Emissions Trading System (EU ETS).
- In the waste sector there are two main targets.
    - By 2020, the landfilling of biodegradable municipal waste will be phased out, ahead of the statutory ban that applies from 2021 in Scotland.
    - By 2030 it is expected to reduce food waste by 50%, following the UN Sustainable Development Goals.
- On agriculture, the objective is for Scotland to be among the lowest carbon and most efficient food producers in the world.
- In terms of the Land Use, Land Use Change and Forestry (LULUCF) sector the draft Plan sets out the Scottish Government's ambitions specifically on forestry and peatland.
    - By 2020, 50,000 hectares of degraded peatland will have been restored, relative to a 1990 baseline.
    - By 2030 the peatland will be increased to 250,000 hectares, representing an improvement of valuable soils in around 20% of Scotland's landmass.
    - Also, by 2032, Scotland's woodland cover will increase from around 18% to 21% of the Scottish land area.

3.2 The Draft Scottish Energy Strategy

The draft Scottish Energy Strategy: The Future of Energy in Scotland (Scottish Government, 2017b) is presented as a free-standing companion to the draft Climate Change Plan (described in section 3.1). This draft Energy Strategy presents a statement of Scotland's long-term vision of energy supply and use, aligned with the greenhouse gas emissions reduction targets.

The energy strategy document takes a more exploratory approach, providing opportunities to demonstrate and consider alternative sources of low carbon energy supply. There are four separate consultation documents published to accompany the draft Scottish Energy Strategy:

- Onshore Wind Policy Statement
- Scotland's Energy Efficiency Programme
- Local Heat & Energy Efficiency Strategies and District Heating
- Unconventional Oil and Gas

The draft Scottish Energy Strategy explores the choices to be taken about Scotland's future energy system, against the requirements of:

- the continued, sustainable and inclusive growth of Scotland's economy;
- secure and reliable energy supply;
- better and more affordable energy for consumers; and
- long-term, sustained decarbonisation – as set out by Scotland's 2050 climate change targets.

Moreover, the Scottish Government's 2050 energy vision is aligned to three themes: a) a whole-system view, b) a stable, managed energy transition, and c) a smarter model of local energy provision.

3.2.1 A whole-system view

As mentioned in section 3.1, the draft Scottish Energy Strategy follows a whole-system view of energy policy. The proposed integrated approach recognises the interactions and effects that the elements of the energy system have on each other, and it was one of the main motivations on using TIMES in the climate change plan (Scottish Government, 2017a). Therefore, a new 2030 'all-energy' target has been established, aiming for **the equivalent of 50% of Scotland's heat, transport and electricity consumption to be supplied from renewable sources by 2030** (Scottish Government, 2017b).

The 'whole-system' approach is also represented by the introduction of Scotland's Energy Efficiency Programme (SEEP) (Scottish Government, 2017c). SEEP highlights a renewed emphasis on energy efficiency as a strategic priority, recognising the significant economic benefits of energy efficiency investment and the importance of tackling fuel poverty. The SEEP document is described in detail in section 3.3.

3.2.2 A stable, managed energy transition

In the draft Scottish Energy Strategy: The Future of Energy in Scotland (Scottish Government, 2017b), it is mentioned that the Scottish Government is taking actions to tackle climate change while boosting the economy. Note that the draft does not present potential development paths for the economy (the wider economy is not modelled in TIMES), and it does not specify a unique energy mix for 2050. Instead it tries to highlight the range of technologies and fuels that will meet the energy needs at that period of time. The draft focuses on the following priorities:

- Continuing to support the recovery of North Sea oil and gas as a highly regulated source of hydrocarbon fuels
- Supporting the demonstration and commercialisation of Carbon Capture and Storage and CO2 Utilisation
- Exploring the role of new energy sources in Scotland's energy system
- Increasing renewable energy generation
- Increasing the flexibility, efficiency, and resilience of the energy system as a whole.

According to the draft Energy Strategy, the Scottish Government remains committed to maintaining domestic oil and gas production and maximising economic recovery from the oil and gas fields in the North Sea and west of Shetland. One of the main reasons for maintaining domestic production of offshore oil and gas industry is to prevent Scotland becoming more dependent on imports, potentially contributing more to lower net global emissions than in the opposite scenario.

In the exploration of new energy sources and carriers, the production of hydrogen seems a promising solution as it is a low carbon energy carrier that can be used in a variety of ways. For instance, in stationary power and Combined Heat and Power (CHP), in the gas main supply for heating, or to power fuel cells in different vehicles. It is envisaged that hydrogen gas will be present in the gas network moderately from 2020, and it is reckoned that there may be areas of the gas network where hydrogen could fuel 100% of the gas demand.

In this document it is also remarked that hydrogen may have the potential to deliver the lowest cost and least disruptive solution for the decarbonisation of heat. Nevertheless, other energy sources will also be explored, in particular, biomass (and derived versions) to join liquid biofuels as options for replacing fossil diesel and petrol in internal combustion engines.

As mentioned before, the draft Energy Strategy consultation is accompanied with a full public consultation on unconventional oil and gas (UOG), addressing developments involving hydraulic fracturing (fracking) and coal bed methane extraction in Scotland. Once that consultation closes and the responses have been independently analysed, Ministers will consider the full range of evidence, and make a recommendation to Parliament on the future of unconventional oil and gas in Scotland.

It is also stated in the draft Energy Strategy that carbon capture and storage has been identified as an essential element in the energy transition, and that Scotland is currently the best-placed country in Europe to realise Carbon Capture and Storage (CCS) at a commercial scale (Scottish Government, 2017b). Therefore, the Scottish Government will work with industry to assess opportunities for small scale CCS demonstration and CO2 utilisation projects. Also, it will explore the opportunity to combine hydrogen and bioenergy production and CCS[4].

According to the draft Energy Strategy, the Scottish Government will be supporting the continued growth of the renewable energy sector, with the objective of achieving the renewable energy targets of delivering 30% of energy from renewable sources by 2020, and 50% of all energy needs by 2030. Some of the technologies that will attract most efforts are offshore wind and marine renewable technologies. However, it is intended that onshore wind, hydro and solar power will continue to grow in the following years. Indeed, one important ambition of the Energy Strategy draft is to make Scotland the first area in the UK to host commercial onshore wind development without subsidy.

The draft Climate Change Plan pathway shows that electricity demand could increase by approximately 30% in Scotland as a result of further electrification of heat and transport. Hence, it is necessary to improve the flexibility and efficiency

[4] One of the cheapest ways for producing hydrogen is through steam methane reforming of natural gas ("Role of Hydrogen in UK energy system," n.d.).

(and presumably the scale) of the electricity system in order to accommodate the increasing demand. This will provide great potential for investment in a range of smart, flexible and grid-friendly technologies that can provide a range of benefits to the energy system in Scotland. In addition, new flexibility mechanisms and storage, including battery systems and pumped hydro storage (PHS), could play an even greater role in the future energy system.

3.2.3 A smarter model for local energy provision

It is recognised in the Draft Energy Strategy that Scotland has been moving away from traditional centralised energy supply and passive consumption models. The existence of numerous areas of constrained electricity grid and the desire for renewable generation, have driven innovation in technology, systems, business and engineering models for local energy provision (Scottish Government, 2017b).

The Scottish Government has committed long-term funding to develop local energy systems through a number of initiatives, such as:

- the Low Carbon Infrastructure Transition Programme (LCITP)
- Home Energy Efficiency Programme – Area Based Schemes
- the Scotland Heat Map
- the District Heating Loan Fund
- the Renewable Energy Investment Fund (REIF)
- the Community and Renewable Energy Scheme (CARES)
- schemes delivered under CARES such as the Local Energy Challenge Fund and the Infrastructure and Innovation Fund

According to the draft Energy Strategy, there are nearly 600 operating installations across Scotland, with active projects ranging from small scale hydro schemes of under 100 kW to wind farms of up to 9 MW.

The Scottish Government also mentions that, with a focus on local energy, some of Scotland's most pressing issues can be tackled, from security of supply to demand reduction, making energy supplies more affordable for households and businesses, and stimulate regeneration and local economic renewal(Scottish Government, 2017b). More detail on the local energy provision approach is presented in SEEP (see section 3.3).

3.3 Scotland's Energy Efficiency Programme (SEEP)

Following the targets set in the draft Climate Change Plan (Scottish Government, 2017a), of reducing emissions in Scotland by 42% by 2020 and at least 80% by 2050 (relative to 1990 levels), the plan outlines the actions and individual targets for the different sectors across the economy. In particular, the residential and services (non-domestic buildings) sectors will have emissions reductions of 75% and 98%, respectively, by 2032 in comparison with 2014 levels. These targets will require a transition of all homes, commercial properties and the public sector in Scotland, to be near zero carbon by the middle of this century (Scottish Government, 2017c).

Scotland's Energy Efficiency Programme (SEEP) (Scottish Government, 2017c), which is under development, and will be rolled out from 2018, has been proposed to be the cornerstone to achieve these decarbonisation targets. The specific goals of SEEP are to:

- improve the energy efficiency of Scotland's buildings;
- decarbonise their heat supply; and
- tackle fuel poverty.

The Scottish Government points to the multiple benefits that it says will accompany SEEP. These benefits not only contributes to meeting Scotland's climate change targets but also offer significant wider economic, social, health and regeneration benefits (Scottish Government, 2017c). These include:

- Measures to make the Scottish homes and work places warmer and more comfortable, in an affordable way. This will, at the same time, help to tackle fuel poverty and improve the competitiveness of the economy.
- The opportunity to build a substantial market and supply chain for energy efficiency services and technologies. This is expected to create 4,000 jobs per annum across Scotland, when fully operational.

- Health and early year's improvements thanks to people living in warmer homes.
- Regeneration of districts and communities thanks to the upgraded building stock.
- Substantially reduced greenhouse gas emissions.

3.3.1 Aims and Objectives of SEEP

As previously mentioned, SEEP aims 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.

The draft Climate Change Plan sets a series of policy outcomes, which SEEP has adopted as its objectives, including that:

- 94% of non-domestic buildings' and 80% of domestic buildings' heat will be supplied using low carbon heat technologies by 2032; and
- improvements to the fabric of Scotland's non-domestic and domestic buildings results in a 10% and 6% reduction, respectively, in their heat demand by 2032.

The draft Climate Change Plan recognises that installation of low carbon heating solutions such as renewable heat will continue to increase throughout the SEEP period. However, the greatest shift away from gas is likely to take place after 2025.

It is also recognised by the Scottish Government that demand reduction measures (primarily through fabric improvements to buildings, or process improvements to equipment) and heat decarbonisation measures will need to operate together. Hence, the near-zero carbon approach that new buildings are already moving towards, needs to be considered for existing buildings as well (Scottish Government, 2017c).

Note that the above targets concern low carbon heating and energy efficiency for buildings. There is no specific target in SEEP for fuel poverty or a nationwide energy efficiency target (including transport and industry).

3.3.2 SEEP delivery scenarios and challenges

Given the scale and scope of SEEP, a phased approach has been designed to be carried out over a number of years to enable the successful development of all elements of the Programme (Scottish Government, 2017c). The Programme is planned in three key phases:

1. A design phase, including the setting of formal targets for the Programme through the Climate Change Plan and Energy Strategy (see sections 3.1 and 3.2 above), which is expected to continue to run up to early 2018.
2. A development phase in which the key elements of the Programme are developed and deployed over time to create the overall programme structure which is expected to run through until 2021 – 2022.
3. A full deployment phase, which would be subject to regular review, evaluation and refinement (up to 2032).

Additionally, during the initial phases of the Programme, the focus of the Scottish Government will be on supporting and delivering existing programmes more effectively and developing new pilot schemes to test delivery mechanisms for domestic and non-domestic buildings.

Throughout the duration of the programme, the Scottish Government recognises that there are many different routes to deliver and implement SEEP, successfully achieving the described objectives. As shown in in Figure 3 (taken from (Scottish Government, 2017c)), the delivery options can range in the spectrum of choice: freedom of choice vs mandatory action, and how they are balanced between local and central delivery and governance. However, there is no one preferred option, and it is envisaged that the approach will vary across the different elements of the programme.

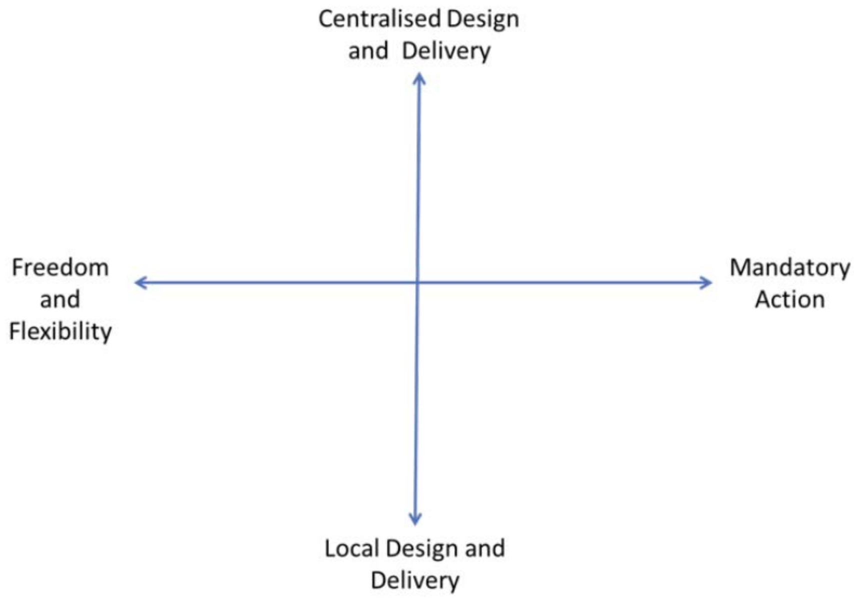

Figure 3. Policy delivery options (Scottish Government, 2017c).

During the scoping of SEEP, different stakeholders were invited to advise on the policy and delivery framework for the programme. The key issues that have been raised by the stakeholders are:

- the role of regulation, standards and financial incentives;
- the definition of sources and level of funding;
- the provision of advice, information and consumer protection;
- the establishment and operation of local supply chains and trusted delivery agents;
- the nature of programme delivery;
- the balance between local and national responsibilities; and
- monitoring and review processes.

From these opportunities and challenges, the importance of the involvement and participation of the people stands out. According to the reviewed stakeholders, the Scottish Government need to have further intervention to stimulate market demand for energy efficiency improvements and low carbon heat. In addition, standards, regulatory frameworks and financial incentives are needed to give clarity to consumers about what is expected, and to make it as easy as possible and the norm to invest in energy efficiency and heat (Scottish Government, 2017c).

The methodology to assess targets and standards will be important. Stakeholders mentioned that SEEP should adopt well-understood and consistent means of assessing the potential for improvement and decarbonisation of buildings. However, many also questioned whether existing methodologies are fit for purpose, basing assessments on modelled energy use, noting the potential for tailored building-level assessment (rather than assessment at individual unit basis) and for area-wide assessment. Further discussion on the potential policy delivery scenarios can be found in the SEEP draft (Scottish Government, 2017c).

3.4 UK energy efficiency policy

The UK has a commitment to reducing its greenhouse gas emissions by at least 80% by 2050, relative to 1990 levels ("Energy efficiency | Energy UK," n.d.). Improvements in energy efficiency are seen as essential to achieving this goal.

The goals of energy efficiency policy in the UK align with the Scottish ones, targeting energy consumption in households, focusing on installing insulation and heating measures, and supporting vulnerable consumer groups ("Energy efficiency | Energy UK," n.d.). With these objectives, the UK has introduced the **Energy Companies Obligation (ECO)** programme ("Energy Company Obligation," 2016). ECO started in 2013 and replaced two previous energy efficiency programmes, the Carbon Emissions Reduction Target (CERT) and the Community Energy Saving Programme (CESP).

The Energy Companies Obligation (ECO) provides support for packages of energy efficiency measures. ECO creates a legal obligation on energy suppliers to improve the energy efficiency of households. Suppliers are given targets based on their share of the domestic gas and electricity market. The targets are grouped in three areas:

- The Carbon Emissions Reduction Obligation (CERO) which focuses on "hard-to-treat" homes and, in particular, measures that cannot be fully funded through the Green Deal ("Green Deal," n.d.). Solid wall insulation and hard-to-treat cavity wall insulation are two examples. Other insulation measures and connections to district heating systems are also eligible if they are promoted as part of a package that includes solid wall insulation or hard-to-treat cavity wall insulation.

- The Carbon Saving Community Obligation (CSCO) which focuses on the provision of insulation measures and connections to district heating systems to domestic energy users that live within an area of low income. 15% of this target must be achieved by promoting measures to low income and vulnerable households living in rural areas.

- The Home Heating Cost Reduction Obligation (HHCRO) under which suppliers provide measures which improve the ability of low income and vulnerable households to affordably heat their homes.

It is interesting to note that ECO will be changing soon. The scheme is coming to an end in 2017 and, starting from April 2017, will be replaced by a one-year transition scheme focusing on the fuel-poor. Key proposals for this new scheme should focus on the customers who need the energy efficiency measures the most. Also, it should enable local authorities to identify eligible customers.

3.5 EU policy

The EU can provide a supportive policy context that aids achieving the Scottish energy and climate change targets.

In 2007, an energy policy for Europe, common to all member states, established goals for the 2020 horizon. Since then, a new energy policy framework has been developed, with revised targets for 2030 ("2030 Energy Strategy - Energy - European Commission," n.d.). The European energy policy is based on three main aspects: sustainability, security of supply and competiveness.

The main objective regarding sustainability is to address climate change by reducing EU emissions to a level that limits the global temperature increments to 2ºC in comparison with pre-industrial levels. To achieve this, a first set of targets were set in 2008 (20% reduction in GHG emissions, 20% improvement in energy efficiency, 20% of renewable sources generation, for year 2020) but, recently, these targets have been revised and adapted for the 2030 framework. It includes the following targets:

- Emission reduction of over 40% by 2030 (in comparison with 1990 levels)
- Reform and improve the EU emission trading system
- Renewable energy target of 27% by 2030
- Energy efficiency target of 27% by 2030 (this is a non-binding target)
- 15% target on energy interconnections between member states

Moreover, EU leaders recognize that energy technological innovation is key to achieving the 2030 targets. Hence, more efforts are considered in research and innovation policy.

Security of supply has become a priority in energy policy after the Russian-Ukrainian gas conflict in 2014. EU leaders have agreed on a European energy security strategy, ensuring solidarity between member states, diversification of supply sources and transportations routes, and improvements on security of oil stocks, gas and electricity generation. This strategy has measures on the short, medium, and long-term, and also pushes for the establishment of a European single energy market.

Regarding competitiveness, the EU sees the energy market as a key element in competitiveness and the affordability of energy. This competitive market foresees a clearer separation of gas and electricity transmission from production and supply, and more collaboration from the energy market regulators of the member states. Another objective to improve competitiveness is to eliminate the "island" status of some few remaining members not connected to the rest of the EU, by infrastructure projects of common interest (PCI). There are two PCIs involving Scotland, one high voltage line connecting to Norway, and another one connecting to Iceland ("PCI Interactive map," n.d.).

4. The energy system

This section provides a brief description of one typical representation of the energy system, highlighting the main processes involved from the extraction of the energy resources until the final end-use of energy, and examples of the different stages the energy carriers pass through. This particular representation of the energy system has been selected as it relates to the way that this is modelled within TIMES.

This overview of the energy system is also intended to assist in understanding the TIMES model (described in section 5).

4.1 The energy system flow chart

According to the IPCC fifth assessment report (Bruckner et al., 2014), the energy sector (energy system), "comprises all energy extraction, conversion, storage, transmission, and distribution processes that deliver final energy to the end-use sectors (industry, transport, and building, as well as agriculture and forestry)." Therefore, in a simple way, the energy system can be described as the series of transformations of the raw energy resources that are needed to supply energy services to end users.

According to (Bruckner et al., 2014), the energy system is composed of four main elements:

- Energy sources
- Energy carriers
- Processes
- Energy demand

The energy sources are the main inputs to the system, and need to be transformed for their end use. The energy carriers are transmitters of energy, occupying intermediate steps in the energy-supply chain between primary energy sources and end-use applications (IPCC, n.d.). Examples of energy carriers include solid, liquid and gaseous fuels, as well as electricity and heat. The energy system processes comprise all the necessary steps to supply energy to the end user, such as energy conversion, transmission and distribution. Lastly, the outputs of the energy system are the energy services used to meet the energy users' need. Figure 4 shows the general energy system flow chart, including 7 blocks. These blocks are described in detail below.

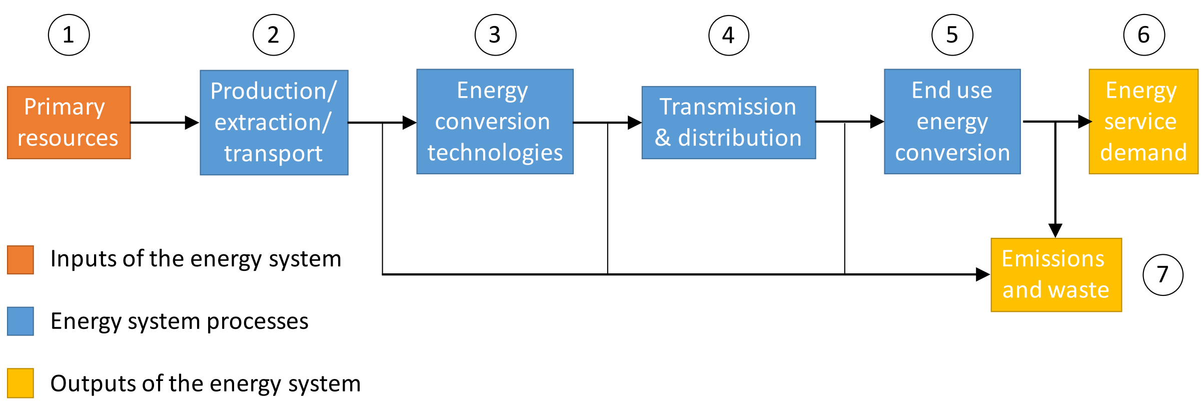

Figure 4. Energy system flow chart

Block 1 represents the main inputs for the whole energy system, referring to raw materials and raw energy resources that cannot be used in their current form. Examples of such resources include:

- oil and gas reserves;
- renewable resources, such as wind, sun, or rain;
- trees; and
- minerals such as coal (before being mined).

Block 2 represents the first processing of raw materials to make them available and/or usable. This first processing includes extraction of the raw material, transportation and any other processes that the raw energy carrier might need before energy conversion. The inputs of this block will be raw energy sources. The outputs will be processed energy carriers (ready for energy conversion).

As an example of block 2, we can take crude oil (see Figure 5). The raw version of oil is in a reserve. It needs to be extracted, transported to a petrochemical facility, and refined. These processes will fall in block 2. Therefore, the input of this block would be crude oil at a reserve, and the output would be refined oil ready to be transformed in other fuels.

Note that not all energy carriers need to go through some (or any) of these processes (block 2). For instance, some renewable resources, such as wind, do not need any extraction or transportation and can be directly be used to produce electricity (energy conversion in block 3, see Figure 5).

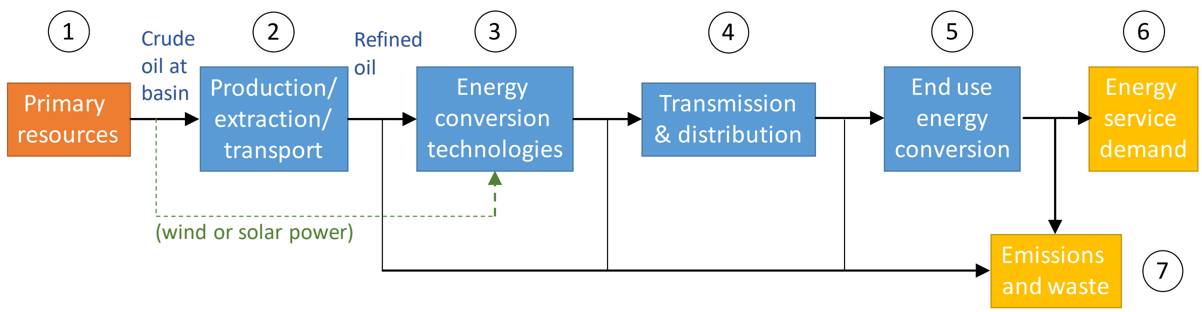

Figure 5. Examples of Block 2, energy system flow chart.

Block 3 corresponds to the conversion process of energy carriers. It does not involve end use, but the transformation of one energy carrier to another, facilitating the transmission and distribution of it.

Continuing with the examples shown in Figure 5, in block 3 the refined oil (previously pre-processed in block 2) is ready to be transformed into a range of different fuels. The input then would be refined oil at a reserve, and the outputs are fossil fuels such as gasoline or diesel (see Figure 6).

Wind power is a different example. Unlike crude oil, wind power does not require any pre-processing (made in block 2), so it can be directly used to produce electric energy with a wind turbine (the energy conversion technology in block 3). Therefore, the input for this block is wind, and the output is electricity (see Figure 6).

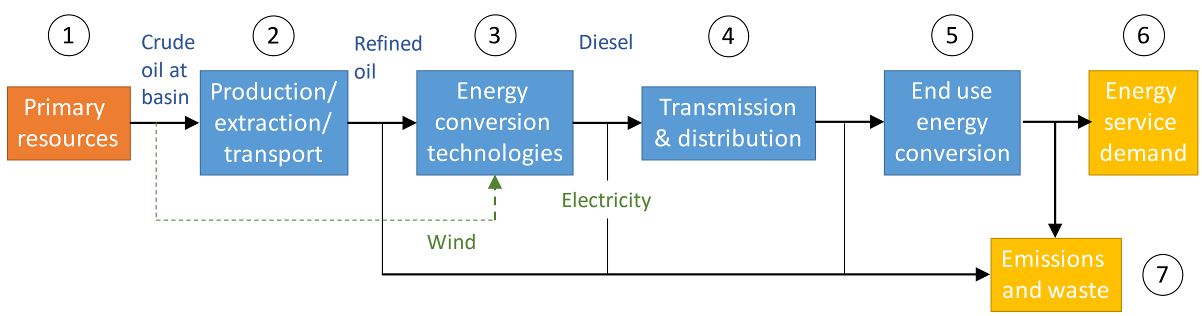

Figure 6. Examples of Block 3, energy system flow chart.

Some energy carriers might pass through several conversion stages (such as hydrogen or any sort of energy storage), while others might only need the end use energy conversion (in block 5). For instance, some types of biomass such as wood, after extraction from the forest (in block 2), can be directly used in an oven (block 5) for cooking (see Figure 7).

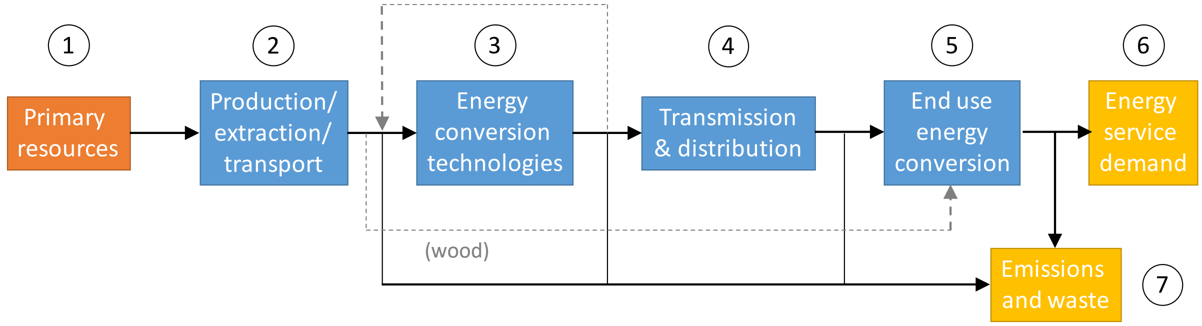

Figure 7. Possible alternative flows in block 3, energy system flow chart.

The processes in block 4 correspond to the transmission and distribution of energy carriers, from the generation side to the final consumer, making it accessible for the end use services. These processes do not involve an energy conversion. In other words, the inputs and outputs will be of the same type of energy carrier (e.g. input electricity, output electricity). The typical energy carriers that go through these processes are electricity, gas, and other fuels, such as gasoline or diesel.

As mentioned before, not all energy carriers require this process and can pass directly from block 2 to block 5. For example, wood as biomass when used locally (see Figure 7).

Typical examples for block 4 include, diesel (or gasoline), and electricity. In the case of the former, the previously processed crude oil is now a fuel and is ready to be taken to consumers via a distribution network (pipes and/or tankers). Hence, the input in this case would be diesel at the refinery, and the output would be diesel at the pump station (see Figure 8). For the latter, the generated electrical energy (from wind power or any other source) is ready to go through the transmission and distribution network to end consumers. In this case, the input is electricity at the power plants, and the output is electricity at your home socket (see Figure 8). Note that, even though there is no energy conversion at this stage, these transmission and distribution processes are associated with costs and losses (e.g. electricity losses, gas leakage or fuel cost in moving petrol or diesel).

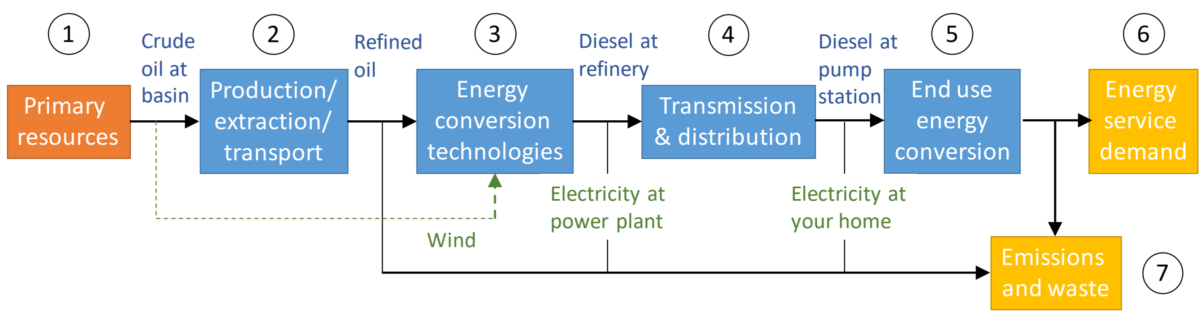

Figure 8. Examples of Block 4, energy system flow chart.

Block 5 is the last process in the energy system, involving the energy conversion technologies to meet end use service demand (represented in block 6). This block represents the wider range of conversion technologies, from house appliances to industrial machines, also including all the vehicles for transportation. It may also be noted that, depending on the energy conversion technology, one energy carrier can have several energy demand outputs. For instance, electricity could be used for heating, domestic hot water and illumination.

Continuing with our previous examples, in block 5 the diesel can be used to fuel a bus, providing a public transportation service. So, the input is the diesel at the pump station and the output is the transportation service. On the other hand, the electricity available at the household is used to power a light bulb, providing light. Hence, the input is the electricity from the mains and the output is the illumination service (see Figure 9).

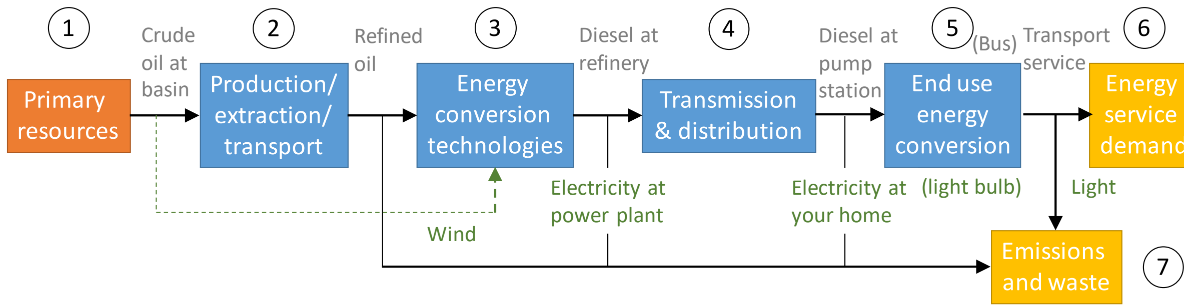

Figure 9. Examples of Block 5, energy system flow chart.

Block 6 represents the last link of the energy system chain. It includes the energy service demands (end-use of the energy) across all sectors. As mentioned before, most services (especially in the residential sector) could be met by different energy carriers and/or conversion technologies. Examples of residential services that could be supplied by electricity, gas or other fuels are heating, domestic hot water, illumination, cooking, etc.

Besides emissions and waste, all the processes present energy losses (block 8, see Figure 10). Processes in blocks 2, 3, 4 and 5 are carried out with certain energy efficiency. Therefore, energy efficiency measures could be implemented at all these stages, and not only at the end use energy conversion process (block 5). Examples of energy efficiency measures at the different stages of the energy system can be found in section 5.7.

Also, energy efficiency could be measured in different ways and at different points. For instance, energy efficiency could be measured in block 3, looking into the amount of input energy and the output. For a full energy system efficiency measurement, it would be necessary to check from block 1 to block 6.

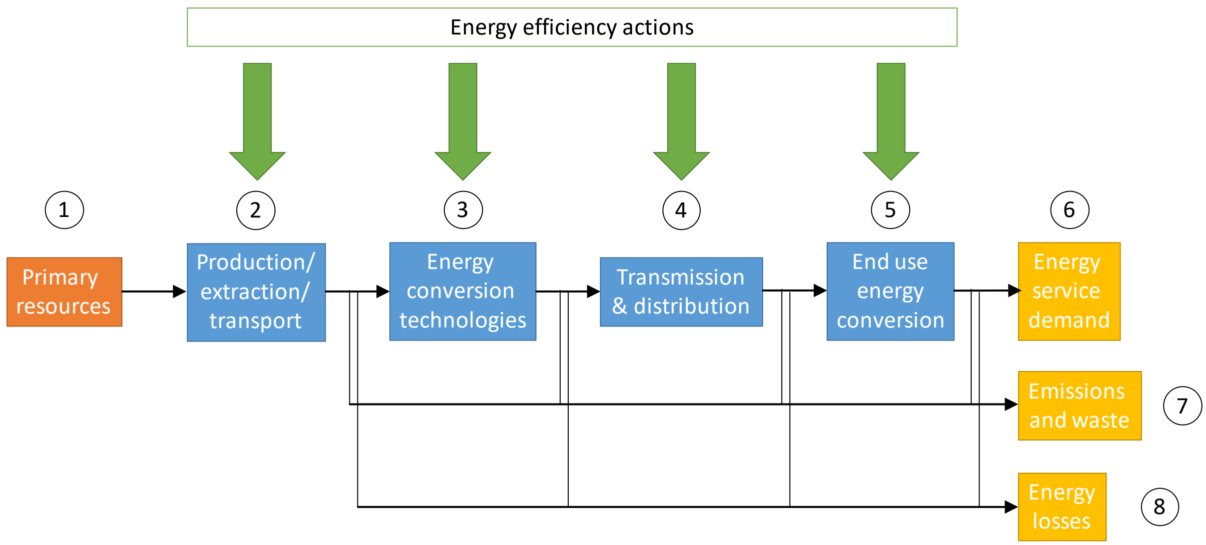

Figure 10. Potential energy efficiency actions in the energy system.

5. The TIMES model

The TIMES (The Integrated MARKAL-EFOM System) model was developed by the IEA-ETSAP (Energy Technology Systems Analysis Program) to conduct in-depth energy and environmental analyses (Loulou et al., 2004). TIMES is an energy system-wide bottom-up model, which considers a great number of different technologies. TIMES uses linear-programming to find a least-cost provision of energy to meet specified energy service demands, according to a number of user constraints (including GHG emissions, energy use, etc.), over medium to long-term time horizons. Therefore, the main objective of TIMES is to be used to explore possible energy futures based on contrasted scenarios (Loulou et al., 2005).

TIMES models cover all the processes of the energy system (see section 4 for a description of the energy system). In other words, it covers all the steps from primary resources through all the processes that transform, transport, distribute and convert energy to supply energy services. On the energy supply-side, it comprises fuel mining, primary and secondary production, and exogenous imports and exports. Energy is delivered through various energy carriers to the demand-side, which is structured by sectors: residential, commercial, agricultural, transport and industrial ("IEA-ETSAP | Times," n.d.).

Note that the TIMES review provided in this section is a brief description to give a general understanding of the model. More detailed documentation can be found in (Loulou et al., 2004) and (Loulou et al., 2005).

5.1 TIMES general structure

TIMES models the energy system as shown in Figure 11. Contrasting this scheme with the energy system presented in section 4.1, it can be seen that the inputs and outputs of the TIMES model are different. The inputs (exogenous variables to the model), driving all the energy system, are the data of the supply and demand side. The former is composed by the primary energy resources and imports availability (block 1), and the latter corresponds to energy service demands (block 6). The outputs of the model (endogenous variables) include emissions and waste variables (block 7), energy losses associated with the different processes (block 8), capacity planning of the different technologies and different economic variables (block 9), including energy prices, costs, profits, etc. In addition, energy carrier variables (energy flows) between the different steps of the energy system are also endogenous to the model, while the numerous techno-economic parameters of the technologies and processes are exogenous. These parameters include technology costs (per unit), discount rates, efficiencies, and other technical constraints.

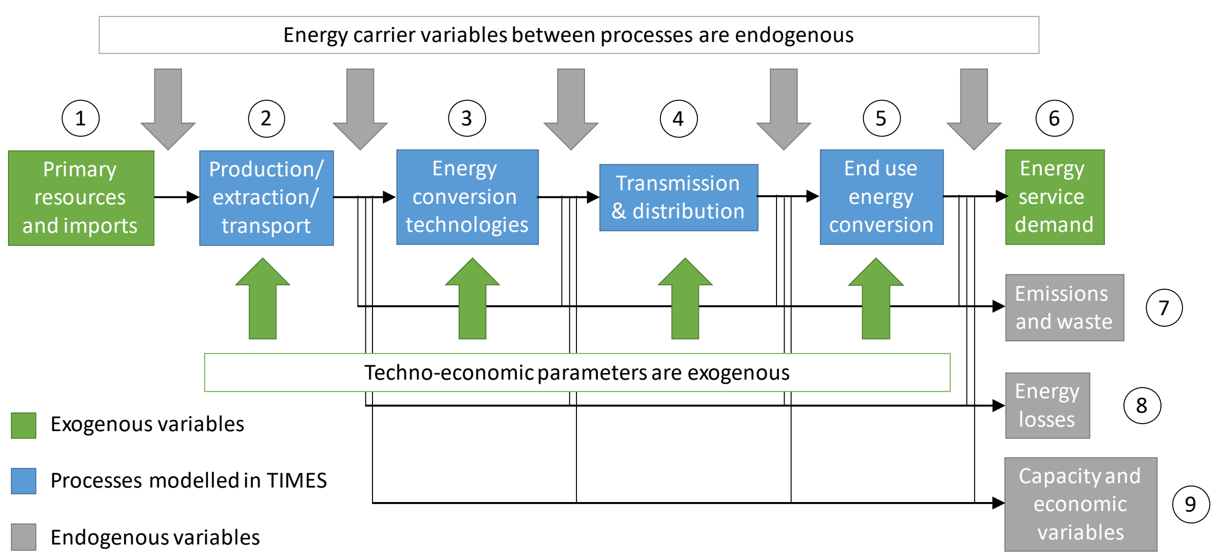

Figure 11. Modelling of the energy system in TIMES.

The IEA-ETSAP provides a different schematic of the TIMES model, as shown in Figure 12. This figure is a different representation of the energy system but it is composed of the same elements described previously. The inputs in Figure

12 correspond to blocks 1 and 6 of Figure 11, being from the supply side the domestic sources and energy imports, and from the end-user side, the energy service demands. All the processes of the energy system (shown in blocks 2 to 5, in Figure 11) are aggregated in the red blocks shown in Figure 12. Then, Figure 12 shows explicitly the way the demand is aggregated in four sectors: Industry, commercial and tertiary sector, households and transports (brown blocks). Note that there are other outputs of the model, as shown in Figure 12, including: energy prices and energy flows, technology capacities, emissions and economic costs.

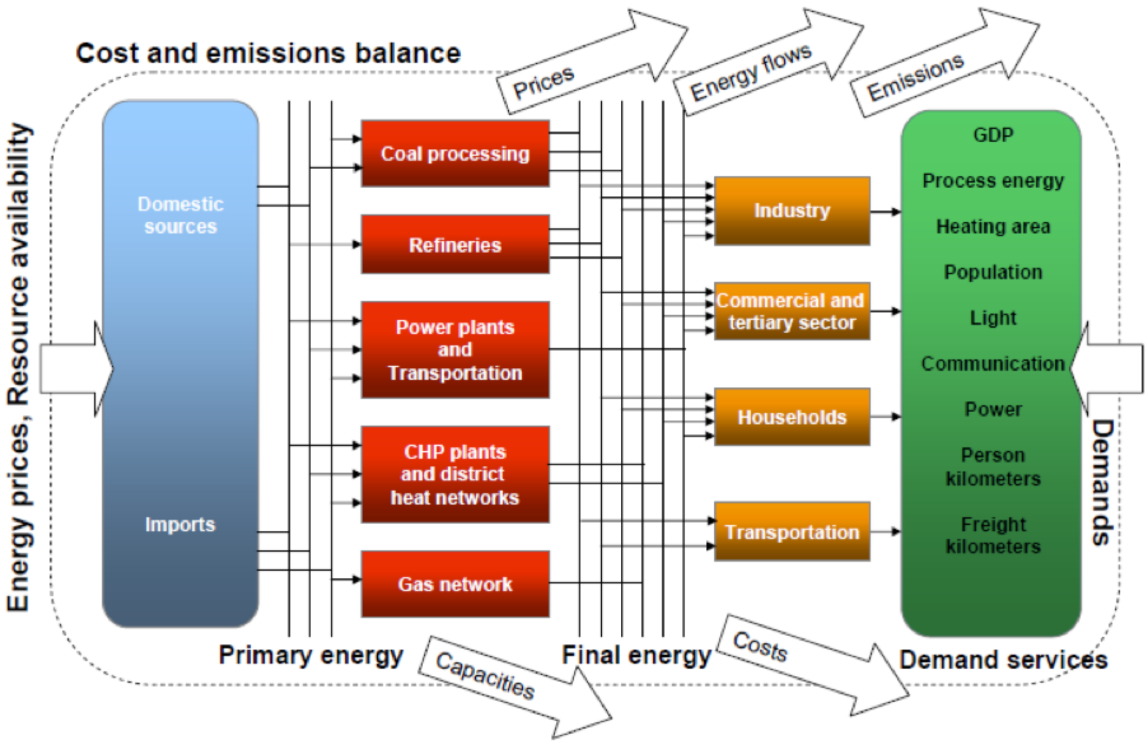

Figure 12. TIMES model schematic ("IEA-ETSAP | Times," n.d.).

5.2 TIMES modelling elements

After reviewing the general structure of the TIMES model, it is now possible to describe the specifics of the modelling approach of the energy system used in TIMES.

The first important characteristic to consider is that all the elements, processes, inputs and outputs of the energy system are modelled in TIMES as these three elements ("IEA-ETSAP | Times," n.d.):

- Technologies (also called processes)
- Commodities
- Commodity flows

In TIMES, the commodities are all the energy carriers, energy services, materials, monetary flows, and emissions. Some examples of commodities are electricity or coal (energy carriers), heating or transportation of heavy goods (energy services), costs (monetary flows), and CO2 or NOx (emissions).

The Technologies or processes are representations of physical devices that transform commodities into other commodities, including not only energy conversion technologies but also extraction, production, transport, and transmission and distribution technologies. Hence, the processes modelled in TIMES could be the primary sources of some commodities (e.g. mining processes, import processes), or could be the transformation of commodities. For instance, conversion plants that produce electricity, energy-processing plants such as refineries, end-use demand devices such as cars and heating systems, etc.

Lastly, commodity flows are the links between processes and commodities. In other words, a flow is of the same nature as a commodity but is attached to a particular process, and represents an input or an output of that process. Note that some processes can have more than one input commodity and/or more than one output commodity, and the input/output commodity could be of the same type or different (see *Figure **13***). An example of a technology providing two different output commodities are combined heat and power systems (fuel cells, micro turbines, etc.), that uses a single input energy carrier such as gas, producing two energy carriers: electricity and heat.

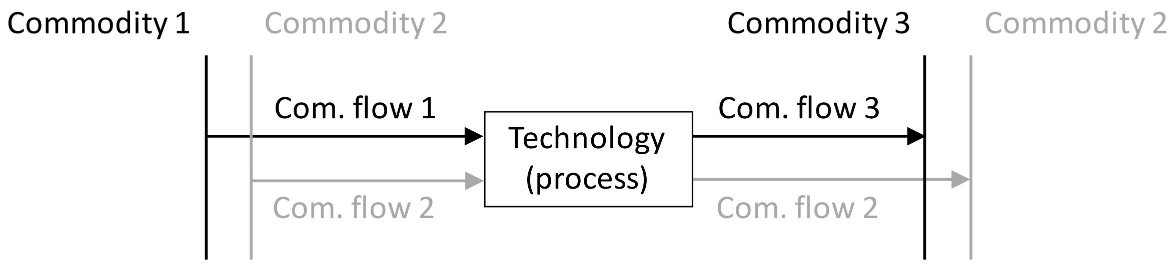

Figure 13. Basic schematic of technology, commodity and commodity flow in TIMES.

Note that, besides the energy carrier output commodities, most technologies and/or processes in TIMES produce other commodities such as emissions, money flows (costs and or profits), and energy losses. Also, the technologies and/or processes in TIMES are modelled by different exogenous techno-economic parameters. These parameters define the types of commodities used as inputs and outputs, and the performance and costs of the process and/or technologies. Examples of these parameters include: operational efficiency, technology investment costs, operation and maintenance costs, discount rates, technology lifespan, emissions per unit of production, etc.

Taking the energy system example of crude oil shown in Figure 9, the equivalent TIMES modelling would be as follows:

- The crude oil at the basin would be a commodity. The maximum availability of this commodity will be defined exogenously (e.g. 10 million of barrels), and the TIMES model will decide how much of that reserve will be used and when (the commodity flow).
- The commodity flow would be the amount of crude oil that goes into the extraction, production and transport processes (grouped together in block 2 of Figure 9, but in TIMES they could be separated processes with many technology alternatives). In these processes the input and output commodities are different, as well as the commodity flows. For instance, 1 million barrels of crude oil is the input to the process, and 800 000 barrels of refined oil is the output commodity flow.
- The commodity refined oil goes into a refinery (energy conversion process, block 3 in Figure 9) to obtain the commodity diesel. In this case, the commodity flows are 800 000 barrels of refined oil as input, and 1500 MWh of diesel.
- The next process is the transmission and distribution of the diesel commodity (block 4 in Figure 9). In this process, the input and output commodities are the same: diesel. However, in TIMES it will be defined as two different commodities: diesel before and after distribution, and the commodity flows are different due to losses. For instance, an input of 1500MWh, will deliver an output of 1450 MWh of diesel.
- The final process involves the energy conversion technologies for end use (block 5 in Figure 9). The commodity, diesel, is transformed in the energy service public transport (also a commodity), the energy conversion technology being the bus. For this process, the input commodity flow is 1450 MWh of diesel, and the output commodity is 1200 MWh of public transport, for example. The demand of the public transport commodity, in this case expressed in MWh of energy demand, is dictated as an exogenous variable.

Note that this example is a simplified version of all the elements involved in an actual TIMES implementation, yet it provides an adequate overview of equivalent elements and the modelling approach carried out in TIMES. Also, note that the figures of commodity flows given in the above examples are for illustrative purposes only, and might not represent realistic values.

5.3 Time and data management

TIMES is a long-term planning model, with time horizons up to 2050 or 2100. Considering that most variables in TIMES are time specific (e.g. energy flows, emissions, etc.), the number of variables duplicates with each time step considered. Therefore, it becomes impractical to model every hour of every year, as the size of the problem increases considerably and with exponentially longer solution times.

To avoid overcomplicating the optimization model, TIMES considers only some representative time-slices that work as an average of the elements of that time period. Figure 14 (taken from (Loulou et al., 2005)) shows an example of the time-slice organisation in TIMES. Note that it is not time-sequential simulation.

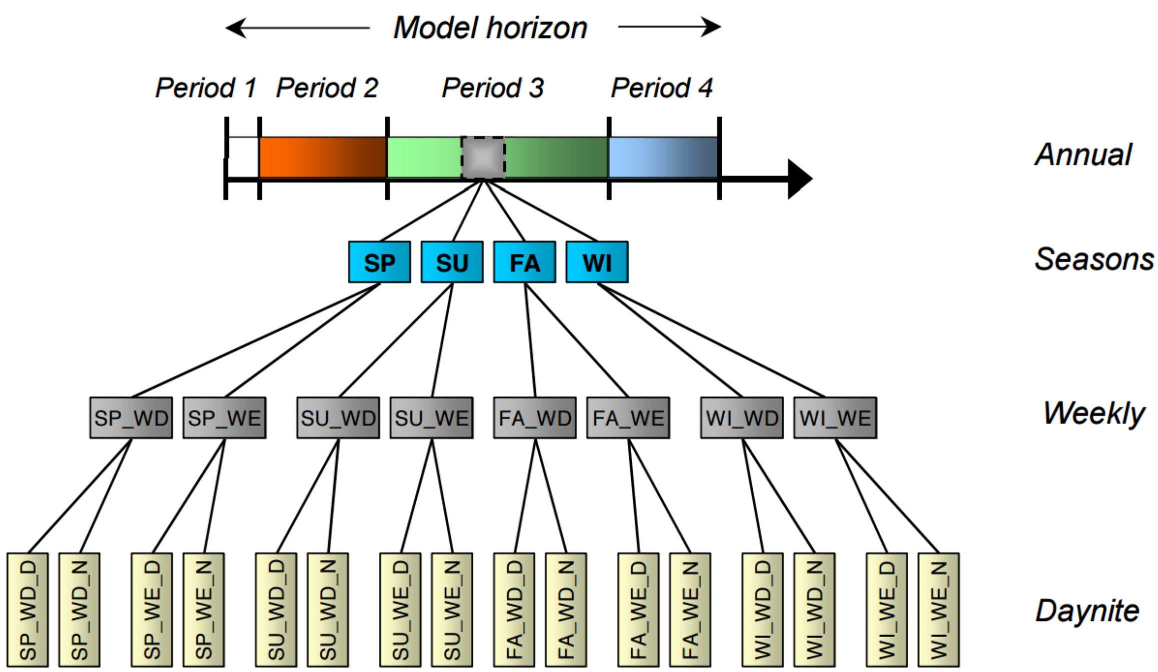

Figure 14. Example of time-slices in TIMES (Loulou et al., 2005).

It can be seen in the figure that TIMES considers four levels of time granularity. The first level, which is the coarser, is the time period division. Each time period is composed by several years, and is represented by a milestone year. These periods are designed so the model can make long-lasting decisions and changes, such as technology investments or policy changes. Therefore, each year in a given period is considered identical (capacities, commodity flows, operating levels, etc.), except for investment variables, which are usually computed only once in a period (the milestone year). In other words, the model only considers building new facilities or adding new technologies in certain years. Note that the size of the time periods and the selection of milestone years can be defined by the user, and it does not have to be the same for the whole time horizon. For instance, four time periods of five years with the milestone year at the middle of the period, followed by two time periods of 10 years with the milestone year at the beginning of the period.

The second level of granularity is the time divisions within a year, normally representing seasons (spring, summer, fall and winter, as in *Figure 14*), but may be defined at will by the user. Hence, these seasonal slices normally represents groups of months.

The third level of granularity is the weekly divisions, normally differentiating between working days and weekends at each season, representing several similar days (which are assumed to be equal between them).

Lastly, the fourth level of granularity corresponds to the daily divisions. These are the finer time slices, grouping a small number of hours. In the example shown in Figure 14, the daily division is only in two slices (day and night) but other typical TIMES version implement four slices: night, day, evening peak and late evening.

Considering that many energy service demands (and thus, the energy supply side) are significantly different at different seasons, type of days and even time of the day, the time-slices are a particularly important feature in TIMES. For instance, heating requirements are very different in winter in comparison with summer, and they are also different in a working day than in the weekend. Also, some energy production technologies have different characteristics depending on the time of year (independently of the demand side), such as wind turbines, solar panels, or run-of-the-river hydro plants. Therefore, it is important that many of these commodities are modelled with this time slicing.

Regarding data management, TIMES relies on interpolating or extrapolating to fill up any data gaps. Due to the future long term horizon of the optimization problem, it is necessary to use data projections in TIMES. Examples of such projections include: international energy prices, energy service demand, technology costs, etc. The projections are given to TIMES as exogenous variables (see Figure 11), but normally the projections do not have the same detail as the model, making it necessary to extrapolate or interpolate the missing data from the actual projections. An example of this could be the following:

- Data of 2015 are input to the model.
- Time periods of five years are selected with milestone years at the beginning of the period, and a time horizon until 2050.
- A projection of 20% of electricity demand decrement by 2050 (in comparison to 2015 levels) is given to the model.
- If the demand details for the milestone years are not provided by the user, these values will be populated as a linear interpolation between the values of 2015 and 2050.
- Similarly, if the time horizon is extended to 2060, the missing demand values would be extrapolated from the given values.

5.4 The optimization process in TIMES

As mentioned, the objective of the optimization process in TIMES is to find the least cost energy system, while making sure that there is a balance between supply and demand sides. In other words, the energy supply technologies must produce the required energy in a cost-effective way to meet the energy service demands.

Indeed, the Objective Function in TIMES is the discounted sum of the annual costs minus revenues across all time periods (i.e. assumes perfect foresight). This includes construction costs (technology investments), operation costs (O&M, imports, delivery and transport costs, etc.), and revenues from energy supply, exports and decommissioning.

The energy service demands are exogenous to the model. However, the technology use and energy flows are endogenous, meaning that TIMES can decide which energy carriers and technologies can be used to meet the demand. This feature is one of the mains strengths of TIMES, as it allows commodity (energy carrier) substitution and technology (process) substitution. Therefore, many different potential energy roadmaps can be found under different economic, energy efficiency[5], and emission reduction scenarios. For instance, Figure 15 shows an example of the possible substitution of energy carriers and conversion technologies to provide one or two commodities in the residential sector.

[5] More detail on how energy efficiency scenarios are created in TIMES can be found in section 5.7.

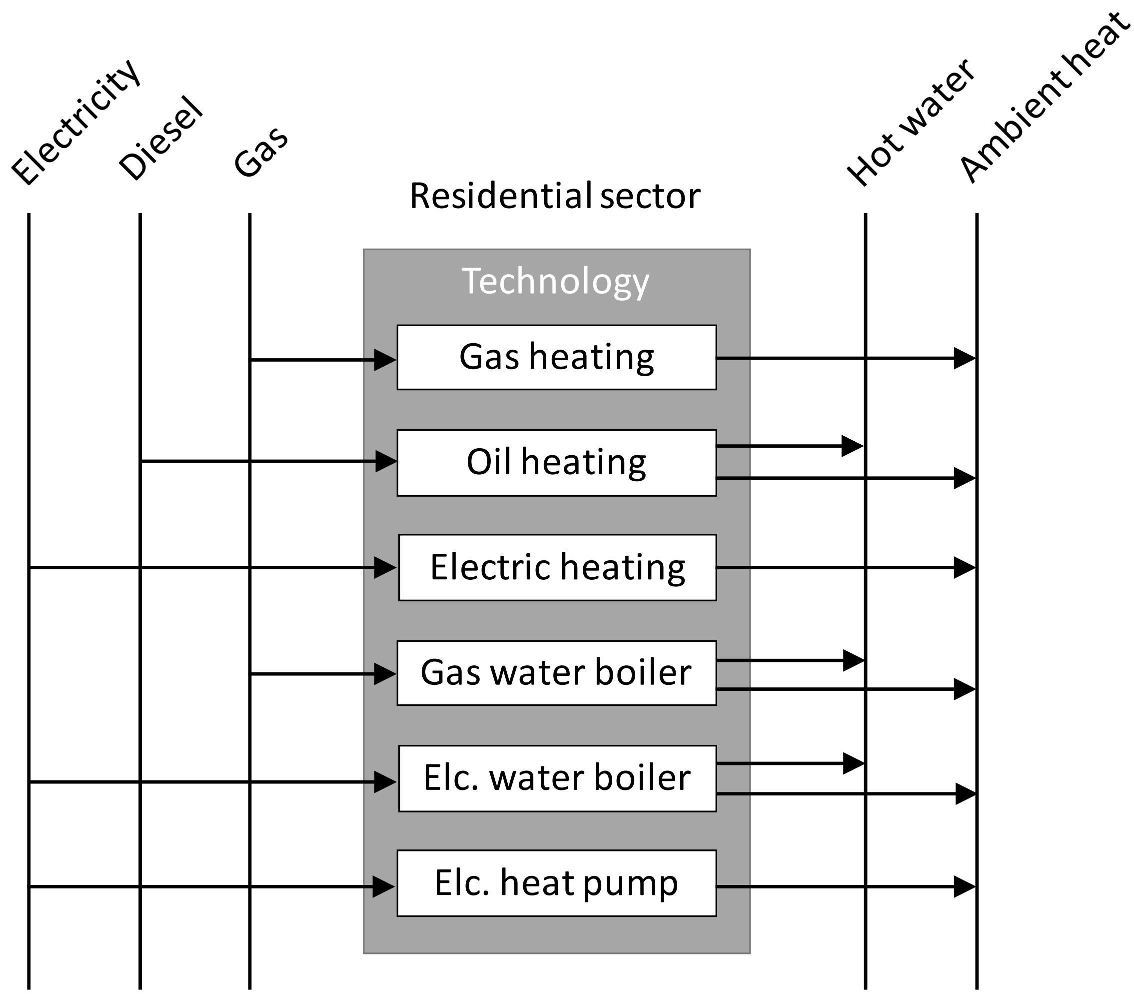

Figure 15. Technology and energy resource substitution example in TIMES.

Note that TIMES scenarios can be built as a combination of different input data sets (e.g. different demand scenarios), and/or user defined constraints, such as GHG emission caps or technology adoption and usage limits.

5.5 Summary of inputs and outputs

Figure 16 shows a summary of the inputs and outputs of the TIMES model.

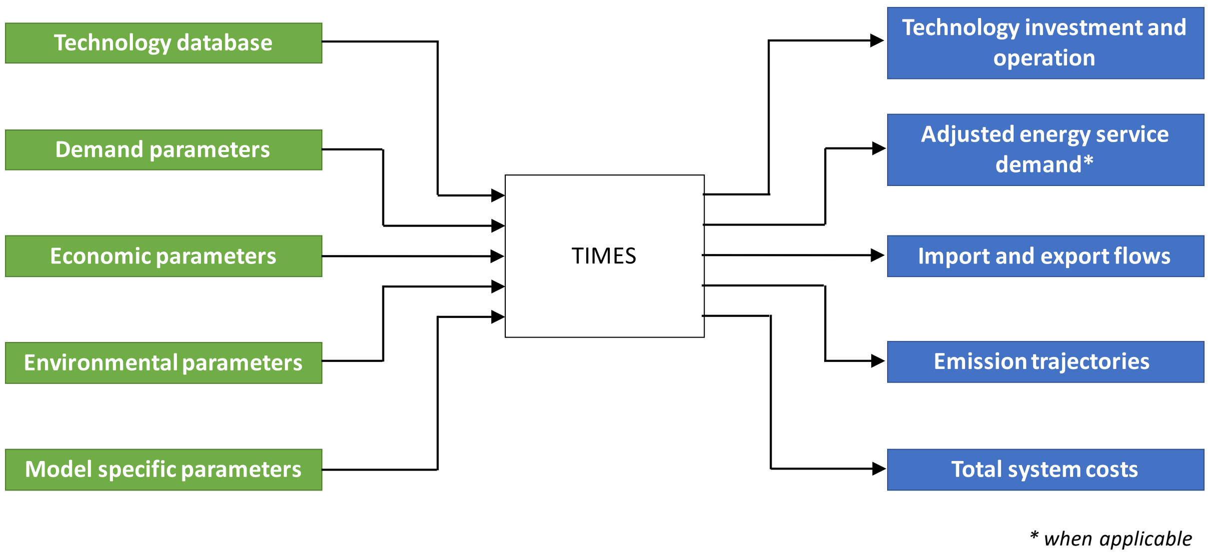

Figure 16. Summary of TIMES inputs and outputs.

The inputs (exogenous variables) of TIMES can be grouped in five categories:

- **Demand parameters**, mainly composed by end-use demands (normally measured in energy units) and energy demand elasticities. In TIMES, the demands for energy services can implement certain elasticity, simulating economic feedback in the energy system. Note that the energy service demand elasticity is a feature that is available in the general TIMES model, but not all model versions implement it.
- **Technology database**, which is the largest part of the input data for TIMES. This includes all the techno-economic attributes that described the different technologies and processes modelled in TIMES. Examples of such parameters include operation efficiency, technology investment costs, operation and maintenance costs, discount rates, technology lifespan, etc.
- **Environmental parameters**, mainly used to estimate the emissions produced at all stages of the energy system. They include technology emission coefficients, environmental targets, taxes and/or subsidies related to environmental performance.
- **Economic parameters**, including the energy and material prices and availability of primary resources and imports (block 1 in Figure 11) and the discount rate. There is a general discount rate for TIMES. However, different discount rates can be implemented by technology and/or sector.
- **Other model parameters**, required for the correct operation of TIMES. For instance, the time periods, time slices, year management, etc.

Regarding the outputs of TIMES (endogenous variables), they can be summarised in:

- **Technology investment and operation**, including installed capacities and energy flows. Cost information and revenues are also provided (technology investments, operation and maintenance costs, revenues, etc.).
- **Energy and material imports and exports**, energy flows organized by energy commodity, and the related costs and profits are obtained as well.
- **Emission trajectories and sectorial measurements**, referring to the emission production detail for each process and technology, individually or aggregated by sector.
- **Adjusted demand for energy services**, when demand elasticity has been implemented. This give information of changes on the end-use energy demand.

- **Marginal prices of energy commodities**. This is obtained when the equilibrium between supply and demand is met, and the marginal prices derive from the energy sources merit order[6].
- **Total system costs**, including all the energy, operation and maintenance, and investments, per annum or at the end of the time horizon.

5.6 Assumptions and considerations when using TIMES.

As in all models, there are some considerations and assumptions to be made. It is important to recognise these assumptions and particular characteristics in order to understand better the capabilities and limitations of TIMES, and to interpret the model results. Some of the main TIMES considerations and assumptions are:

- The objective function is designed to minimize total cost (or the equivalent: maximize net social surplus).
- It is a demand driven model, represented in physical units (other models can represent demand in monetary units).
- The demand is given exogenously.
- Price-elasticities can be implemented for end-use demands.
- A perfect market is assumed:
    - perfect competitions among suppliers;
    - there is perfect information and forecasts are perfect;
    - there are no entry barriers;
    - buyers are rational;
    - etc.
- Technologies are selected optimally from the perspective of total system cost.
- The study time horizon is modelled with representative time slices, grouping similar hours, days and months, and not all years or hours are individually modelled.
    - The non-modelled years and hours are considered to be equal to their respective representative.
- Input data gaps are filled by extrapolating or interpolating values linearly.
- Other assumptions are captured within the values chosen for exogenous variables:
    - demographic and economic development;
    - technology evolution;
    - deployment and policy decisions;
    - etc.

Note that a discussion of some of the implications of key assumptions (e.g. exogenous demand or perfect market assumption) is developed is section 8.

5.7 Energy efficiency modelling in TIMES

In TIMES, energy efficiency measures can be mainly implemented by technology substitution, changing a process or technology for a more efficient one. Looking at the energy system diagram Figure 10, most possible substitution technologies fall in the energy conversion stages (supply and end-use sides, blocks 3 and 5), and to a lesser degree in the extraction, production and transport processes (block 2). In addition, there are some "energy conservation" technologies modelled in TIMES that would simulate energy efficiency measures. For instance, loft insulation and other building envelop technologies.

Figure 17 shows an example of how these two energy efficiency options are modelled in TIMES. On the one hand, the energy efficiency by technology substitution can be seen in the grey upper block, where technology 1 can be directly substituted with technology 2, that uses the same input fuel but it is overall more efficient. Conversely, the substitution

[6] Ranking of energy supply sources, based in their marginal costs. The generators with lower marginal costs are used before those with higher costs.

could be done with technology 3 that uses a different input fuel but also presents better performance than technology 1. The selection between technology 2 and technology 3 would be based on investment costs and fuel costs. On the other hand, the energy efficiency by energy conservation technologies is shown in the lower grey block in Figure 17. As mentioned before, demand is exogenous in TIMES, so the energy conservation measures cannot directly change the demand, which will be the case in a real scenario (implementing loft insulation in a building, for instance). Therefore, the energy conservation technologies are modelled in TIMES as other energy conversion technologies but without an input commodity. The "production" of these energy conservation technologies will reduce the production of other conversion technologies for the same end-use service demand, simulating the outcome of a real implementation.

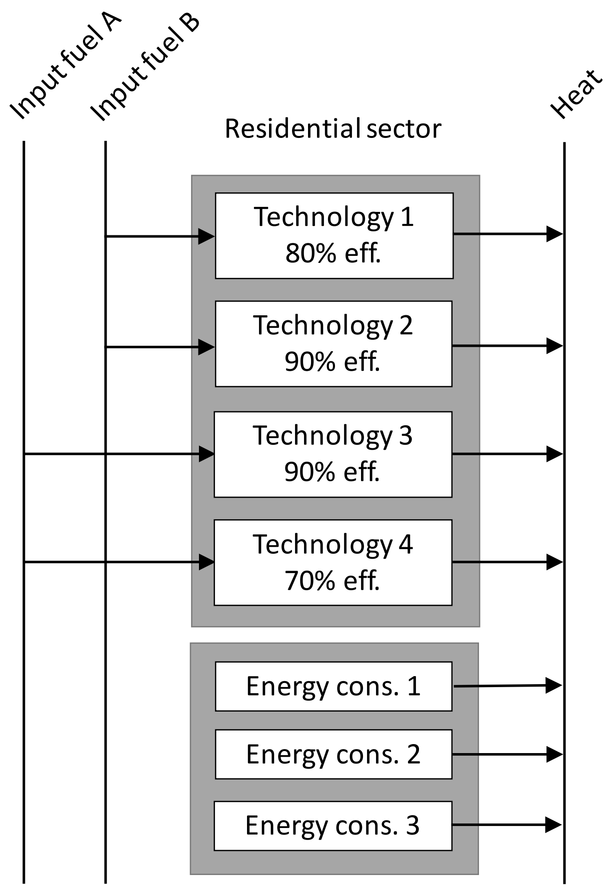

Figure 17. Example of energy efficiency modelling in TIMES.

Note that in TIMES, certain processes of the energy system do not have any option of technology substitution, and thus, energy efficiency measures cannot be directly implemented. For instance, the distribution and transmission networks in TIMES have a fixed efficiency. These processes can be expanded if needed, but there is no other technology that could substitute them directly. However, energy efficiency could be introduced in these processes in two ways:

- directly, by modelling an alternative in TIMES (e.g. a new more efficient distribution process that could be available from certain year); or
- indirectly, by replacing some of the energy that goes through that process with a different technology that does not require it (e.g. distributed generation).

The former option would require modifications to the TIMES model. The latter option, even though it could potentially improve the efficiency of the transmission and distribution processes, might be less efficient from an overall perspective. Hence, such an approach should be carried out with caution. Lastly, Figure **18** summarizes the potential energy efficiency options modelled in TIMES for the whole energy system. High energy efficiency options mean that there are several technology substitution possibilities for most of the processes considered. Medium energy efficiency options means that not all process considered at that stage have technology substitution options, but others do. Low energy efficiency options mean that the processes at that stage have very limited (if any) technology substitution options.

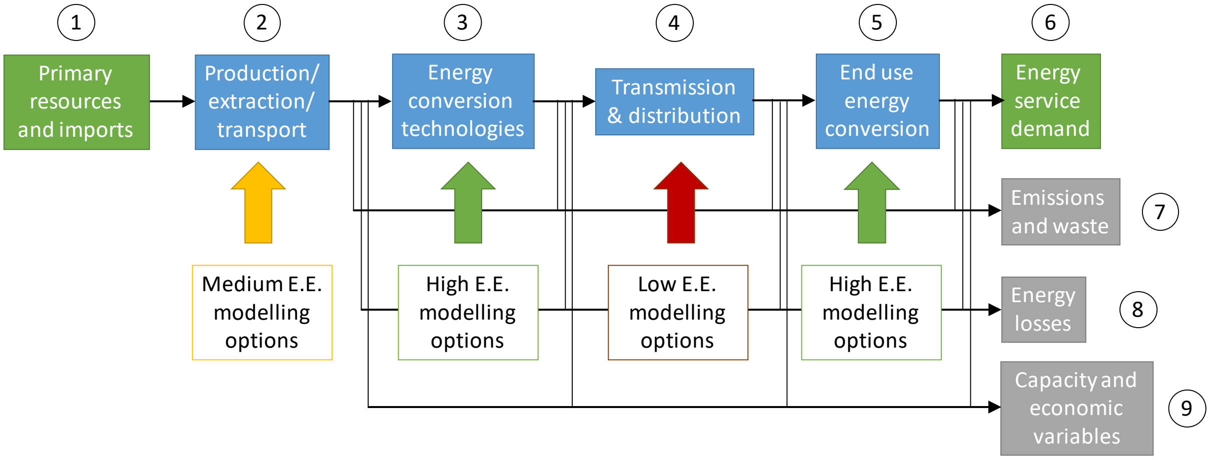

Figure 18. Energy efficiency (E.E.) options in TIMES at the different energy system stages.

5.7.1 Creation of energy efficiency scenarios in TIMES

Many types of scenarios can be modelled and analysed in TIMES. Unfortunately, the creation of energy efficiency scenarios is not straightforward in TIMES. In other words, it is not possible just to set a 10% energy efficiency constraint. Therefore, energy efficiency scenarios in TIMES are normally modelled by:

- setting a fuel cap; or
- setting a minimum use for a more efficient technology.

However, both cases might generate undesired outcomes.

The fuel cap does not necessarily translate to more efficient technologies or energy conservation measures; it might just represent a change of energy carrier to be used with potentially less efficient technologies. Taking the example of Figure **17**, if the current heat technology is technology 1, setting a cap on the input fuel B could make a substitution to a more efficient technology, such as technology 2, and/or to implement an energy conservation technology. However, it could also be that technology 1 is substituted with technology 4, which is less efficient but uses a different fuel technology, complying with the fuel cap. In this second case, the “energy efficiency constraint” would actually result in higher energy consumption.

Setting a minimum activity for energy efficiency technologies might be an adequate alternative to the fuel cap, as it forces TIMES to be more energy efficient. However, the adoption of a more efficient technology, when it does not occur naturally (due to its profitability), might give unrealistic technology adoption scenarios. Therefore, it is important to analyse and compare different energy efficiency scenarios in TIMES to assess if the results align with potential policies and provide reliable outcomes.

5.8 TIMES application example: decarbonisation pathways

A typical TIMES application example is presented in this section, showing some of the potential uses and capabilities of TIMES, and analysing some representative results. This example is a case study using the UK TIMES model, analysing a GHG reduction scenario: 80% emission reduction by 2050, in comparison with 1990 levels. Note that the Scottish TIMES model is not available to us yet. However, case studies such as this one, or others directly focusing on energy efficiency, can be developed for testing initially in the UK model over the next 6 months of the project.

Two scenarios were run with UK TIMES: a low GHG emission scenario, constraining the maximum emissions for the whole energy system, and a base scenario (business-as-usual) without any emission constraints. For both cases, the same exogenous values were considered (demand and international price projections, techno-economic parameters, etc.)

Note that there is a very large quantity of results provided by TIMES. For the sake of brevity, only some representative results are briefly reviewed here. Also note that these results are for illustrative purposes only. The results considered are:

- Evolution of the GHG emissions of the different sectors
- Electricity and gas consumption changes (per sector)
- Example of technology changes in a particular sector (residential heat)

Figure 19 shows the GHG emissions by sector from 2010 to 2050. The colour code in the figure is solid lines for the base scenario (labelled BASE) and dotted lines for the low emission scenario (labelled LOW_GHG), and all sectors have different colours. For instance, the industrial sector emissions are in grey colour, in the base scenario (IND_BASE) is a solid grey line, and in the low emission scenario (IND_LOW_GHG) is a dotted grey line.

Figure 20 shows a direct total emissions comparison between both scenarios. This figure was created to complement Figure 19, and to help the reader in looking into the GHG emission differences per sector.

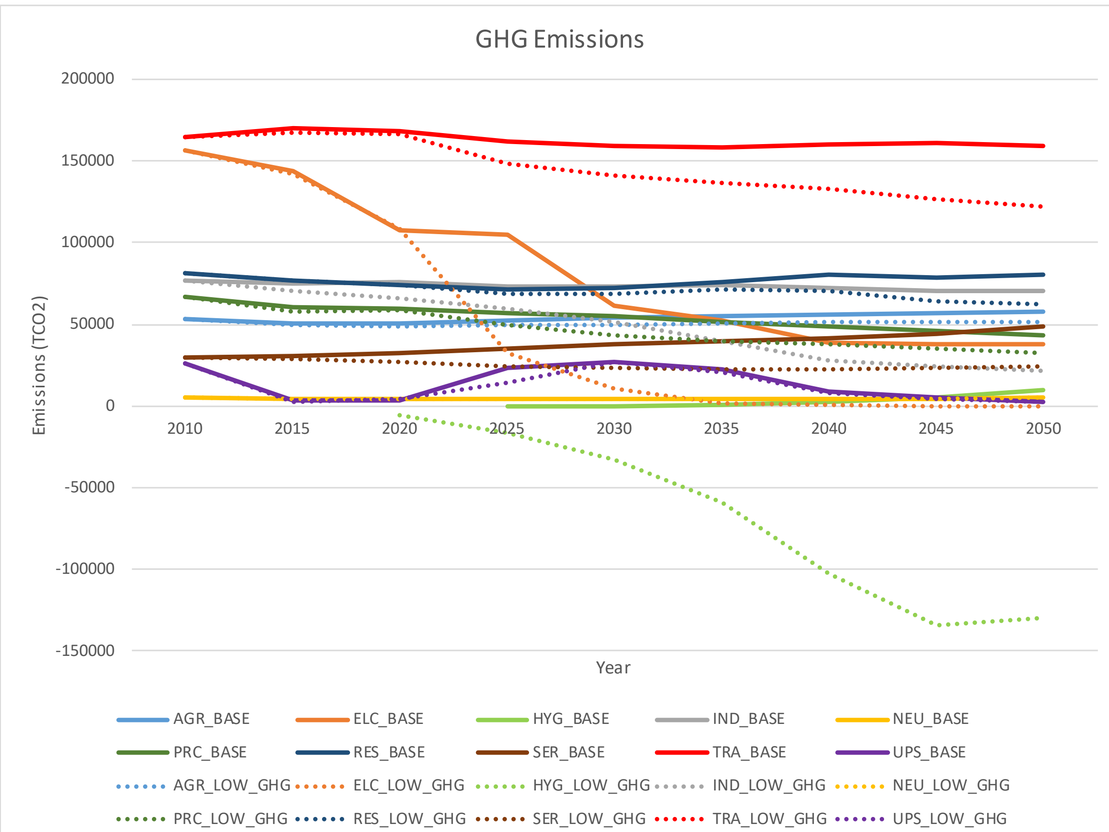

Figure 19. Total GHG emissions by sector.

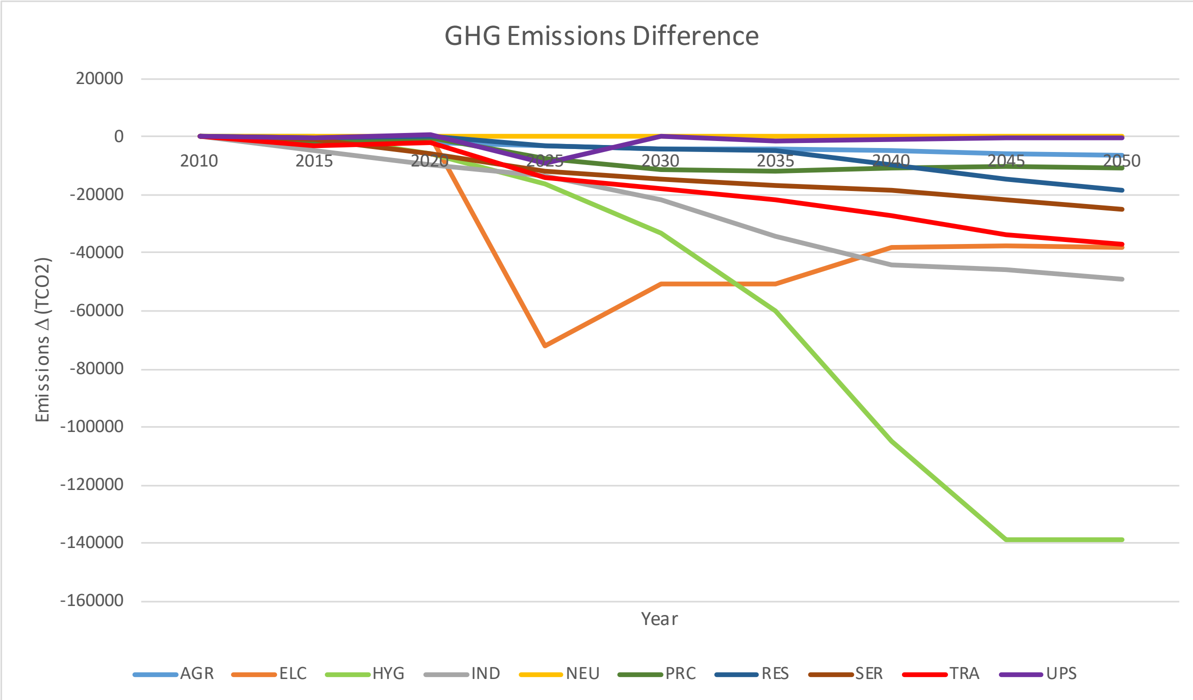

Figure 20. GHG emissions difference between scenarios (LOW_GHG - BASE).

Comparing the emissions in both scenarios, it can be seen that the largest change appears with hydrogen (light green, see Figure 19). In the base scenario, the hydrogen sector appears from 2025 but it does not seem to have any important changes until 2050 where it increases slightly. Conversely, hydrogen is the base of the decarbonisation pathway in the LOW_GHG scenario, with important negative reductions (suggesting that hydrogen production uses CCS), starting from 2020. The other sectors also present significant emission reductions, especially transport (red), industry (grey) and electricity (orange). Note that the electric sector also presents important reductions in the base case, but in the LOW_GHG scenario it reaches almost zero emissions by 2030.

The electricity end-use (after distribution) is depicted in Figure 21. It can be seen that agriculture (AGRELC, in light blue) and industrial (INDELC, in light green) sectors do not change their electricity use significantly. However, the residential (RESELC, in yellow), services (SERELC, in dark blue) and transport (TRAELC, in red) present considerably usage increments from 2030 – 2040 until the end of the analysis.

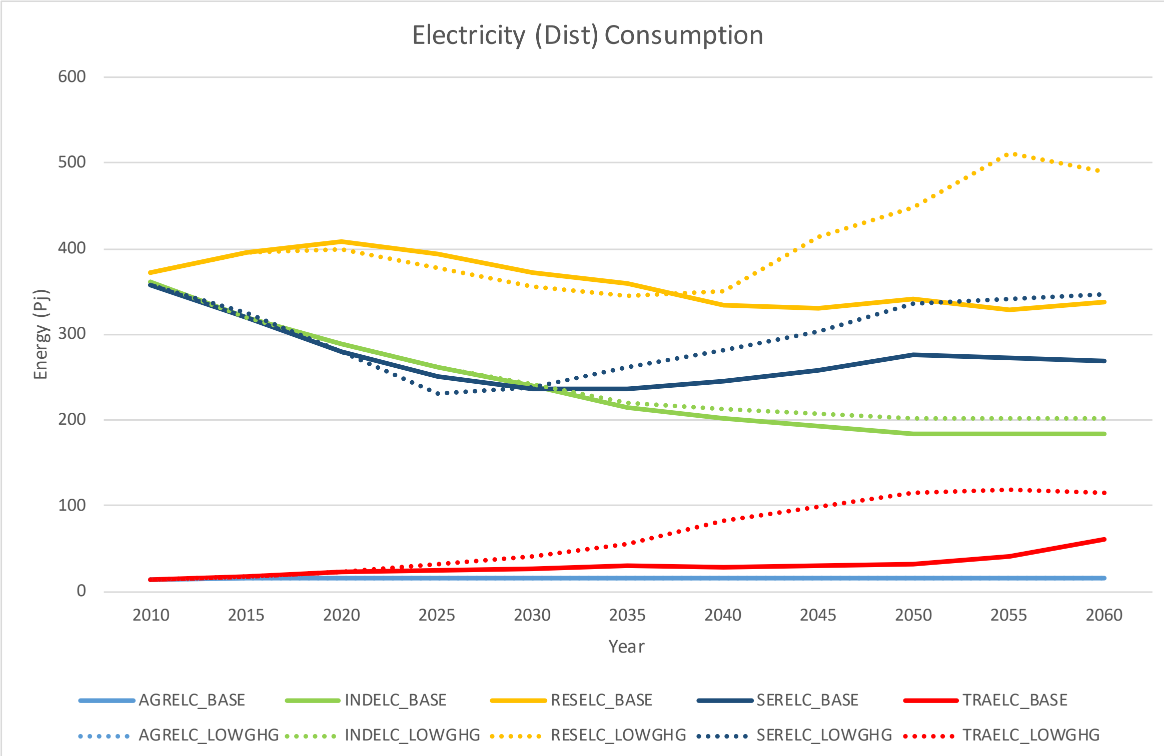

Figure 21. Electricity consumption (from distribution grid) by sector.

Figure 22 shows the gas end-use (after distribution) by sector. It can be seen that the residential (RESGAS, in dark green) and services (SERGAS, in brown) sectors start decreasing gas usage from 2020, which corresponds to some extent with the electricity use increase (see Figure 21), suggesting that there is a substitution between these two energy carriers. Other interesting outcome is the use of gas in the transport sector (TRAGAS, dotted line in purple), which was not used in the base scenario. This implies that conventional fuels (petrol and diesel) are partly substituted with gas and electricity.

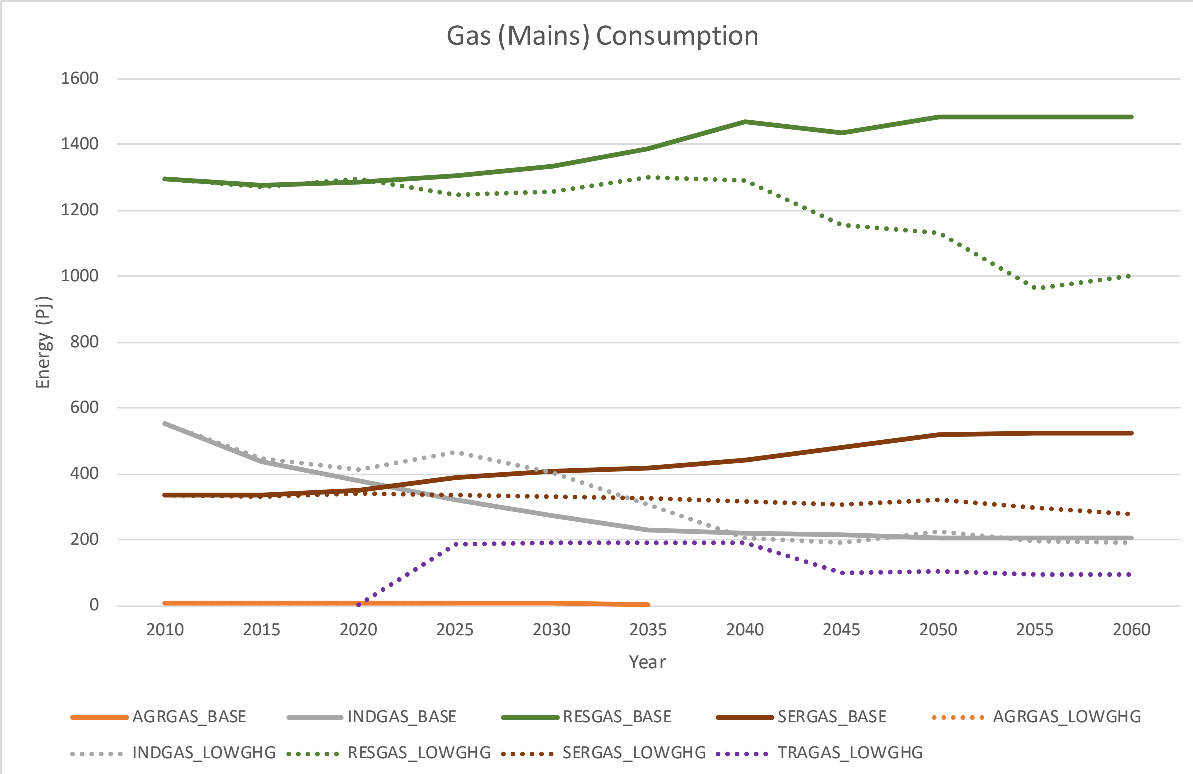

Figure 22. Gas consumption (from distribution grid) by sector.

The evolution of residential heat technologies for both existing and new houses can be seen in Figure 23 and Figure 24, respectively. On the existing houses, it can be seen that, for both scenarios, at 2010 the main heating technology is the gas boiler (yellow lines, see Figure 23), and slowly changes to CHP (orange lines, see Figure 23). In the case of the LOW_GHG scenario, the CHP is less used from year 2040, as the use of HP (dark green) also increases.

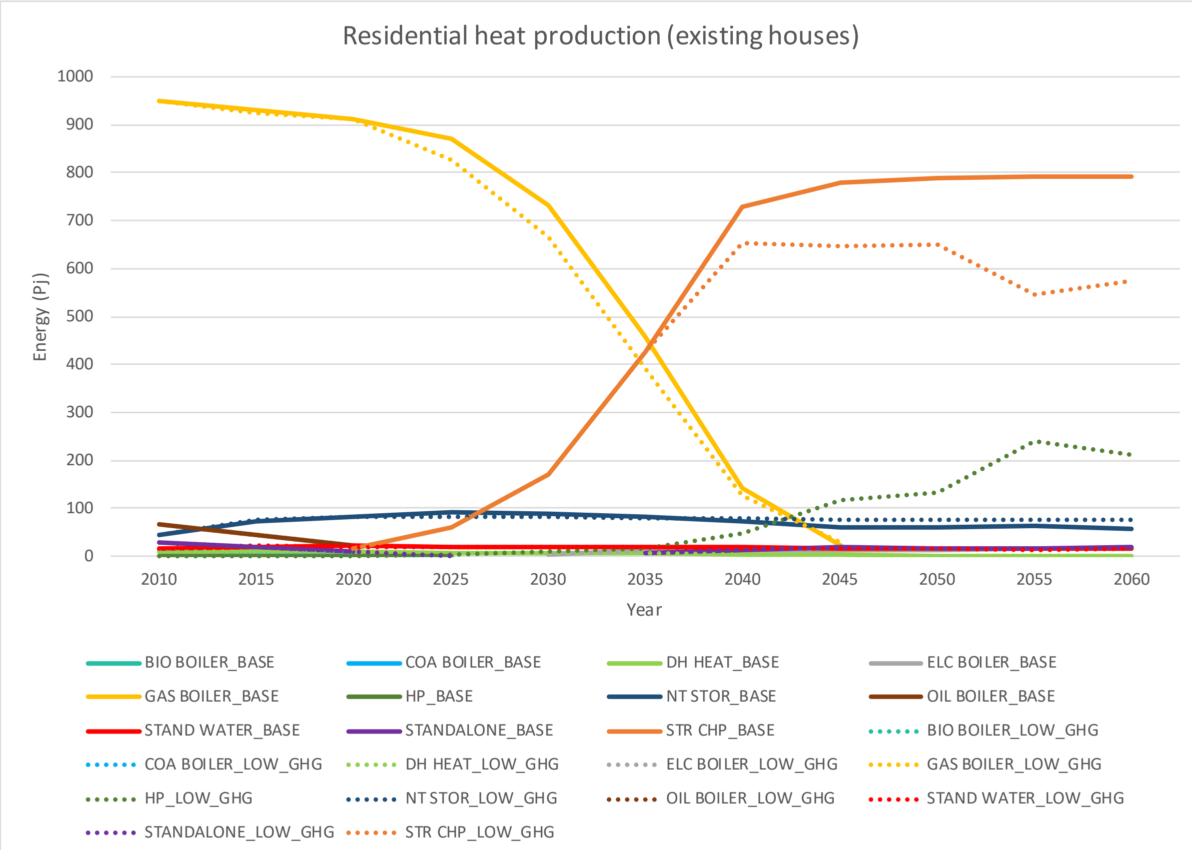

Figure 23. Residential heat production by technology (existing houses).

The heat technologies in new houses (Figure 24) follow a similar trend to the existing houses in the base scenario, where the main technology is the gas boiler (light green) and it is slowly substituted with CHP (dark blue). However, in the LOW_GHG scenario, such substitution does not appear, and the gas boiler continues to be the main heating technology (dotted light green line) complemented with district heating (DH HEAT_LOW_GHG, in red). The rest of the technologies do not evidence significant changes.

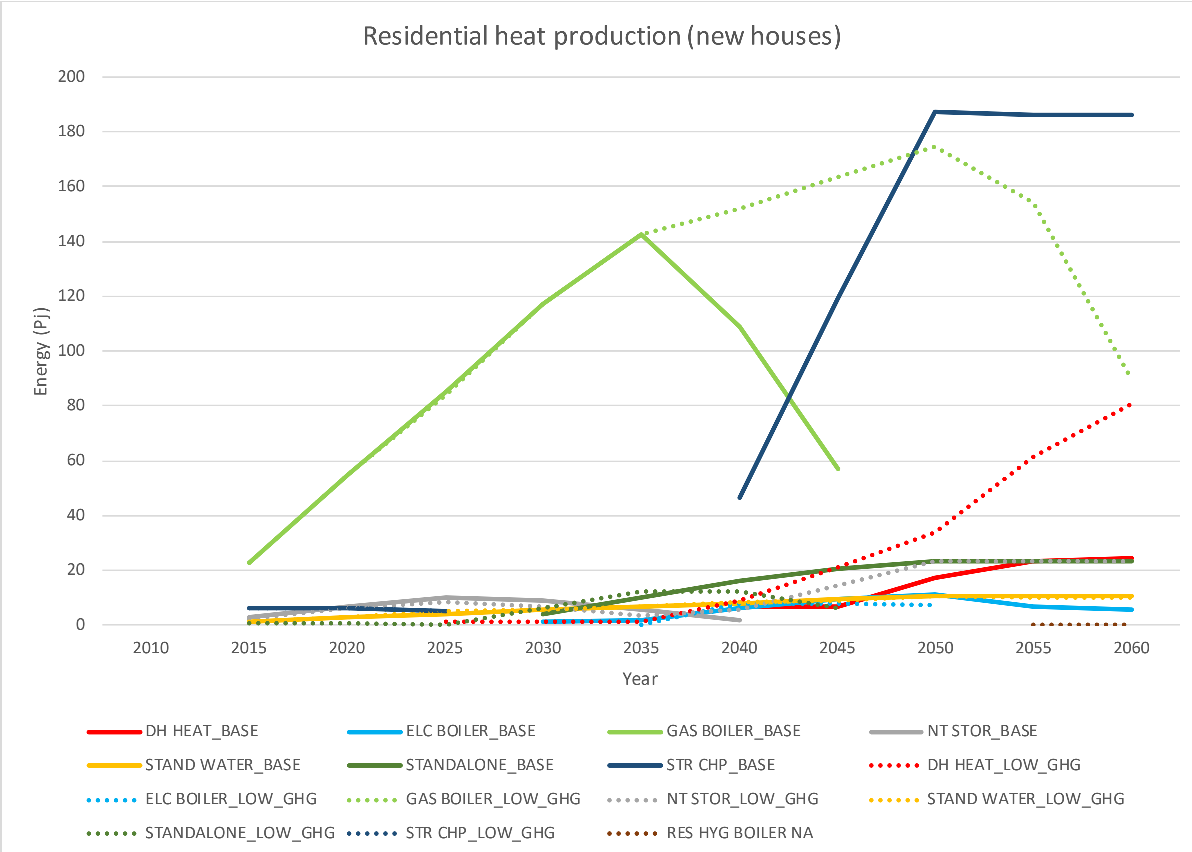

Figure 24. Residential heat production by technology (new houses).

Once again, this example has been presented to get insight on the possible information that could be obtained in TIMES. For instance, the sector contribution on different metrics such as emissions (as in Figure 19) or costs; the energy flows by sector, including generation and use (as in Figure 21 and Figure 22); or the technology adoption and use (as in Figure 23 and Figure 24). The obtained results can assist policy makers in finding:

- Which sectors require more attention
- Which energy carriers seem more promising
- Which technologies are the most cost-effective
- Potential costs and benefits

With this insight, policy makers can take more informed decisions to achieve their targets.

6. Review of energy efficiency related research in TIMES and further developments of the model

This is a brief literature review related to TIMES model applications, where issues associated with evaluation of energy efficiency measures or interventions are highlighted. Also, examples of further developments and improvements of TIMES are reviewed.

As remarked in (Connolly et al., 2010), there are over 100 country versions of TIMES and considerably more related studies. Hence, the review of TIMES applications presented here does not try to be exhaustive, but to provide insight on the typical uses and the type of research developed related to TIMES.

6.1 Exploratory studies using TIMES

Most of the literature found presents some sort of exploratory analysis using a particular version of TIMES. These research works are commonly used in a particular country/region context to achieve a particular goal (such as finding the carbon reduction pathway in Portugal for 2050 (Amorim et al., 2014)). Examples of such analyses are provided below. Note that most research works focus on the exploration of technology adoption and emission reduction scenarios (climate policy support), and even though energy efficiency is not normally considered as one of the targets for the studies, it is implicitly considered and measured in most analyses.

An example of an energy efficiency focused analysis is reference (Blesl et al., 2007), where the authors use TIMES to examine the impacts of additional efficiency improvement measures on the German energy system in terms of energy savings, technological development, emissions and costs. Energy efficiency scenarios are modelled by limiting the average fuel consumption of all technologies in the same sector, to provide the required energy services. Results of the energy efficiency scenarios show that the residential sector offers the largest relative benefits of CO2 reduction and cost savings, mainly through substitution of conventional gas or oil boilers by condensing gas boilers. The transport sector, on the other hand, CO2 reduction is the most expensive, using bio-fuels and methanol to achieve the efficiency targets.

A different energy efficiency policy approach is presented in (Shi et al., 2016), the impact of technical progress (improving energy efficiency) and the use of renewable energy in the Chinese building sector are analysed using TIMES (China version). This study presents four scenarios considering different levels of insulation improvement and renewable technology penetration (such as solar heaters) in the building stock (i.e. these scenarios include the energy efficiency measures in their demand projections). The authors conclude that the energy saving potential in 2050 can be up to 4EJ (around 10% of total residential demand) due to the improvement of building insulation and heating technologies.

TIMES-based analysis has also been used to investigate technology adoption and emission reduction scenarios. For instance, in (Weilong et al., 2014), a study is presented to evaluate the potential role of Carbon capture and storage (CCS) in China's power sector under carbon emission reduction scenarios. The authors use the China TIMES model (with the standard TIMES exogenous demand variables) and consider all energy sectors. The authors conclude that, under a rigorous carbon mitigation scenario, there is a widespread deployment of CCS technologies, nuclear and renewable energy in China's power sector. In particular, CCS will be an important technology option on China's power sector after 2030.

Another study is developed in (Simoes et al., 2015), analysing how specific assumptions (such as demographic and economic development, technology evolution and deployment and policy decisions) influence the outcomes of climate policy scenarios, considering the assumptions separately, instead of together as usually done in the literature. In other words, this study assesses the uncertainty of the results according to the assumptions taken in TIMES. In this case, the authors use TIMES_PT (Portugal) version, considering all energy sectors and the standard TIMES variables. The authors conclude that, contrary to what might be expected, the assumptions on the availability and price of energy resources do not represent important variations on GHG emissions in the modelling outcomes (less than 2% of the Baseline scenario emissions in 2020). The more relevant assumptions to overall uncertainty are related to socioeconomic development (macro-economic and population growth, with up to 9% change of the Baseline scenario emissions in 2020), followed by assumptions on end-use technology deployment (related to energy efficiency and technology adoption), with 2.5% change from the Baseline scenario emissions in 2020.

6.2 Research on further development of TIMES

Another target of many research efforts is the improvement of TIMES model, creating new variants to fulfil certain gaps or add new modelling features. Examples of such research work are presented below.

Reference (Daly et al., 2014) presents a methodology for incorporating competition between private cars, buses and trains in a least-cost linear optimisation model extension for TIMES. This variant includes model choice and investments on transport systems as endogenous variables, and travel time constraints as exogenous variables. Both transport choices and travel time are new features to the standard TIMES model, where typically each travel mode is given certain demand and switching between modes is not an option. Using the Ireland and California TIMES versions, results show that with no travel time constraint, the model chooses public transport exclusively (the model would choose the most efficient and cheapest mode, which means buses in both Ireland and California.) However, with a travel time constraint, mode choice is determined by income and investment cost assumptions, and the level of CO2 constraint, giving a more balanced share between cars, buses and trains. The authors conclude that the considerations presented are important to achieve realistic technology adoption scenarios.

Similarly, in (Cayla and Maïzi, 2015), a modelling approach is developed within the TIMES model framework, to take household behaviour (household daily energy consumption and equipment purchasing behaviour) and heterogeneity into account, stating that, in current TIMES models, this is not adequately modelled (representing energy demand by a single mean household with the same typical behaviour). The version of TIMES used is the French one, and focuses on transport and residential sectors. The authors conclude that due to the highly disaggregated representation of households and their behaviour in the model, the problem of unrealistic technology diffusion pathways could be avoided, remarking that technology adoption is very different in the original model in comparison with the proposed one. In the mean household model, only one technology is diffused at each time period (all households have the same attributes in the mean household model). 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. On the other hand, the proposed TIMES variant can have several different technologies at each time period, responding to energy and technology prices in a more realistic way.

Another example can be found in (Merkel et al., 2014), where the authors state that standard TIMES does not allow for an appropriate implementation of residential heat systems, as it does not consider the indivisibility (referring to the fact that for electricity different systems provide peak, mid-peak and off-peak heat load, which is not normally the case for heat) and exclusivity of heating systems (one system per household and not connected to others). Hence, an extension of TIMES is proposed to accurately model the capacity planning of residential heat supply systems, by modelling the indivisibility and exclusivity of heating systems. Using the German TIMES version, the results obtained show a very different technology adoption from the standard TIMES model in comparison with the proposed one. In the standard TIMES, one technology is used for over 2/3 of the total heat demand and a second technology takes the remaining demand, and the selection of these technologies remains for the complete time period (up to 2050). Conversely, the proposed TIMES version has 3 main technologies sharing the heating demand, and these technologies evidence an evolution over time, presenting new technologies by the end of the study.

The work presented in (Fais et al., 2016) develops a new methodology feature into the UK TIMES model, to incorporate a process-oriented modelling approach for the industrial sector. The objective is to assess the UK industry potential contribution to system wide targets on long-term emission reduction, energy efficiency and renewable energies. According to the authors, the problem with current bottom up energy models, such as TIMES, is that the industrial processes are commonly based on energy services and end-use demands. This means that instead of representing the industrial production steps and the actual technologies used to achieve the final product, the energy service demands and their provision from different fuels are represented in a generic and aggregated manner (like low or high temperature heat, motor drive, drying, etc.), usually specified in units of useful energy.

Hence, a new more detailed process-oriented modelling approach is developed to substitute the conventional aggregated service demand approach. With this new development, the technology options that can be implemented to improve the energy efficiency include:

- Exploitation of already commercial energy efficient or less carbon-intensive technology options (for example, a stronger switch to the electric arc furnace steelmaking route, the use of pre-calciners and kilns with increased waste utilisation in cement production or auto thermal reforming in ammonia production).
- Improvements of already installed processes (for example, heat recovery in different sectors, scrap preheating in electric arc furnaces or online moisture management in the paper industry).
- More radical processes changes (for example, low carbon cement options, alternative steelmaking routes or Fischer–Tropsch processes in steam cracking).

It is remarked by the authors that the new process-oriented modelling approach can identify crucial emission mitigation options, such as CCS technologies, and when comparing this results with previous UK MARKAL outcomes, the contribution of the industry in the decarbonisation of the energy system has clearly increased.

Also, studies using the TIAM (TIMES Integrated Assessment Model) are presented here. The TIAM model has a very similar structure to TIMES, but with a stronger focus on the energy resources in the up-stream sector. However, the main difference is that energy demands in TIAM are endogenous, and can be modelled as functions of several exogenous drivers such as GDP growth, population growth and sectoral outputs; or also considering the endogenous variables of price and price elasticities (Føyn et al., 2011). In other words, TIAM could be considered as an extended version of TIMES.

The authors in (Føyn et al., 2011) present a global climate change analysis using the TIAM global energy system model, testing it to see if it is possible to reach a global 100% renewable energy system with the existing model database. The main conclusion obtained is that the climate change target of 2ºC is possible to reach, but it will be expensive. Also, the high economic growth scenario used in the current TIAM version makes it hard to reach a 100% renewable system.

Another example of using TIAM can be found in (Selosse and Ricci, 2014), where TIAM-FR (France) is used to evaluate the possible deployment of BECCS (bioenergy with carbon capture and storage) in the power sector. The authors modified the multi-region model TIAM-FR to include a wide variety of CCS technologies on coal, gas, co-combustion of coal and biomass, and biomass power plants. Results of the study suggest that BECCS technology offers an environmentally and economically viable option to achieve stringent targets. On the other hand, the regional analysis shows that industrialized countries will develop CCS (carbon capture and storage) mainly on biomass power plants while CCS on fossil fuel power plants will be widely deployed in China.

7. Review of soft-linking approaches with TIMES

Examples of research studies linking TIMES with other models are reviewed here. The main motivation of linking with other models is to enhance and add value to the results of the TIMES modelling (Deane et al., 2012). In particular, linking with other models is commonly carried out to address issues related to the use of exogenous variables, and to add detail to parts of the energy system where the modelling approach used in TIMES might be insufficient. These issues and how they are addressed with soft-linking are described in more detail below.

According to (Labriet et al., 2015), there are different methodologies to couple TIMES with other models. From these options, linking models by the exchange of data (soft-linking) is the most common as it requires minimal modification. In soft-linking, the two models are run independently, exchanging data, until convergence according to a predefined criterion.

7.1 Studies linking TIMES with power system models (PLEXOS)

Examples of research linking an energy system model (such as TIMES) with a power system model (PLEXOS in this case) are presented next. PLEXOS is a power systems modelling tool (includes both electricity and gas modelling) commonly used to determine power systems investments and/or the least cost unit commitment and dispatch, respecting generator technical-economic constraints (Deane et al., 2012). Note that one of the biggest differences between TIMES and PLEXOS is the higher level of detail provided in the latter (time slices of 1 hour or less, and representing the whole year), making it possible to represent many of the technical constraints of the power system, which cannot be implemented on TIMES (the time management of TIMES is described in section 5.3). Figure 25 shows an example of the typical methodology for TIMES-PLEXOS soft-linking (taken from (Deane et al., 2012)). Note that, although the soft-linking examples presented here are with the PLEXOS model, the approach would, in principle, be similar for other power system models, such as the Scottish Electricity Dispatch Model (SEDM) (see for example (Pennock et al., 2016)).

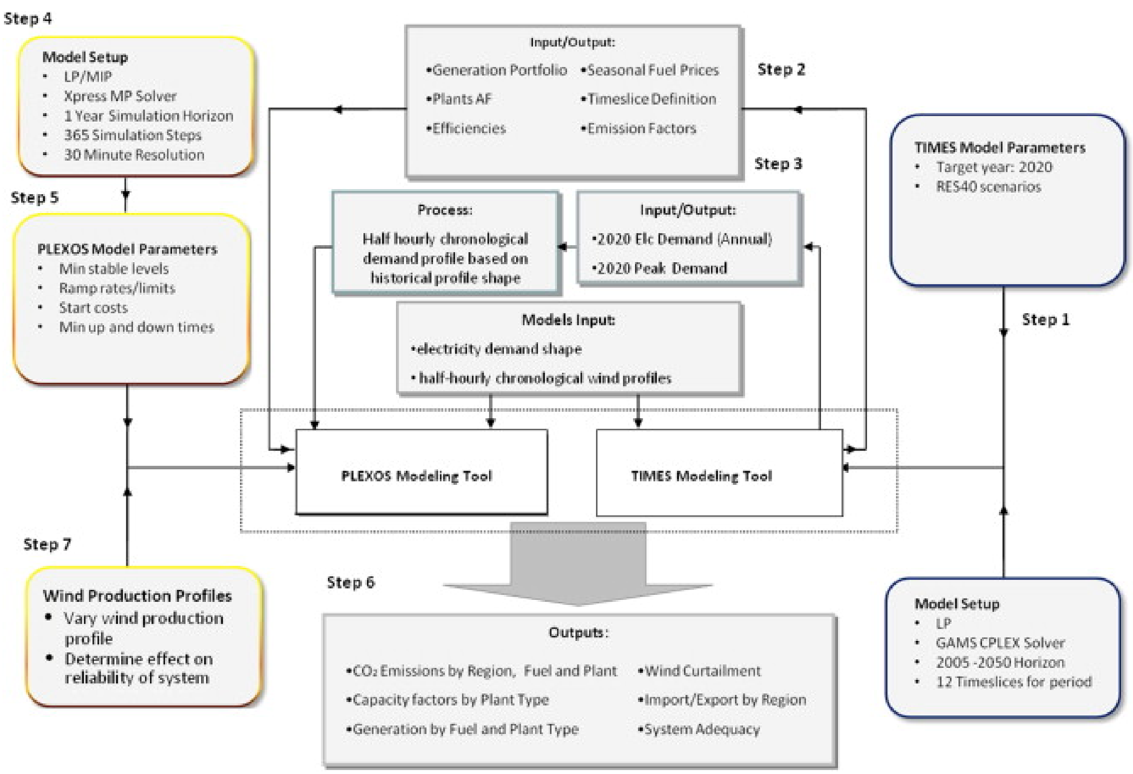

Figure 25. Flow chart of TIMES-PLEXOS soft-linking methodology (Deane et al., 2012).

One such linking exercise is presented in (Deane et al., 2012), where the Irish-TIMES model is used. The soft linking methodology proposed consisted of taking the TIMES generation portfolio output, including energy prices and demand, and input them into PLEXOS (modelling the Irish power system), and then comparing the results. For the reviewed scenarios, the unit commitment and dispatch of the different generators could vary up to 20% between TIMES and PLEXOS. These results suggest that in the absence of key technical constraints (such as spatial and network issues), an energy system model, such as TIMES, can potentially undervalue flexible resources and storage, underestimate wind curtailment and overestimate the use of baseload plant.

Another example can be found in (Deane et al., 2015b). In this case, MONET (a six-region TIMES model of the Italian energy system) is linked to the power systems model PLEXOS_IT, with the objective of investigating energy security issues within power systems. The analysis provided focuses on the Italian power sector, and the soft linking methodology is similar to the one previously described (the TIMES output of generation portfolio, including energy prices, import/exports, and demand are used as inputs for PLEXOS). Two main outcomes are reported in this study: firstly, the increasing need for flexibility in the Italian system due to larger penetration of variable energy systems; secondly, results show reasons for concern about the adequacy of the Italian energy system to provide the right incentives to investors, towards optimal capacity expansion plans. These concerns, according to the authors, are mainly due to the high price volatility present with large variable energy resources scenarios.

A different approach is adopted by (Welsch et al., 2014), where an extended version of an open source energy system model (OSeMOSYS) is examined and compared with an Irish case study (TIMES and PLEXOS). The proposed OSeMOSYS model is modified so it can be able to capture operating reserve and related investment requirements. Results of the enhanced OSeMOSYS model converge to results of TIMES and PLEXOS: Investment mismatches decrease from 21.4% (before the modification) to 5.0%. The authors also remarked that when short-term variability of supply and demand was ignored, power system investments in 2050 were found to be 14.3% lower. This might imply that energy policies derived from such long-term models may underestimate the costs of introducing variable renewables.

In (Deane et al., 2015a) some other examples of soft-linking TIMES-PLEXOS exercises are presented. For instance, the soft-linking of a TIMES model (Irish-TIMES) to a power system (PLEXOS) and a housing stock model (ArDEM) to explore the impacts of increased electrification of residential heating on the power system and associated emissions from the residential sector. Under this setting, the Irish-TIMES model is used to assess the full energy system of Ireland under an emission mitigation scenario. PLEXOS is then used to examine the impact and technical appropriateness of the heating requirement for the target year (2020). The ArDEM archetype dwelling model is used to determine which type of houses should install heat pumps, and the number of dwellings that could be served, considering the amount of heat energy supplied. The outcomes of this study suggest that electrification reaches a level of approximately 914 ktoe (10.6 TWh) by the year 2020. This represents the heating requirements of approximately 817,000 dwellings, and it is produced mainly through direct electric heating and heat pumps. These new technologies mostly displace oil and coal based systems. Note that, although the impact on electricity generation capacity and operation is addressed in the study through the soft-linking approach, the impact on the electricity network (due to the electrification of heat) was not covered, as this is rarely modelled within PLEXOS.

7.2 Studies linking TIMES with CGE models

This section presents a different multi-model approach considering the linking of bottom-up energy system models such as TIMES, coupled to top-down computable general equilibrium (CGE) models, considering the whole economy. According to (Glynn et al., 2015a), the rationale behind linking energy systems models with macroeconomic models is to include the feedback effects between energy cost and energy service demands. This coupling enables analysis of heterogeneous sectoral dynamics that energy systems models on their own can only approximate with elastic demand.

The example provided in (Labriet et al., 2015), uses the soft-linking methodology for TIAM-WORLD model and GEMINI-E3, which is a global multi-regional CGE ("GEMINI-E3 | EPFL," n.d.). The GEMINI-E3 model receives data from TIAM-WORLD on energy and CO2 prices, technical progress on energy use (energy mix) and capital consumption, while TIAM-WORLD receives sector economic production data (macro-drivers, such as GDP or industrial outputs) to recalculate energy service demands. The authors report that convergence is typically achieved in 6 iterations for the analysed climate constrained scenarios. Also, it is reported that the differences in sectoral emissions between TIAM-WORLD used in a standalone manner and the coupled models are smaller than 5 % over the model time horizon. This result suggests that the inter-sectoral effects of climate policies have little effect on overall aggregated sectoral emissions.

A similar example is shown in (Dai and Mischke, 2014), using a modified version of the global TIAM model to introduce three sub-regions of China, linking it to the global Asia-Pacific Integrated Modelling/Computable General Equilibrium (AIM/CGE) model. This CGE model is also expanded from the one region dynamic country model to a global one that represents 30 provinces of China and several regions of the world. The objective of this analysis is to explore different energy and economic development scenarios up to 2050, concluding that energy consumption and emissions are decreasing in China until 2050 while important regional differences within China (East, Central, and West) continue to exist.

In (Glynn et al., 2015a), other examples of world models linked to CGE models are described. For instance, TIAM-ECN (developed by Energy research Centre of the Netherlands) and the global macro-economic model E3ME (developed by Cambridge Econometrics ("E3ME," n.d.)) are linked in order to enhance the energy and economic analysis capabilities focusing on Latin American energy topics. Energy sector results (capacity, production and economic outputs) from TIAM-ECN are processed and input to E3ME, contrasting the outcomes of the independent and the coupled models. The authors remark that the consequences of increasingly higher carbon prices in terms of reduced consumer spending and GDP are linear in the CGE models; but divergent and non-linear in the soft-linked modelling approach. This is something to consider when doing future projections.

A regional assessment of different energy policy scenarios in Portugal is developed in (Fortes et al., 2014), using the integrated technological, economic modelling platform (HYBTEP), built through the soft-link between TIMES and GEM-E3 (General Equilibrium Model for Economy, Energy, Environment) models. The soft-linking consists of the TIMES_PT providing the configuration and the evolution of energy costs for the Portuguese energy system, which is taken as input for GEM-E3_PT. The CGE model in its turn, defines the configuration of the national economic structure, driving the energy services demand for TIMES_PT. In this Portuguese case study, results show that the economic framework in HYBTEP partially offsets the increase or decrease in energy costs from the policy scenarios (reducing uncertainty), while TIMES is very sensitive to energy services-price elasticities, setting a wide range of results (less reliable results).

A similar study is developed for South Africa in (Arndt et al., 2016). In this case, the South African TIMES model (SATIM) (using only the power sector module) is coupled to the South African General Equilibrium (SAGE) model, with the objective of analysing the implications of (i) a carbon tax, (ii) liberalization of import supply restrictions in order to exploit regional hydropower potential, and (iii) a combined policy where both carbon taxes and import liberalization are pursued. The proposed methodology consists of SATIM computing an optimal 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 authors conclude that a regional energy strategy, based on hydropower, represents a potentially inexpensive approach to decarbonizing the South African economy.

Other soft-linking efforts focusing on regional analysis are summarized in (Glynn et al., 2015b). For instance, there are ongoing developments of hybrid models TIMES-CGE in the Scandinavian countries (Norway, Denmark and Sweden). Unfortunately, (and to the best of our knowledge) there are not particular applications of these models published in the literature yet.

Lastly, a different analysis is carried out in (Bye et al., 2016) where an energy efficiency study is developed using TIMES-Norway and the CGE model SNoW (Statistics Norway World model). The focus of the study is to analyse and compare the results of both models in a scenario where the residential heating service demand is reduced 27% by 2030 (in comparison with 2010). Note that this paper does not implement a soft-linking approach, but contrast the results of both models, providing an interesting analysis. As expected, the target reduction was achieved by the models in very different ways:

- In SNoW, almost all the reduction takes place reducing the household energy demand, through energy efficiency measures. In this model, besides the heating target (27% reduction), electricity use also exhibits a decrement of 10% (in comparison with the base year 2010).
- In TIMES-Norway, the reduction is achieved by replacing heating technologies with heat-pumps and other more efficient systems (replacing the old ones). For this model, the heating target is achieved, but the electricity demand at the end of the study remains practically equal (in comparison with 2010), which is attributed to the electrification of heating.

The authors remark that these outcomes are heavily affected by the structure of the models and the assumptions made. On the one hand, the substitution of technologies is not a straightforward option in SNoW. Therefore, the decision was to reduce demand within the CGE model. On the other hand, all the demands are exogenously given to the TIMES-Norway model, and thus, for this particular study (and version of TIMES) it is not possible to change the demand and the only option was to invest in new technology replacing older systems, or improving the housing energy performance.

Also, the authors state that, despite best efforts on improving the models to better approach reality, there are still differences and the results should be taken with caution. Finally, the authors conclude that, considering the strengths, limitations and important differences between models, policy makers should not rely in a single model to decide on important energy efficiency policies.

7.3 Challenges in soft-linking of models

From the research reviewed in this document, several challenges in the soft-linking of models were identified. Three main difficulties seem to appear more regularly:

- **Data aggregation and timeframes**. Models normally have different time horizons and/or time slices that require the extrapolation or interpolation of results from one model to the other. Also, even if less common in the soft-linking between TIMES and CGE models, data aggregation could represent a problem when an aggregated outcome needs to be disaggregated to be input in another model. For example, the annual energy service demand of residential electricity (a single value) needs to be disaggregated into the time slices considered in TIMES: different seasons, type of day (working days and weekends) and time of the day (morning, evening, night).
- **Model fitting**. Commonly, the two soft-linked models are based on two different statistical databases (for instance, national accounts versus energy statistics). Hence, when identifying connection points, several overlaps and mismatches could appear and some "conversion" step needs to be carried out.
- **Common scenario assumptions**. This seems to be obvious but is not always evident. As mentioned in the previous point, models could be created with different databases. Therefore, a crucial step to achieve consistency among the models is associated with the definition of common scenario assumptions (e.g. fossil fuel import prices, interest rates, energy constraints and policy assumptions).

8. Discussion of strengths and limitations of the TIMES model

Many strengths and limitations of TIMES for energy policy analysis have been identified in the literature. The most relevant ones are described in this section.

8.1 TIMES Strengths

There are many elements that could be considered important features in TIMES, especially those referring to technical modelling. Some of the most relevant TIMES strengths identified are:

- scope: system-wide energy model;
- technology rich with detailed GHG emission modelling;
- long-term horizon;
- cost driven (allows the least cost energy system to be found that complies with a given set of constraints);
- relatively flexible
  - user constraints (possibility to create multiple scenarios); *and*
  - time slices, and time horizon; and
- linear programming problem
  - gives an optimal solution; and
  - relatively fast to solve (UKTM runs in 5 – 7 mins on a standard desktop PC).

The **energy system-wide scope** has been recognized in the literature and in policy contexts (for instance, in the draft climate change plan (Scottish Government, 2017a)) as one of the most important characteristics of TIMES, as it allows the intersectoral dynamics of the energy system to be captured. Similarly, the **richness of technology options** across all the sectors in the energy system allows for better analysis of possible technology and fuel substitution (i.e. the model has multiple options to choose from to meet the energy service demands in a cost-effective way), and to assess the impact of new disruptive technologies. In addition, the **long-term horizon** of the model gives valuable insight on energy roadmaps to achieve climate change and other long-term targets.

TIMES model is **cost driven**, which allows the least cost energy system to be found according to certain constraints. In systems as complex as the energy one, there are a multitude of options to achieve policy targets, such as emission reduction. Therefore, it is important to obtain the solution that will reach the desired target at the minimum possible whole energy system cost.

Another important characteristic of TIMES is its **flexibility**. Unfortunately, the internal code is not available to the user, but the modelling of commodities and processes is very flexible, allowing the user to add, remove or modify technologies and commodities as required. Also, the system settings, including time slices and time horizon, can be modified to tailor the analysis to user's requirements, and user constraints can be included to create a great variety of scenarios.

Lastly, it is important to remark that TIMES is modelled as a **linear programming problem**. This is not a trivial feature, considering the scope and size of the model (hundreds of thousands of variables and constraints). A linear problem can be solved exponentially faster than a non-linear or mixed-integer one. For instance, running a scenario in UKTM takes 5 – 7 minutes, which is a reasonable time if many runs are required to analyse different scenarios. Furthermore, a linear programming problem gives you a global optimal solution all the time, which is not the case in a non-linear problem, possibly falling in a local optimum (sub-optimal solution). Note that, in order to be linear, several modelling simplifications had to be taken in TIMES (see section 8.2 for a more detailed discussion of the simplification problems in TIMES).

8.2 TIMES limitations

Despite the many strengths of TIMES, there are certain characteristics that might not be well represented in the model and that are relevant for energy policy analysis. Note that there are some general modelling "problems" that are not particular to TIMES but apply to any model, that should be taken into account. For instance: **high dependency on data**, and **modelling compromises** (Mancarella et al., 2016).

TIMES, as with many other models, requires a large quantity of historic data and forecasts. The model results are as good as the quality of the fitting data and the data assumptions (exogenous variables such as demand projection). In other words, particular attention should be paid to the quality of the data used on the model, to have more confidence in the results.

Similarly, all modelling tools such as TIMES, present modelling compromises. By definition, all models are an abstraction of reality, an approximation, and the more complex the real system, the more compromises you need to make in order to keep it practical (to be of a manageable size, solved in a reasonable time, etc.). For instance, all the non-linear behaviours of technologies and systems in TIMES have been linearized (e.g. performance of generation technologies, such as CHP) to have an easier to implement and faster model, sacrificing detail. These modelling compromises are unavoidable, but it is important to understand their existence to make a better assessment of the outcomes (i.e. do the compromises still allow for sensible results?).

Focusing on more particular issues for energy policy analysis in TIMES, some shortcomings have been identified in the literature and in the analysis developed throughout this document:

- Energy efficiency implementation is not straightforward.
- Decisions are cost driven:
    - Market "problems" and other drivers for consumer behaviour are not captured.
    - Cost minimisation algorithm would lead to corner solutions (extreme specialisation), if not prevented by user determine constraints (e.g. on shares of technologies).
- Level of detail on the modelling of certain elements:
    - Lack of heterogeneity on the demand side.
    - Oversimplification of technologies.
    - Coarse representation of different time periods and the relationships between them.
- Exogenous demand.
- Wider economy impacts are not modelled.

Energy efficiency in TIMES is mainly modelled by technology substitution. However, not all processes in TIMES present an alternative technology (e.g. transmission and distribution processes), so energy efficiency measures cannot be directly implemented. Moreover, energy efficiency scenarios are mainly implemented with fuel caps or minimum technology adoption (to replace less efficient technologies), but as discussed in section 5.7, these approaches might deliver undesired outcomes.

In section 6.1, it was mentioned that one of the strengths of TIMES is that **decisions are made based on economic values**, allowing the model to find least cost solutions. However, this is also a modelling problem as, in reality, not all decisions are based solely on economic factors (substitution between certain energy services and technologies is not well modelled). In short, technology adoption is based on economic benefit, overlooking other important factors for stakeholders, such as social benefits. Similarly, it has been discussed in (Bye et al., 2016) and in (Turner et al., 2017) that there are market entry barriers (or the lack of a market altogether) for certain technologies and/or measures, such as energy efficiency in buildings, even if those measures are profitable from an economic point of view. These modelling issues could provoke dramatic technology changes, which translate to unrealistic technology adoption scenarios. An example of this effect is shown in (Daly et al., 2014), where the authors state that if the selection of transport mode is only based on costs, everyone will travel by bus, which is a very unrealistic scenario.

TIMES models a very large number of technologies and processes. However, there are certain elements that might not be modelled with the adequate level of detail, leading to a potential oversimplification. Demand in TIMES is largely disaggregated (e.g. residential energy use is disaggregated in dozens of technologies and end-use services), but in many cases **the demand lacks heterogeneity**. For instance, in a typical TIMES model, residential demand is based on the behaviour of one representative household, assuming that all residential consumers will follow that "typical behaviour" (Cayla and Maïzi, 2015). This approach produces "one-size-fits-all" policy solutions that might present real-life delivery problems and sub-optimal outcomes.

A different problem appears with the potential **oversimplification of technologies** in certain sectors, in particular, by aggregating different processes and technologies as a single commodity, or not considering relevant technology characteristics. An example of the former is that industrial processes in TIMES are represented in a generic and aggregated manner based on energy services, instead of process-oriented modelling (Fais et al., 2016). An example of the latter is that the indivisibility and exclusivity of residential heating systems is not well represented (Merkel et al., 2014). According to these authors, the oversimplification can produce unrealistic technology diffusion pathways or undervalue the impacts of certain technologies (such as CCS). Nevertheless, it is important to remark that adding extra detail to the model might not represent an “improvement”. Adding deeper and more sophisticated representations of certain sectors could potentially bias the model results. Hence, there is an important consideration that any changes within the model itself should respect the broader design and goal of TIMES and adhere to the model paradigm.

The relatively **coarse representation of time periods** in TIMES allows the model to do long-term analyses while still capturing, to some extent, seasonal, weekly and intraday dynamics. However, it does not allow for fine detail and to include some key technical constraints. For instance, storage, i.e. the ability to shift demand from one period to another, is not well represented and some power plant technical constraints are not considered (ramping, start up, down time, etc.) (Deane et al., 2012). Also, the Short-term variability of supply and demand is ignored, which might produce a suboptimal unit commitment and investment planning, compromising security of supply. As remarked by (Deane et al., 2012), TIMES can potentially undervalue flexible resources and storage, underestimate wind curtailment and overestimate the use of baseload plant. Similarly, (Welsch et al., 2014) mentioned that energy policies derived from such long-term models may underestimate the costs of introducing variable renewables.

As described in section 5, **demand is exogenous** in TIMES. (Glynn et al., 2015b) remarked that it is important to analyse the feedback effect between energy cost and energy service demands, as it is unrealistic to think that the demand won’t respond to changes on prices. Indeed, TIMES can model a certain elasticity, but this is a limited approximation, not considering the implications of other sectors of the economy. Moreover, in an energy efficiency policy context, “energy efficiency” measures normally relate to both:

1. efficiency, meaning the number of units of energy required to deliver a certain end service; and
2. conservation, meaning the reduction or avoidance of a certain end service.

The latter is closely linked different social and economic factors within the wider economy, something that the treatment of demand in TIMES as an exogenous factor cannot capture. The former is better captured in TIMES. However, there are some modelling limitations as described in section 5.7.

In addition, **wider economy impacts** are not modelled in TIMES. This is an important issue for policy makers, as changes on the energy system impact other sectors, and extra costs/benefits of energy policies might be overlooked. For instance, energy efficiency has been argued to produce rebound effects (Turner, 2009), which are not captured by TIMES. Also, energy efficiency produces economic, health and social benefits outside the energy system (Turner et al., 2016).

8.3 Possible solutions for TIMES shortcomings

TIMES, like any other model, is not perfect. TIMES presents several opportunity areas, as shown in section 8.2. Nevertheless, several solutions have been proposed to fix or mitigate these problems, which can be classified in three groups:

- Artificial constraints (based on assumptions)
- Further developments in TIMES
- Soft-linking with other models

User defined “artificial” constraints are commonly used in TIMES to avoid the unrealistic technology adoption scenarios, produced by energy efficiency constraints (see section 5.7.1), economic driven decisions, market problems, or technology oversimplification. Taking the example of transport mode choice, to avoid the whole of demand going to a single transport option, a constraint is implemented to set minimum technology shares (e.g. 20% bus, 20% train, 50% car, 10% others). Also, these kinds of constraints are used to avoid dramatic technology changes in a short period of time, which could happen when, according the input cost data, there is one overall better technology available, setting a maximum level of technology adoption at each time period (e.g. 20% max. penetration by 2020, 50% by 2030, 100% by 2040). Certainly, these constraints are commonly used in TIMES to achieve more realistic technology pathways, with the drawbacks of not letting the model freely find the optimal technology mix, and the dependency on assumptions and projections that might heavily influence the model outcomes and be sensitive to even very small differences between options ('penny switching'). Hence, these types of artificial constraints should be actively considered, especially when affecting important investment decisions or security of supply. However, these constrains should be considered separately from outputs (i.e. avoid imposing constraints because the answer is not 'satisfactory') and imposed consistently across all sectors/technologies. Therefore, when trying to interpret results, the existence of such constraints should be clearly acknowledged and the sensitivities to changes in their values tested[7].

Many research works about **further developments in TIMES** can be found in the literature (see section 6.2). In many cases, these new features deal with the cost driven problems, substituting the artificial constraints previously described. In other words, these new modelling developments "bring other factors into the equation" and let the model decide on the optimal technology mix, producing more realistic technology adoption paths. For example, in (Daly et al., 2014) travel mode choice and travel time constraints are included in TIMES. With this new development, the transport mode is not purely based on economic factors, representing reality more accurately.

Other modelling problems such as the lack of demand heterogeneity or the oversimplification of systems can also be dealt with new TIMES developments. For instance, more heterogeneous demands with different purchasing behaviours can be added as in (Cayla and Maïzi, 2015), and the oversimplification can be addressed by improving the technology modelling approach, such as heating systems (Merkel et al., 2014) or industrial processes (Fais et al., 2016).

The exogenous demand issue has also been addressed in TIAM (TIMES Integrated Assessment Model), which could be considered as an extended version of TIMES. Energy demands in TIAM are endogenous, and can be modelled as functions of price and price elasticities (endogenous variables), or several exogenous drivers such as GDP growth, population growth and sectoral outputs (Føyn et al., 2011). Indeed, TIAM is an interesting solution to simulate better the demand feedback of the energy system. However, the demand elasticity can only approximate other relevant economy effects (Glynn et al., 2015a).

Lastly, the coarse modelling of time intervals and lack of more detailed modelling, which do not allow consideration of short-term variability of supply and demand and some key technical constraints, can be solved by **soft-linking with other models**. For example, the soft-linking of TIMES with a power system model, such as PLEXOS, has often been described in the literature, e.g. (Deane et al., 2012). Similarly, the wider economy effects, particularly important in assessing the efficacy of energy efficiency measures, can be considered by soft-linking TIMES with CGE models. This TIMES-CGE setup enables the analysis of heterogeneous sectoral dynamics and economic feedback (Glynn et al., 2015b). In addition, it allows for better data projections to be made, and provides a better representation of consumer choices, obtaining better and more accurate overall results (Glynn et al., 2015a).

[7] One way in which this might be done could through inspection of which constraints are 'binding' and the 'shadow costs' associated with relaxation of different constraints.

9. Plans for further use of TIMES in energy efficiency analysis

For a policy analysis perspective, TIMES is a very powerful tool that could be used to support decision making. In section 8, some of the main strengths and limitations of TIMES have been summarised, also commenting on possible solutions to improve or mitigate the modelling shortcomings. In this section, the possible TIMES uses and ways to go forward are described, and can be grouped as:

- Using TIMES as it is
- TIMES improvements
- Soft-linking with other models
  - Power system models (e.g. PLEXOS or SEDM)
  - Economy models (CGE)
  - Transport models
  - Heat system models
  - Agriculture models
  - Etc.

Note that there is not a single "right way" to proceed, as it depends to a significant degree on the intended goals of the analyses to be carried out.

9.1 Use TIMES as it is

Using TIMES without further modification can be seen as the easiest approach from which rapid results can be gained. The reason is that the current version of TIMES can deliver reasonable outputs and useful insight. However, any limitations of TIMES should be taken into account (see section 8.2) when interpreting the results.

Recommendations for energy efficiency analysis:

- This should be considered as the first step in energy efficiency analysis.
- The results should be seen as providing approximate numbers and rough pathways, instead of the absolute right energy system.
- Due to the previously mentioned limitations and the dependency on the quality of input data, it is important to run multiple scenarios and conduct sensitivity analysis, especially in respect of any artificial constraints that have been introduced and the potential for different energy efficiency measures to change demand, and contrast the results before taking decisions.
- Analyse if there is any particular area that requires more detail, according to the particular energy system under consideration:
  - E.g. very heterogeneous industry or residential sectors, might require different energy efficiency policies. Therefore, more detail modelling of these demands in TIMES could be necessary.
  - In effect, this analysis provides the motivation for identifying areas where improvements in TIMES are likely to significantly enhance our understanding of energy efficiency policies.

9.2 TIMES improvements

The literature review presented in section 6.2 shows that there are many potential improvements for TIMES. Some of these developments might require relatively little time and resources to implement (e.g. more heterogeneous residential demand), while others will require important changes on the model structure and data, which could be difficult to get and/or time consuming to implement. Hence, an assessment of the potential benefits in relation to the required resources for a TIMES improvement must be done beforehand, as it might be more convenient to rely on soft-linking with other models.

Recommendations for energy efficiency analysis:

- Implementing improvements in TIMES is potentially a second step in the analysis of energy efficiency changes, one that is likely only to be feasible in the medium term.
- TIMES improvements are particularly interesting when the energy policies being analysed are targeting very specific sectors and/or technologies.
    - E.g. energy efficiency in the industrial sector might require a more detailed industrial process modelling approach, in order to obtain more accurate results (Fais et al., 2016).
- Demand heterogeneity could be very useful to implement, as it allows analysis of the effects of energy efficiency policies on different types of consumers. Also, this model improvement is relatively easy to develop (if the required data are available). For other improvements, it is necessary to assess if required data are available, and if they are, whether the time/effort required for implementation is adequately compensated by the benefits of the new modelling approach.
- Also, it is important to make sure that any improvements made do not bias the model (in in such a way as to generate the modeller's desired outcome).

9.3 Soft-linking with other models

The third set of options for energy efficiency analysis with TIMES is the soft-linking with other models. This solution can potentially give relevant and/or more accurate information that could be very difficult to get from TIMES alone (even when augmented by improvements), or as an alternative to model improvements that could potentially bias the outcomes. As shown in section 7, there are two typical types of models that have been soft-linked with TIMES: power system models (such as SEDM or PLEXOS) and economic (CGE) models. The former is very useful to contrast and compare power system results, to analyse security of supply issues and check the technical feasibility of a plan for electricity generation capacity and electrified heat and transport obtained with TIMES. The latter provides valuable feedback from the economy to the energy system, adapting the energy service demands, potentially producing more accurate results. Also, it allows an assessment of other economy-wide impacts and benefits that could be difficult to estimate otherwise (e.g. job creation). Note that the alternatives improve TIMES results in different ways and, thus, the selection of the soft-linking model should reflect the purpose of the analysis.

Recommendation for energy efficiency analysis:

- The soft-linking of TIMES with another model could be seen as a second (or third) step, after using TIMES alone, which could be developed in the medium term.
- The soft-linking with a power system model approach could be interesting to analyse the impacts of other policies closely related to energy efficiency, such as the decarbonisation (and electrification) of heating, or the wider introduction of heating networks in Scotland (see the energy plan strategy and the Scottish energy efficiency programme, described in sections 3.2 and 3.3, respectively).
- The soft-linking with a CGE model approach is very relevant for energy efficiency policy analysis, as many of the expected outcomes go beyond the energy system and impact on other important policy objectives such as reducing energy poverty, boosting economic activity and job creation. In addition, this setup explicitly models consumer and producer behaviour, which translates to more realistic technology adoption scenarios. In the context of liberalised energy markets, policy has to work through market mechanisms inducing changes in transaction behaviour (through changing incentives, for example). CGEs can help capture this key aspect of policy interventions.
- The soft-linking with a CGE model approach is very relevant for energy efficiency policy analysis, as many of the expected outcomes go beyond the energy system (e.g. reducing energy poverty, job creation, economy boosts, etc.). In addition, this setup better represents consumer behaviour, which translates to more realistic technology adoption scenarios.
- Note that the soft-linking process requires the management of an additional model and presents several challenges (see section 7.3). Nevertheless, considering the importance of the decisions to be taken, the potential benefits of soft-linking seem to be necessary for adequate policy making.

10. Conclusions

TIMES is a very useful tool, with many notable features, capable of a wide variety of analyses. However, it is not perfect (to be fair, there is no perfect model). Therefore, it is convenient to use TIMES for the type of analysis that take advantage its strengths but it should not be relied on too much for analysis where the limitations become more important. In other words, TIMES cannot answer all the questions but it can give very useful insights, not least in helping articulate more precise questions. For instance, good initial questions for TIMES could be: can our emission targets be achieved? What might the energy system look like? Do certain technologies seem to be critical to achieving targets?

Certainly, TIMES is a widely used model to analyse the energy system as a whole. However, a key limitation is that energy demands are treated as exogenous.

A particular focus for this work is the use of TIMES to aid the evaluation of policy options in respect of promoting energy efficiency and supporting the implementation of Scotland's Energy Efficiency Programme (SEEP). In this context, it is important to note a key distinction made by, among others, the IEA ("Energy efficiency," n.d.):

- Energy efficiency is delivering the same services with less energy input of more services for the same energy input.
- Energy conservation is reducing or not using a service to save energy.

A clear distinction between these two effects will be important not just for modelling and the setting of policy but also for measuring its effectiveness as a simple observation of reduced emissions in a particular sector. It will not, on its own, reveal whether it was due to improved efficiency or changes in the precise services sought and gained from use of energy.

Looking into SEEP delivery options (see section 3.3), centralized mandatory actions, like carbon taxes, can be easily modelled and analysed with TIMES[8]. However, the regional modelling in TIMES is limited and the locally delivered measures might not be well represented. Furthermore, the more free and flexible policies (e.g. change of appliances to more efficient ones) are difficult to analyse in TIMES in an appropriate way. It has been identified that, on the one hand, TIMES does not model consumer choice (besides economic benefit) very well, and on the other hand, There is currently no commercially viable market mechanism through which the scale of energy efficiency improvements and low carbon heat envisaged in the draft Energy Strategy seems likely to be delivered (Scottish Government, 2017c). A soft-linking approach with a CGE model could help address this problem, providing more realistic market and consumer behaviours, translating to better policy design.

In the Scottish context, the main possibilities for using Scottish TIMES for energy efficiency policy analysis are:

- In the short term, use TIMES as it is, and perhaps do small improvements, such as including demand heterogeneity.
  - There are many assumptions to be made (demand and population projections, technology prices, artificial constraints, etc.), so there is a need to ensure that those assumptions are well-thought through, realistic and clearly documented.
  - Run multiple scenarios, do sensitivity analysis and "control the things you can control", to get more reliable results.
  - These results could give insights into the potential impacts of policy interventions, and assist in the creation of general guidelines and targets for the policies.
- In the medium term, analyse the possibility of soft-linking with a Scottish CGE model (AMOS, for instance).
  - First, by running similar scenarios with TIMES and the CGE model independently, and contrast the results. A similar exercise has been developed by (Bye et al., 2016), remarking that the exercise provides insight on potential problems with the assumptions and the assessment of energy policy impacts.
  - Then, implementing a soft-linking approach. A feedback of the changes to the economy resulting from changes to the energy system should translate into better and more realistic TIMES results. Also, the wider impacts of energy efficiency policies can be assessed with the CGE model.

[8] At least from an energy system perspective. To fully analyse the effects in the wider economy, it will be needed the soft-linking with CGE models.

    - These results could assist in the design of more detailed policies, targeting (insofar as they are modelled in a whole economy model) different groups of consumers and selecting the best delivery options.
- Additionally, the possibility of soft-linking with a power system model (such as SEDM or PLEXOS) could also be considered.
    - Soft-linking with a power system model can give more accurate results on how energy efficiency measures and the decarbonisation of heat change the need of investments on energy generation capacity. However, what a power system model is able to say about network impacts depends very much on the model.
    - These results could help to identify areas or technologies that might need incentives to achieve the policy objectives of security of supply, while maintaining competitiveness.

Lastly, it is important to remark that one model is not enough to adequately test energy efficiency policies. For example, the TIMES modelling used in development of the draft Climate Change Plan and draft Energy Strategy has been complemented by separate housing, agriculture and transport modelling (Scottish Government, 2017b). However, TIMES limitations in energy policy analysis can be addressed in different ways (see section 8.3), with soft-linking with other models one of the most promising solutions.

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