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# Clearing the cloudy crystal balls: Hybrid modelling for energy and climate change mitigation scenarios

**– A case study for Portugal –**

Dissertação para obtenção do Grau de Doutor em Ambiente

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# ABSTRACT

Energy and greenhouse gas (GHG) emissions scenarios, generated by energy-economy-environment (E3) models, have been used to explore alternative futures and support energy and climate mitigation policy decisions. The uncertainty carried in these scenarios comes from inherent uncertainty of future conditions, reflected in the models input assumptions, and from the models intrinsic features (e.g. technology bottom-up vs. economic top-down models).

The present research aims to improve future scenarios generation for energy and climate policy analysis by advancing on E3 modelling, using the Portuguese energy system as the case study. Main objectives include: (i) the assessment on how uncertainty impacts climate-energy policy decisions, (ii) the integration of storylines with energy modelling, providing a coherent context to modelling assumptions; (iii) the development of an hybrid modelling platform, combining the strengths of bottom-up and top-down models.

Socio-economic driver was identified as a major assumption contributing to overall uncertainty on GHG emissions scenarios. Therefore, the socioeconomic storylines, built by stakeholders from different knowledge fields, were translated directly into energy modelling assumptions, which proved to increase the robustness of scenario development and its comprehensiveness.

Separate use of the bottom-up TIMES_PT and top-down GEM-E3_PT revealed different mitigation options, which have a significant impact on policy design (i.e., low-carbon technologies vs. end-use energy efficiency). In consequence, the hybrid-modelling platform (HYBTEP) was built through the soft-link between TIMES_PT and GEM-E3_PT, combining cost minimizing detailed energy technology choices with sector disaggregated macroeconomic responses, respectively.

The research also provides an empirical understanding of how to enable a low carbon transition for Portugal. According to TIMES_PT, it is technological feasible to reduce, in the long term (2050), the country's energy-related GHG emissions up to 80% below 1990 emissions, being renewable power generation technologies a key for decarbonisation. However, HYBTEP outcomes suggest that, with a carbon tax in line to what is projected at EU-wide level, the country do not accomplish such mitigation target, reducing just 47% its GHG emissions, associated with loss of gross domestic product (GDP) of around 2% (according to revenue-recycling scheme assumed). On the opposite, a subsidy to renewable energy revealed long-term positive impacts at both environmental and economic level (i.e., emissions reduction by 31% and GDP gains above 2.8%). These results highlights the relevance of addressing the impacts to economy while considering the most cost-effective technologies over the development of low carbon scenarios, which is accomplish by HYBTEP modelling platform.

**Keywords:** climate change mitigation, energy system, greenhouse emissions and energy scenarios, storylines, energy-economy-environment models, hybrid modelling.

# RESUMO

Cenários de energia e de emissões de gases com efeito estufa (GEE), elaborados através de modelos energia-economia-ambiente, têm vindo a ser utilizados para explorar futuros alternativos e apoiar decisões de política energética e climática. A incerteza associada a estes cenários resulta da incerteza das condições futuras, reflectida nos *inputs* de modelação, e das diferentes características dos modelos (tecnológicos *bottom-up* vs. económicos *top-down*).

A presente investigação pretende melhorar a elaboração de cenários utilizados na análise da política energia-clima, melhorando a modelação energia-economia-ambiente e utilizando o sistema energético Português como caso de estudo. Os seus principais objectivos incluem: (i) avaliação do impacto da incerteza na tomada de decisão das políticas climáticas/energéticas, (ii) integração de narrativas na modelação energética, proporcionando um contexto coerente para os pressupostos de modelação, (iii) desenvolvimento de uma plataforma de modelação hibrida, combinando as mais-valias dos modelos *bottom-up* e *top-down*.

A evolução socioeconómica foi identificada como o pressuposto que mais contribui para a incerteza geral nos cenários de emissão de GEE. Deste modo, foram construídas por *stakedolders* de diferentes áreas de conhecimento, narrativas referentes ao desenvolvimento socioeconómico, as quais foram traduzidas para os pressupostos de modelação, aumentando a robustez e a compreensão dos cenários.

A utilização do modelo *bottom-up* TIMES_PT e modelo *top-down* GEM-E3_PT separadamente revelou que os mesmos determinam diferentes opções de mitigação com impacte no desenho de políticas (i.e., tecnologias de baixo carbono vs. eficiência energética) Por conseguinte, foi desenvolvida da plataforma hibrida HYBTEP construída através de ligação dos modelos TIMES_PT e GEM-E3_PT, combinando respectivamente, escolhas tecnológicas detalhadas e associadas a uma minimização dos custos, com uma resposta macroeconómica sectorialmente desagregada.

Esta investigação apresenta também uma análise empírica relativa a uma transição de Portugal para uma economia de baixo carbono. De acordo com o TIMES_PT é tecnologicamente viável reduzir, no longo prazo (2050), as emissões de GEEE relacionadas com energia, até 80% abaixo das emissões de 1990, sendo as tecnologias renováveis de geração de electricidade um elemento chave para a descarbonização. Os resultados do HYBTEP sugerem contudo, que uma taxa de carbono em linha com o que é projectado a nível Europeu, não permite ao país atingir essa meta de mitigação, reduzindo apenas 47% as emissões de GEE associadas a uma redução do produto interno bruto (PIB) em cerca de 2% (de acordo com o sistema de reciclagem da receita considerado). Pelo contrário, um subsídio às energias renováveis revelou impactes positivos no longo prazo quer a nível ambiental, quer a nível económico (i.e., redução das emissões em cerca de 31% e ganhos no PIB acima de 2.8%).

Estes resultados ilustram a importância de determinar os impactos económicos considerando as tecnologias mais custo-eficazes no desenvolvimento de cenários de baixo carbono, o qual é possível através da utilização da plataforma de modelação HYBTEP.

**Palavras-Chave:** mitigação das alterações climáticas, sistema energético, emissões de gases com efeito-estufa, narrativas, modelos energia-economia-ambiente, modelação hibrida.

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# ABBREVIATIONS & UNITS

| | |
|---|---|
| BU | Bottom-up |
| CES | Constant substitution elasticity |
| CCGT | Combined Cycle Gas Turbine |
| CCS | Carbon capture and storage |
| CGE | Computable General Equilibrium |
| $CH_4$ | Methane |
| CHP | Combined heat and power |
| $CO_2$ | Carbon dioxide |
| $CO_2e$ | Carbon dioxide equivalent |
| CPV | Concentrated photovoltaic |
| CSP | Concentrated Solar Power |
| E3 | Energy-Economy-Environment |
| EC | European Commission |
| ETS | Emissions Trading Scheme |
| ETSAP | Energy Technology Systems Analysis Program |
| EU | European Union |
| FEC | Final Energy Consumption |
| GAMS | General Algebraic Modelling System |
| GDP | Gross Domestic Product |
| GEM-E3 | General Equilibrium Model for Economy–Energy–Environment |
| GHG | Greenhouse Gas(es) |
| GVA | Gross Value Added |
| IAM | Integrated Assessment Model(s) |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| MAC | Marginal Abatement Cost |
| MCP | Mixed Complementarity Problem |
| $N_2O$ | Nitrous oxide |
| Non-ETS | Emissions not included in the EU Emissions Trading Scheme |
| NEEAP | National Energy Efficiency Action Plan |
| NREAP | National Renewable Energy Action Plan |
| OECD | Organisation for Economic Co-operation and Development |
| ppm | parts per million |
| PV | Photovoltaic |
| RCP | Representative Concentration Pathways |
| RES | Renewable energy sources |
| RES-E | Renewable Energy Sources for Electricity |
| RES-H&C | Renewable Energy Sources for Heating and Cooling |
| RES-T | Renewable Energy Sources for Transport |
| SAM | Social Accounting Matrix |
| SRES | Special Report on Emissions Scenarios |
| TD | Top-Down |
| TIMES | The Integrated MARKAL-EFOM System model |
| TFEC | Total Final Energy Consumption |
| TPES | Total Primary Energy Supply |
| UNFCC | United Nations Framework Convention on Climate Change |

| | |
|---|---|
| °C | degree celsius |
| bbl | oil barrel |
| Gg | gigagram ($10^9$ gram) |
| Gt | gigatonne ($10^9$ tonne) |
| GW | gigawatt ($10^9$ watt) |
| GWh | gigawatt-hour ($10^9$ watt-hours) |
| Mbtu | million British thermal unit |
| Mt | Million metric tonnes |
| MW | megawatt ($10^6$ watt) |
| p.a. | per annum |
| PJ | petajoule ($10^{15}$ joule) |
| pkm | passenger-kilometre |
| t | tonne |
| tkm | tonne-kilometre |
| toe | tonne of oil equivalent |
| TWh | terawatt-hours ($10^{12}$watt-hours) |

# CHAPTER 1

## INTRODUCTION

*Limiting climate change will require large and sustained reductions of greenhouse gas emissions. We need to act now, otherwise we will jeopardize the future of our children, grandchildren and many future generations. Time is not on our side*

Michel Jarraud (Secretary-General of World Meteorological Organization) (2013)

Climate change is currently recognized as one of the major challenges of the 21st century. Its long-term impacts can affect the planet in a decisive way, changing the pace of economic activities, human well-being, available resources and ecosystems. The mitigation of greenhouse gases (GHG) emissions in order to avoid dangerous anthropogenic pressure on the climate system is consequently on the top of the political agenda. Several countries and regions have been setting mitigation targets, and defining GHG reduction policies and measures, mostly linked with their energy systems. Due to the uncertainty surrounding socio-economic and technological development, key drivers of GHG emissions, and the complexity of changing a country's energy system towards a low carbon future, decision makers are supported by scientific knowledge in the form of GHG mitigation and energy scenarios, which are used as inputs in the political debate.

*How much can we reduce our GHG emissions? What is the most cost-effective configuration of the energy system compatible with such mitigation target? What will be its costs and economic impacts? What is the effect of a particular policy instrument (e.g. carbon tax, renewable subsidy) on GHG emissions, energy system and economy?* These are just a few examples of the questions made by country's decision makers. Mitigation scenarios (frequently generated with mathematical models) are a common tool used for providing replies.

Not surprisingly, model-based scenarios present limitations due to the inherent uncertainty of future conditions translated in the model's input assumptions, e.g. socio-economic evolution. Moreover, frequently used modelling tools have different structures and characteristics, which can result in different answers. Model-based scenarios do not forecast the future, they only help to understand and explore it as "cloudy crystal balls".

The core motivation of this thesis is to contribute to the advance of model-based GHG mitigation scenarios by exploring the uncertainties associated with the modelling tools and their assumptions, analysing its relevance within the policy support framework and proposing methodologies to tackle those uncertainties – "clearing the cloudy crystal balls". Furthermore, by using Portugal as a case study, this dissertation explores alternative mitigation scenarios, providing insights on how the Portuguese energy system can shift towards to a low carbon configuration.

This chapter lays out the context and motivation of this dissertation, including a brief background information on the Portuguese energy system, used as a case study. Finally it specifies the dissertation objectives and outlines.

## 1.1 THE CHALLENGE OF CLIMATE CHANGE MITIGATION

It has become increasingly evident that the growth of carbon dioxide ($CO_2$) concentrations intensifies the greenhouse effect with the consequent gradual warming of the Earth's climate system. According to the Intergovernmental Panel for Climate Change (IPCC)[1], it is extremely likely (i.e., more than 95% certain) that the dominant cause of global warming since the mid-20$^{th}$ century are the cumulative concentrations of GHG produced by human activities (IPCC, 2013). Since pre-industrial times, anthropogenic GHG emissions have grown, with an increase of 75% between 1970 and 2010 (UNEP, 2012), i.e., 28.7 to 50.1 Gt $CO_2$ equivalent[2]. As a result, atmospheric carbon concentrations increased more than 100 parts per million (ppm) in comparison to its pre-industrial level, reaching in the last years the highest levels ever recorded (e.g. 416 ppm $CO_2$e in 2011 (EEA, 2014)).

Data on air temperatures at land and ocean surfaces show an average warming of 0.89° Celsius (°C) since the beginning of the 20$^{th}$ century and each of the last three decades has been successively warmer than any preceding decade since 1850 (IPCC, 2013). This has been leading to other changes on natural and human environment, changes in global water cycle, rising of sea levels, acidification of the oceans, reduction of snow and ice and alterations in the weather patterns, with an increase of extreme climate events. Agriculture and the respective food supply, freshwater, biodiversity and human health are just few examples of major systems under threats from climate change (a broad overview of climate change impacts and its effects in Europe, is given by IPCC (2007) and Ciscar et al. (2009), respectively).

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[1] IPCC is an international body established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) and endorsed by the United Nations General Assembly. Its mission is to provide a comprehensive view of the state of knowledge about climate change and its potential environmental and socio-economic impacts trough the compilation of scientific, technical and socio-economic information produced worldwide.

[2] Carbon dioxide emission equivalent is a common metric scale used to compare the emissions from various greenhouse gases based upon their global warming potential for a given time horizon (IPCC, 2013).

The impacts of climate change and the global concerns about them led countries to join an international treaty in 1992 – the United Nations Framework Convention on Climate Change (UNFCCC). Currently signed by 195 Parties, the ultimate objective of UNFCCC is to achieve the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (…) within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." (Article 2 of (UNFCCC, 1992)).

In 1997, the adoption of the Kyoto Protocol emerged as a first effort to limit global GHG emissions, becoming a milestone in climate change policy. As part of the Protocol, and recognizing that developed countries are the main responsible for the current high levels of GHG emissions, thirty seven industrialized countries and the European Union (EU) have agreed to legally-binding GHG emissions reduction targets. Globally, these represented up to an average of 5% reduction compared to 1990 levels over the first commitment period, 2008 to 2012 (UNFCCC, 2008). In 2012, the Kyoto Protocol was amended – the Doha Amendment – defining the commitment of thirty-eight countries to reduce its global GHG emissions by at least 18% below 1990 levels, in the period 2013-2020 (UNFCCC, 2013). However, due to the changes in the parties composition, this second commitment period covers a smaller share of global emissions (around 14-15%) than the first (EC, 2013). Moreover, the new amendment target does not represent a legally-binding mitigation goal as it is needed the acceptance by at least three fourths of the Parties.

The Kyoto Protocol is not the only instrument addressing specific climate change mitigation. Since the Copenhagen Accord (UNFCCC, 2009) and Cancun Agreements (UNFCCC, 2010), signed by the Parties of UNFCCC, the goal to limit average global temperature rise within 2 °C above pre-industrial level, to prevent "dangerous" climate change impacts, has been widely disseminated in the climate policy discourse and used to justify mitigation targets and inform policy making on adaptation (Jordan et al., 2013).

However, recent research suggests that many ecosystems are more sensitive to impacts at 2 °C of warming than previously assumed (Smith et al., 2009; Warren et al., 2013). Some parties, particularly the Small Island Development States and Least-Developed Countries, are already concerned about the fact that this threshold might be excessively high, claiming that local and regional impacts associated with 2 °C warming, namely sea-level rise, water stress and increased incidence and re-emergence of climate-related diseases, might exceed the adaptive capacity of their societies and actually jeopardize the sovereign existence of many small islands. The UNFCCC negotiations took these concerns into account in the Cancun Decision underlining the need to "strengthening the long-term global goal on the basis of the best available scientific knowledge, including in relation to a global average temperature rise of 1.5°C", in its review by 2015 (UNFCCC, 2010).

As part of the above-mentioned Agreements, countries have been announcing commitments on national and regional emission reductions. According to a wide range of studies, there is an emission gap between the 2020 emissions consistent with a "likely" (>66%) chance of meeting the 2 °C target, around 44 Gt $CO_2$e (41-47 Gt $CO_2$e), and the emissions estimated according to the national pledges – 55 Gt $CO_2$e within a range of 54-55 Gt $CO_2$e (UNEP, 2012). According to the last Emissions Gap Report of United Nations Environment Programme (UNEP), the range of 2020 emission levels implied by current pledges is more consistent with pathways limiting global temperature increase (with >66% chance) from 3 to 5°C above pre-industrial levels (UNEP, 2012). Figure 1.1 illustrates the gap between the pledges and the GHG emissions level that are "likely" to keep global warming below 2°C.

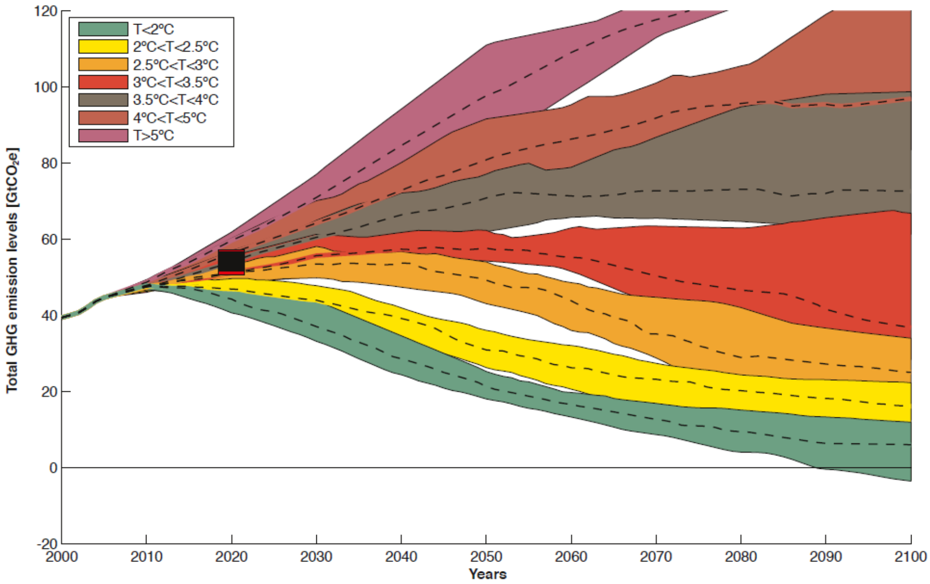


**Figure 1.1** | Emissions pathways and corresponding "likely" (66%) chance of staying in various temperature limits. Black box around 2020 indicates the emissions levels consistent with the current pledges. *Source:* UNEP (2012).

New economic developments, emerging technologies and data on environmental factors have motived IPCC to collect and set new emission scenarios (Moss et al., 2008). The Representative Concentration Pathways (RCPs) scenarios are supported by four radiative forcings[3] (RCP 8.5, RCP6.0, RCP4.5, RCP2.6) each exploring different levels of climate mitigation. RCP8.5 represents

[3] Radiative forcing is a measure of the change (expressed in $Wm^{-2}$) in the net balance between incoming and outgoing energy in the climate system. Due to changes in the atmospheric constituents, namely higher concentration of CO2, radioactive forcing has been increasing since pre-industrial levels, leading to the warming of Earth's climate system (IPCC, 2013).

the 90th percentile of the reference energy and industry $CO_2$ emissions range, while RCP2.6 represents pathways below the 10th percentile of mitigation scenarios, with the use of bio-energy and carbon capture and storage resulting in negative emissions (Moss et al., 2010). At present, emissions are tracking just above RCP8.5 (Sanford et al., 2014). According to IPPC (IPCC, 2013), global surface temperature in 2100 is likely to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6 and likely to exceed 2 °C for RCP 8.5 and RCP 6.0 (Figure 1.2).

This means, that more ambitious domestic mitigation pledges are necessary in order to achieve the UNFCCC objective – this is valid both for the short term and long term. Global emissions need to peak and decline before the end of this decade to land in the 41-47 $GtCO_2e$ window in 2020 and decrease substantially thereafter. Following the RCP2.6 path would require a decrease of global carbon emissions by 50% compared to 1990 levels by mid-century.

Additional policies and measures must be designed and implemented and new low carbon technologies must emerge, otherwise staying below 2 °C during the 21st century will have serious risks of not being feasible.

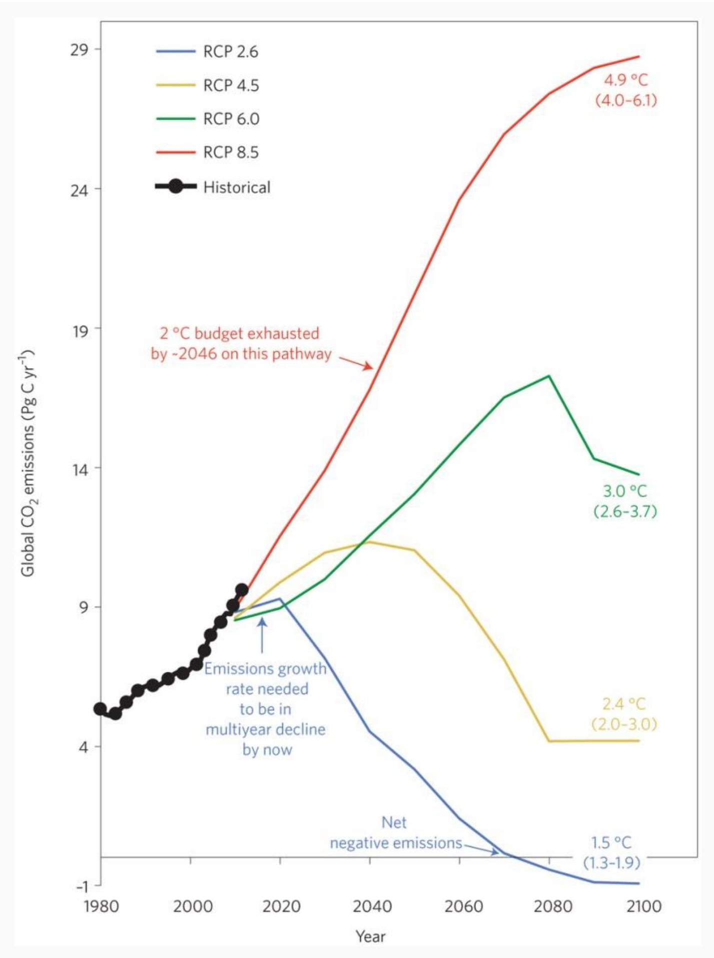


**Figure 1.2** | Global temperature change (mean) associated with the RCP scenarios. *Source:* Sanford et al. (2014).

## 1.2 SUSTAINABLE ENERGY SYSTEM

Climate Change and energy are closely intertwined as the energy sector is currently responsible for more than two-thirds of global GHG emissions (IEA, 2013a). Energy is also one of the main pillars of human society, as it satisfies most of its needs (e.g., cooking, lighting, mobility, communication, industrial production), being a critical factor for economic development. Although in the last decades there has been a decoupling of energy consumption from economic growth, due to structural changes in the economy, energy efficiency and fuel switching, over a century, cheap and abundant fossil energy has been supporting the industrialisation of many countries and increasing the higher standards of living of their inhabitants. Historical trends show that economic development has been deeply associated with energy consumption, with developed countries presenting higher values of energy consumption per capita (Figure 1.3).

A sustainable social and economic development requires a secure and affordable energy system, which has not been compatible with environmental protection up to today. Global energy demand has grown almost 50% from 1990 to 2011, led by fossil fuels, which account more than 81% of the primary energy consumption (IEA, 2013b). If the current global energy trends continue, $CO_2$ emissions will almost double by 2050, paving the way towards a 6 °C rise in average global temperature when compared to pre-industrial level (IEA, 2012). Non-sustainable energy systems also led to other problems, such as depletion of natural resources and air pollution with negative effects in public health and economy. Moreover, fossil fuels resources, like oil and gas, are not equally distributed among regions which, besides the negative economic effect on demanding countries, can also result in some vulnerability, namely because of potential political instability of suppliers.

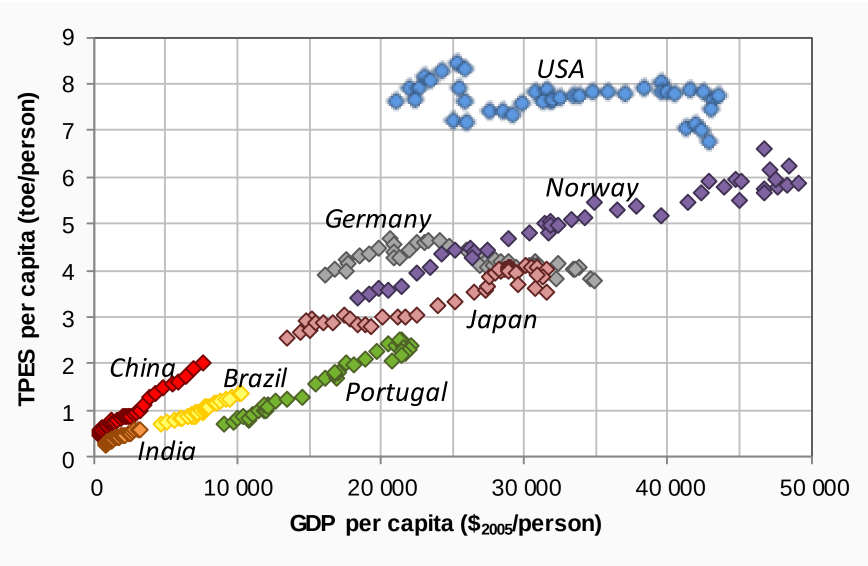


**Figure 1.3** | Relation between Total Primary Energy Supply (TPES) per capita and Gross Value Added (GDP) per capita by Purchasing Power Parities. Values from 1971 to 2012 (2011 for China, India and Brazil). *Source:* author's own elaboration based on (IEA, 2013c) and (OECD, 2013a, 2013b).

Over the last decade, energy security has re-emerged on the political stage mostly due to the rising energy demand in emerging economies leading to a "demand shock"; high and volatile oil prices; increasing dependence on imported natural gas in Europe and; the vulnerability of energy infrastructure to terrorism, natural disasters and accidents (Jewell, 2013), whose concerns were enlarged after the Fukushima nuclear power plant accident, in 2011, as a consequence of an earthquake and tsunami.

Thus, the decarbonisation of the energy system through low-carbon technologies and the improvement of energy-efficiency, can simultaneously tackle climate change, improve air quality, and provide energy security by promoting a more dependable, resilient, and diversified energy portfolio (McCollum et al., 2013).

Today, policy makers are facing the challenge to decide on new policies and strategies towards a sustainable energy system, across the economic and environmental spheres, i.e., an affordable, cost-effective, secure and low carbon energy system that meets its demand.

Energy-environment-economy (E3) interactions play therefore a crucial role in driving climate change mitigation and energy policies. The integrated EU energy and climate policy is a clear example of the relevance of the E3 interactions and how these three components could be combined. The climate and energy package 2020 (EC, 2008) integrates the reduction of GHG emissions with the reduction of EU's energy imports dependence, with the goal of improving energy security, supporting growth and increasing competitiveness, innovation and jobs. These objectives are delivered by three key marks up to 2020:

- A reduction of 20% of GHG emissions relative to the level registered in 1990[4]. This goal is associated with two distinct targets and segments of GHG emissions: *i)* emissions from energy-intensive sectors covered by the EU Emissions Trading Scheme (ETS), which are subject to an EU-wide annual decreasing cap until achieve a reduction of -21% in 2020 comparing with 2005 emissions; and, *ii)* emissions from the sectors not covered by ETS (non-ETS), which are subject to national pledges embodied in the so-called Effort Sharing Decision (EC, 2009a). Each Member state has differentiated annual targets set on the basis of their relative prosperity. By 2020, these national targets will collectively correspond to a reduction of around 10% in total EU non-ETS emissions compared with 2005 levels.

[4] EU has also proposed a conditional commitment to reduce its global GHG emissions to 30% in 2020 if "other developed countries commit themselves to comparable emission reductions and economically more advanced developing countries contribute adequately according to their responsibilities and respective capabilities" (EC, 2008).

- 20% share for renewable energy sources (RES) of the energy consumed, including 10% in transport. Each Member State has a specific national binding target (EC, 2009b) reflecting its different starting points and potential for increasing renewable consumption.
- 20% savings in energy consumption compared to projections. Although the energy-climate package does not address the energy efficiency target directly, each Member State has to set national energy efficiency objectives under the EU Energy Efficiency Directive (EC, 2012).

In parallel, the EU introduced a regulatory framework to drive the creation of an open, integrated and competitive single market for energy to promote the security of energy supplies.

Being on the forefront of international climate negotiations, EU has also proposed post-2020 goals, suggesting a unilateral target to cut its GHG emissions by 40% below 1990 levels by 2030 (EC, 2014), with the ultimate goal of achieving a 80% reduction by the middle of the century (EC, 2011a). These targets are once again integrated with sustainable energy goals, translated as an increase of renewable energy consumption by 45% and a level of energy savings of approximately 25% (in 2030). One question now is how these goals will be delivered in each EU Member State.

## 1.3 SCENARIOS: A DECISION-SUPPORT TOOL FOR ENERGY AND CLIMATE CHANGE

The achievement of low carbon targets requires a transition to sustainable energy systems and medium and long-term perspectives on GHG emissions and energy technology pathways are a crucial key to support decision making. The climate system has a slow response to changes in the GHG concentrations and current emissions will continue to affect the Earth's temperature over the next century. Structural changes of economy, such as the replacement of fossil-based energy by less carbon-intensive alternatives, are also slow processes. Energy infrastructure takes time to plan, build and usually has a long lifetime, which makes replacement a lengthy process. Additionally, new technologies, more efficient and less carbon intensive, need time to develop and even longer to reach their maximum market share (IEA, 2003; Kramer and Haigh, 2009).

Long-term perspectives are associated with large uncertainty due to the limitations of our knowledge. Basing our decisions on the assumption of continuation of present trends presents risks (IEA, 2003), and many examples of failure in statements on future trends are available (Craig et al., 2002). Thus, decisions about mitigation targets operates within a context of uncertainty which can assume considerable proportions if we consider the uncertain impacts of climate change and the uncertain associated with the future availability and costs of different technologies.

Given the impossibility of knowing what has not yet unfolded, scenarios arise as a suitable tool to tackle the uncertainties of the future through a structured and imaginative process (Rounsevell and Metzger, 2010). They help to explore the *what*, *how* and/or *if* in future pathways and allow to understand how different key driving forces might lead to different outcomes. However, scenarios are not predictions or forecasts but rather are a collection of pictures that sets the limits of plausible futures (Wilson, 2000).

Scenario analysis has been applied for a wide range of disciplines and scopes. Since the 70's when Shell used it after the oil crisis of 1973, to explore discontinuities in the oil supply path and position the company for different market development (Wack, 1985), the approach was diffused and became a popular and recommended method to address uncertainty and to improve decision making (Varum and Melo, 2010).

When applied in climate change research, scenarios help evaluate the uncertainty about the human contribution to climate change: the response of the climate system to human activities; the impacts of different future climates; the implications of human activity and mitigation approaches in GHG emissions; and the consequences of different actions that facilitate the response to new climate conditions, i.e. the effects of adaption measures (Moss et al., 2010). Scenarios play a central role in this dissertation as a tool for exploring energy systems and GHG emissions pathways, mostly associated with mitigation goals.

"Emission scenarios are descriptions of potential future discharges to the atmosphere of substance that affect the Earth's radiation balance, such as GHG" (Moss et al., 2010). Because GHG emissions are the result of a complex process between several driving forces as, demographic and economic evolution, environment awareness or technological development, emission scenarios have been traditionally produced by modelling tools based on assumptions about such driving forces. They allow exploring alternative energy and technology futures, understanding the role of each driving force in the GHG emission and inform policy-makers about potential options forward a lower emission path.

The uncertainty in emissions and energy scenarios results from the inherent uncertainty of future socioeconomic, technology and policy conditions, and the differences in representations of processes and relationships across modelling tools (Moss et al., 2010), i.e. the uncertainty associated with different models characteristics. *How can these uncertainties influence the GHG emissions scenarios? Which are the most relevant uncertainties regarding the use of scenarios for support policy decision? And, what is the consequence for decision making process?* These are examples of questions that should be answered in order to improve scenarios development and increase the confidence of stakeholders in using them to support decisions.

Two prominent approaches have been applied to deal with uncertainty in energy and GHG emissions scenarios (IPCC, 2005; van Vuuren et al., 2008): i) probabilistic approach (e.g. (Webster et al., 2002, 2003; Labriet et al., 2012)) and, ii) storylines approach (e.g. (Nakicenovic et al., 2000)). The first captures uncertainty by defining probability distributions for the most important model parameters and uses statistical techniques to create a range of results or a hedging outcome, while the latter builds narratives around the scenario driving forces, creating relations between them and getting different possible scenarios. Although complementary, an ongoing debate about the strengths and weakness of these two approaches has been held. Some authors argue that policy and decision-makers need probability estimates to assess the risks of climate change impacts (Schneider, 2001; Webster et al., 2002). Multiple scenarios can place decision-makers in a quandary (Labriet et al., 2012) or make them define their own assumptions about the probability of different outcomes, possibly in ways that the authors did not intend (Schneider, 2002). However, other authors outline that it is not meaningful to assign subjective probability estimates as the ones associated with social systems, i.e., society, economy, technology and policy (Nakicenovic et al., 2000). Socio-economic variables and their alternative future development paths are not freely interchangeable because of their interdependencies. Uncoupled sampling within distribution ranges of these variables may result in inconsistent combinations (Grübler and Nakicenovic, 2001). Focusing attention on a very small number of most-likely futures can negate the benefit of using scenarios, i.e., covering a wide range of possibilities, ignoring the lessons from history (Schnaars and Ziamou, 2001; Grubler et al., 2006; O’ Mahony, 2014). The research work in this dissertation only focuses in this last approach.

### 1.3.1 QUALITATIVE AND QUANTITATIVE SCENARIOS

The scenario literature can be classified into two major categories – qualitative narratives and quantitative modelling (Morita et al., 2001).

Qualitative scenarios (“storylines”) are usually used to analyse complex situations with high levels of uncertainty or when the information cannot be entirely quantified, like human values, emotions, or behaviour (van Notten et al., 2003). They result from stakeholders’ workshops, interviews or other participatory methods. Quantitative scenarios, on other hand, assume a quantitative feature, describing the future with numerical figures, generally obtained by complex modelling tools. Emission scenarios are traditionally quantitative, requiring assumptions and simplifications that tend to highlight the research team's own expertise (Varho and Tapio, 2013). Table 1.1 summarizes the main characteristics of qualitative and quantitative scenarios, allowing a comparative analysis between them.

**Table 1.1** | Characteristics of qualitative and quantitative scenarios. *Source:* adapted from Vliet et al. (2010).

| **Qualitative scenarios** | **Quantitative scenarios** |
|---|---|
| Capture future worlds in stories, ideas and visions mostly developed from participatory process with stakeholders | Capture future system in numbers and rules on systems' behaviour mostly through models use |
| All aspects important to stakeholders can be included | Inclusion of aspects depend on data availability and modellers knowledge |
| No rules for validation on current system | Validated on current system |
| Large flexibility and creativity | Limited flexibility and creativity |
| Social effects included | Hard to include social effects |
| No fixed set of assumptions | Fixed set of assumptions |
| Not always internally coherent | Internally coherent |
| No clear system understanding | System understanding |
| No data needed | Need for data |

Both approaches have strengths, but also limitations which can be overcome by hybrid combinations, making scenarios more consistent and robust (van Notten et al., 2003) due to their structural and methodological diversity (Morita et al., 2001).

The development of storylines associated with quantitative scenarios, gives a consistent support to the modelling assumptions and/or outcomes, making the scenarios more comprehensible and not just a result of arbitrary modelling choices (O' Mahony, 2014). Moreover, qualitative scenarios developed from the participation of diverse stakeholders increase the creativity, relevance and legitimacy of scenarios, enhancing also the communicability of numeric data to a broader audience, i.e., transmitting complex information in a comprehensible way.

Likewise, the introduction of quantitative data to qualitative scenarios enables tests of plausibility and coherence (van Notten et al., 2003), particularly when a quantitative goal as a GHG emission pledge or a RES consumption target is being considered, quantitative scenarios can assess their compliance. Moreover, quantitative scenarios from numerical models can ''enrich'' qualitative scenarios by showing trends and dynamics not anticipated by the storylines (Alcamo, 2008).

Figure 1.4 illustrates the improvements of both qualitative storylines and quantitative formulations based on modelling when integrated in "hybrid scenarios" (Alcamo, 2008).

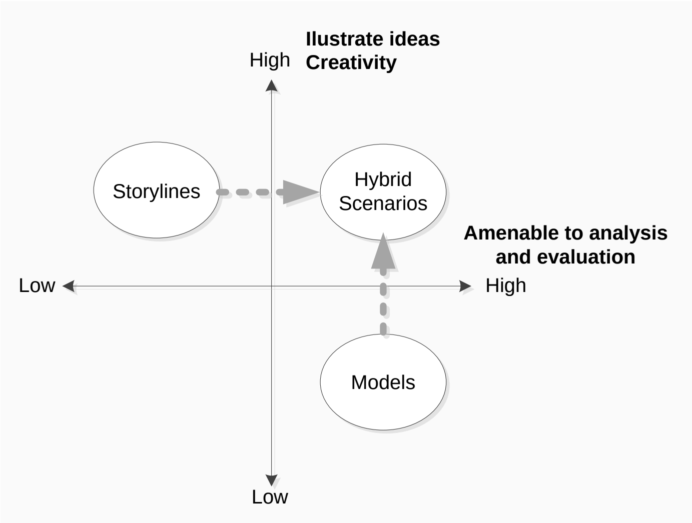


**Figure 1.4** | Schematic illustration of hybrid scenario formulations, from narrative storylines that explore diverse contexts to quantitative models that evaluate their plausibility and compliance. *Source:* adapted from (Ghanadan and Koomey, 2005).

One of the most well-known greenhouse gas (GHG) emission scenario exercises, is the Special Report on Emissions Scenarios (SRES) from the IPCC (Nakicenovic et al., 2000). SRES combined qualitative and quantitative scenario approaches to develop a set of emissions scenarios. It illustrated four storylines, representing different pictures of how the world might develop through 2100 in terms of economy, society and technological progress, in an absence of climate change policies. Using six different integrated assessment models the storylines were converted in forty GHG emissions scenarios, six of them used as markers scenarios, i.e., scenarios that “are no more likely than other scenarios”, but are considered as “illustrative of a particular storyline” (Nakicenovic et al., 2000). According to SRES team, besides making it easier to explain the scenarios to the various user communities, the development of narrative storylines helped “to think more coherently about the complex interplay between scenario driving forces within and across alternative scenarios and to enhance the consistency in assumptions for different parameters”, tackling this way the uncertainty regarding the modelling input assumptions.

Although other global environmental assessments, such as the Global Environment Outlook (UNEP, 2007), the World Water Vision scenarios (Cosgrove and Rijsberman, 2000; Alcamo, 2008b) and the Millennium Ecosystem Assessment scenarios (Carpenter et al., 2005) have combined qualitative and quantitative approaches, most developments occurred separately (Wilkinson et al., 2013). There is little evidence of the combination of storylines and modelling on energy and low carbon scenario development (Söderholm et al., 2011). In fact energy and emission scenarios such as the ones developed by the International Energy Agency (IEA, 2012; IEA, 2013b) or the European Commission (EC, 2011a, 2011b) do not comprise any storyline, representing essentially quantitative outputs of models. Most energy modelling studies show great technical details, but neglect the entire interaction between social, economic and technological factors, ignoring aspects as the interconnection of the economic capability or social behaviour with technological development for example.

The main reason for this is that although storylines and quantitative modelling scenarios are complementary, it is not easy to combine them due to the underlying different communities (modellers versus stakeholders), the time consuming process and the inherent characteristics of each approach as denoted in Table 1.1.

However, in reality, social and technological systems are not constructed independently. Instead, the various systems (social, technological, economic, political) develop in an "iterative and reflexive" manner (Hughes et al., 2009). The absence of storylines and mostly the lack of their inherent participatory building process with stakeholders can result in a blurred picture for the non-modelling community, and tend to reduce the scenarios acceptance, which can assume significant proportions if we consider that those scenarios support energy and climate policy decisions. In short energy and GHG emission scenarios only supported by model outcomes result in scenarios that are too narrow, which is a major drawback.

### 1.3.2 INTEGRATED ASSESSMENT MODELS

Emission scenarios are commonly generated through integrated assessment models (IAM), which combine natural science and socio-economic aspects, primarily for the purpose of assessing climate change policy options (Weyant et al., 1996). They represent key features of human systems, such as demography, energy use, technology, economy, agriculture forestry and land use (Moss et al., 2010).

One of the widespread categories of IAM are the so called E3 models. These models illustrate the interactions between these three spheres: energy-environment-economy, setting future energy demands, defining various options to satisfy it, namely energy resources and/or technologies, and computing its respective GHG emissions. E3 models are the core tool in energy and climate mitigation scenarios, exploring different energy futures and inform policy makers about the potential and the costs or economic impacts to reduce GHG emissions.

To obtain a global climate response IAMs are linked to climate models, representing the atmospheric chemistry and atmosphere-ocean interactions, translating GHG emissions in GHG atmospheric concentrations and defining the respective radioactive forcing and temperature change. Moreover, besides the E3 interactions, IAMs can also include land-use, forestry and agriculture components, which enable them to calculate, in addition to the GHG emissions of the energy system, the emissions from these fields, getting the entire panorama of GHG emissions.

Currently, there is a multiplicity of IAM models as shown by (Nakicenovic et al., 2000; Das et al., 2007; Clarke et al., 2009; Capros et al., 2014). This is a result of their different additional modules, calculation methods, assumptions, disaggregation, among other factors. In particular, the E3 modelling framework, has been traditionally classified in two main approaches: top-down and bottom-up, which differ mainly with respect to the emphasis placed on endogenous economy representation and technology explicitness (IPCC, 2007; Böhringer and Rutherford, 2008).

Top-down (economic) models, focus on the economy as a whole, disaggregating it in several production sectors and consumption categories and incorporating markets interactions. The top-down approach has been dominated by computable general equilibrium (CGE) models (Hourcade et al., 2006) which combine the Arrow-Debreu general equilibrium with realistic economic data to compute the levels of supply, demand and price that support the equilibrium across all the markets (e.g. capital, labour, materials) (Wing, 2004). CGE models have an explicit representation of the micro-economic behaviour of the economic agents (e.g., households, firms and government). However, as a component of the economy, the energy system is represented by aggregated economic functions, which capture substitution possibilities between input factors and energy forms trough historical substitution elasticities (Böhringer and Rutherford, 2008).

On the other hand, bottom-up (engineering) models focus on the energy system, characterizing it with very detailed technology data, including technical and economic information of supply, conversion and end-use technologies (e.g. efficiency, investment and O&M costs). Bottom-up models are typically cast as optimization problems[5] (Böhringer and Rutherford, 2008). They define an optimal set of technology choices to satisfy energy services demand at minimum energy system costs and under technical and/or environmental constraints, leaving energy prices and quantities in equilibrium – partial equilibrium[6]. When technology costs are converted into present value through discount rates, many technologies that provide the same energy service and reduce for example GHG emissions appear as an optimal choice (Bataille et al., 2006). Bottom-up models fail in representing the micro-economic behaviour of economic agents. The greater financial risk of new technologies or the fact that they may not be perfect substitutes to the economic agents is neglected by these models as their technological choices are based on a simple capital and operating financial costs (Jaccard et al., 2003). Additionally, bottom-up models ignore the interrelations and effects of the energy sector on the broader economy, ignoring the macro-

[5] Bottom-up models can also assume a simulation character, describing the development of the energy system with a pre-defined set of rules that do not necessarily assume an optimization.

[6] The "partial equilibrium" term is associated with the fact that BU models only comprise the equilibrium of one particular sector of economy – the energy market.

economic feedbacks of different energy system pathways or accommodating simpler price response trough exogenous energy service-price elasticities. Table 1.2 summarizes the main characteristics of the two approaches.

**Table 1.2** | Main characteristics of top-down and bottom-up models. Source: Adapted from (Bryden et al., 1995; van Beeck, 1999).

| **Top-down models** | **Bottom-up models** |
|---|---|
| Economic approach | Engineering approach |
| Do not explicitly represent technologies | Contain detailed technology description |
| Reflect available technologies adopted by the market | Reflect technical potential |
| Technical change is based on trends rates (usually exogenous) | Technical change is based on a menu of technical options (existent and emergent) |
| Disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements | Disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements - opportunities for no regrets actions identified |
| Determine energy demand through aggregate economic indices (gross national product, price elasticities), but vary in addressing energy supply | Represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption |
| Based on observed market behaviour | Independent of observed market behaviour |
| Responses of economic groups via income and price elasticities | Responses of agents via discount rates |
| Endogenize behavioural relationships | Assess costs of technological options directly |
| Assumes no discontinuities in historical trends | The interactions between energy sector and other economic sectors is negligible |

Due to its own features, top-down and bottom-up modelling approaches have specific strengths and limitations, answering different questions raised within the energy-climate policy debate. Because top-down models represent technological change as an abstract, aggregate form, this approach only helps policy makers to assess economy-wide policy instruments such as taxes and tradable permits, being ineffective in assessing the role of technology (Hourcade, Jaccard et al. 2006). Moreover, the substitution elasticities between energy commodities and energy efficiency parameters are usually set through historical data, with no guarantee that they will remain valid in the future under new energy-climate policy regimes and new technology developments (Grubb et al., 2002). For this reason top-down models tend to suggest that the efforts to move away from a trend scenario would be costly, as the economy's potential for technological switches is restricted by historically-based elasticities (Jaccard et al., 2003; Hourcade et al., 2006; Rivers and Jaccard, 2006). On the contrary, due to its technological detail, bottom-up models enable modelling technology-orientated policies and assessing the role of technology in GHG mitigation. However, because bottom-up models choices do not reflect the micro-economic behaviour of the economic agents and they lack the macro-economic feedback, they often indicate that the shift to a sustainable energy system can be reached at a lower cost. Some bottom-up studies even suggest that mitigation can yield financial and economic benefits, depending on the adoption of best-available technologies and the development of new technologies (IPCC, 2001). Nevertheless, the impact of energy-climate policies is not restricted to the energy system and should therefore be analysed within an economy-wide framework (Böhringer and Schmid, 1996), including the changes in macro-economic variables such as sector production.

In short, top-down models indicate that mitigation policies have economic costs because markets are assumed to operate efficiently and any policy that damages this efficiency will be costly, while bottom-up models advocate that mitigation can even yield financial and economic benefits, depending on the adoption of best-available technologies and the development of new technologies (Barker et al., 2002).

To move towards a low carbon economy, decision makers need clear and consistent information that allow them to answer: *What is the real impact of energy and climate policies in the economy and society? What is the cost-effective technology portfolio that should be promoted?* Separate use of top-down and bottom-up models does not adequately address all the questions. In this context, some studies argued for the need to bridge the gap between these conventional modelling approaches within an integrated hybrid framework that combine their strengths (Hourcade et al., 2006). Their ultimate goal is to build an hybrid tool that is: technological explicit, behaviourally realistic and economic comprehensive, linking energy supply and demand to the evolution of the economy's structure and total output (Hourcade et al., 2006). Figure 1.5 shows the comparison between the dimensionalities of conventional bottom-up and top-down models and their respective changes in an ideal hybrid tool.

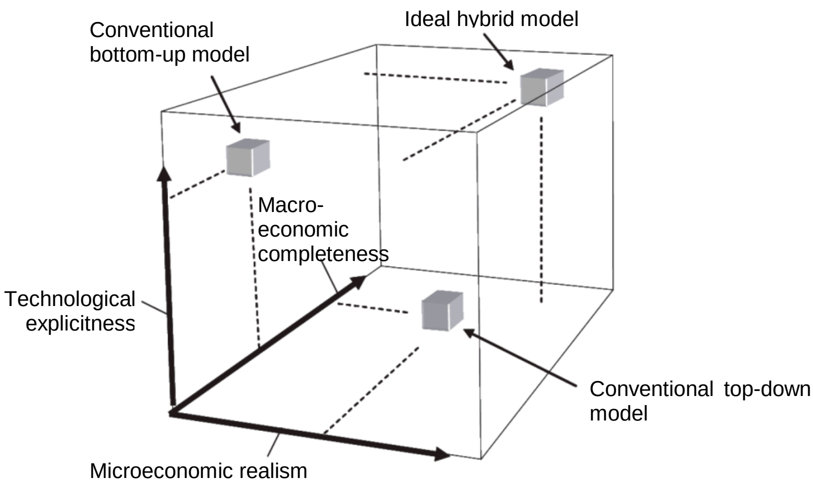


**Figure 1.5** | Dimensionalities of top-down, bottom-up and hybrid models. *Source:* Hourcade et al., 2006.

The development of the existing hybrid models can be roughly grouped in the following methodologies:

- A soft-link between two independent top-down and bottom-up models, exchanging data and solving them iteratively until they converge (Hoffman and Jorgenson, 1976; Labriet et al., 2010);
- A link between one model type with a reduced form of the other, usually a link between a bottom-up model with a simple top-down macroeconomic sector, producing a single non-energy good (Manne and Wene, 1992; Manne et al., 1995; Messner and Schrattenholzer, 2000; Bosetti et al., 2006; Strachan and Kannan, 2008);
- Combine the two approaches in a single integrated model formulated as a mixed complementarity problem (MCP) by introducing bottom-up technological detail (commonly discrete electricity generation technologies) into a CGE framework. (Bohringer, 1998; Frei et al., 2003; Böhringer and Rutherford, 2008; Wing, 2008; Proença and St. Aubyn, 2013).

In spite of the major variety of hybrid tools, most of them present drawbacks. They do not contain extensive technological data (e.g. MCP approach) that cover the whole energy system (i.e. from supply to demand technologies) or disaggregated economic structure (e.g. link with a single macroeconomic sector), which limits the assessment of technology oriented policies and unables the evaluation of the impact of energy and climate policy on specific sectors. Moreover, some hybrid models soft-link top-down and bottom-up models through a single sector alone, e.g., transport (Schäfer and Jacoby, 2005), residential (Drouet et al., 2005), electricity (Martinsen, 2011), thereby lacking the full macroeconomic feedback over the range of technological choices of the entire energy system. The main reasons for these drawbacks are associated with the heterogeneity of the models (presented in Table 1.2), as well as the complexity and dimensionality of their connections and inherent computational challenges and although (Böhringer and Rutherford, 2009) have further outlined a method to decompose and solve iteratively MCP model, overcoming dimensionality issues, this method was just applied considering power sector (Tuladhar et al., 2009; Lanz and Rausch, 2011).

## 1.4 THE PORTUGUESE CASE STUDY

Climate change mitigation entered the Portuguese political agenda when the country signed the UNFCCC in 1992, which was strengthened later in 1998 with the signature of the Kyoto Protocol and the establishment of a national Climate Change Commission. In 2002, in the context of the Kyoto Protocol and EU Burden Sharing Agreement (EC, 2002), Portugal committed to limit, by 2008-2012, its GHG emissions growth to 27%, when compared to 1990 emission levels. Only as of the 90s and largely due to the influence of European directives, the national energy policy has started to focus more strongly and systematically on the environmental impacts of its energy system and on national energy security.

As an EU member state, Portugal is highly affected by what is defined at the EU level, given that any EU adopted policy will be transposed into national legislation. Currently, within the EU 20-20-20 climate and energy policy goals, Portugal is legally committed to:

- Limiting the increase of the GHG emissions from the non-ETS sectors up to +1% through 2020, comparing with 2005 levels (EC, 2009a);
- 31% of gross final energy consumption delivered by RES and a mandatory minimum of 10% share of renewable energy in the transport sector by 2020 (EC, 2009b).

The present Portuguese Energy Policy (Presidency of the Council of Ministers, 2011) aims to strengthen the competitiveness of the sector, fostering environmental and economic sustainability, by the main guidelines: i) ensure compliance with the national commitments undertaken in the context of EU energy-climate policy by 2020, namely the improvement of energy efficiency, contributing to the reduction of the deficit in the balance of payments; ii) reinforce the diversification of its primary energy sources and reduce energy imports dependence, increasing security of supply; iii) enhance liberalized and competitive energy markets, ensuring also competitive final energy prices and an energy model of economic rationality and real incentives to market players, adopting a reduction of tariff deficits path.

The Portuguese energy policy is currently supported by two main planning tools: the Renewable Energy Action Plan (NREAP) and the Energy Efficiency Action Plan (NRAP) (RCM 20/2013), which set measures, lines of action and national commitments with regard to the use of energy from renewable sources and energy efficiency, respectively. NREAP comprises sectorial annual targets up to 2020, namely: 49.6% of renewable electricity (RES-E), 33.6% of renewable energy consumption in heating and cooling (RES-H&C) and 11.5% in transports (RES-T), corresponding to a total consumption of gross final energy from RES of 31.7% in a reference scenario. In an additional energy efficiency scenario the Portuguese NREAP defines a more ambitious goal – 34.5%, disaggregated as followed: 59.6% of RES-E, 35.9% of RES-H&C and 11.3% of RES-T. In its turn, the NEEAP, embraces two additional goals for 2020: 25% savings of the national primary energy consumption as compared with the projections derived by the EU model PRIMES[7] in 2007 and a specific 30% savings target for the Public administration, related with current consumption in public buildings and infrastructure.

In the last decades Portugal has been undergoing profound social and economic transformations, which were also reflected in its energy system and respective GHG emissions.

Following a period of fast economic growth in the 1990s, the Portuguese economy grew modestly in the 2000s until entered a recession in 2009, as a consequence of the global financial crisis, which continues up to today as part of the European sovereign debt crisis (Figure 1.6). Services have gained an increased importance in the Portuguese economy, while industry (manufacturing, mining and quarrying industries), more energy intensive, has been reducing its activity, accounting today only 15% of the gross value added vis-à-vis 69% for commercial, financial and public activities (Eurostat, 2014a).

The national energy consumption has followed a similar trajectory through 2005, when it reached its peak (Figure 1.6). After this period, primary and final energy demands have been sharply declining contributing also to the reduction of GHG emissions. The increased consumption of natural gas and renewable energy sources, the energy efficiency in sectors covered by EU ETS, the "green" tax reform on vehicles and the economic crisis after 2009, are the main reasons for a decoupling of energy supply and GHG emissions (APA, 2014).

Due to the inexistence of endogenous fossil fuels, Portugal is highly dependent on imported energy, which has motivated the diversification of its energy profile. Presently, RES (mostly biomass, hydro and wind power) account for 22%[8] of the primary energy supply (Figure 1.7), against 18% in 1990. Although this represents one of highest shares of renewable energy supply in EU member states (minimum of 1% in Malta and maximum of 37% in Sweden), the Portuguese energy imports

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[7] PRIMES is partial equilibrium model representing the European Union energy markets. It has been widely used by EC as an impact assessment tool developing a series of GHG mitigation an energy scenarios, evaluating their implications on the Member-Sates' energy systems and their costs and prices. PRIMES is currently recognize as one of the EU policy support models. More information about the model can be found in http://www.e3mlab.ntua.gr/.

[8] All the energy indicators mentioned in the present section were calculated based on data from the EU's statistical office Eurostat (Eurostat, 2014a, 2014b), the Portuguese Directorate-General for Energy and Geology (DGEG, 2013a, 2013c) and the International Energy Agency (IEA, 2013c), unless stated otherwise.

dependency (around 79%) is far above the EU28 average of 53%, making the country highly exposed to the volatility of the energy markets.

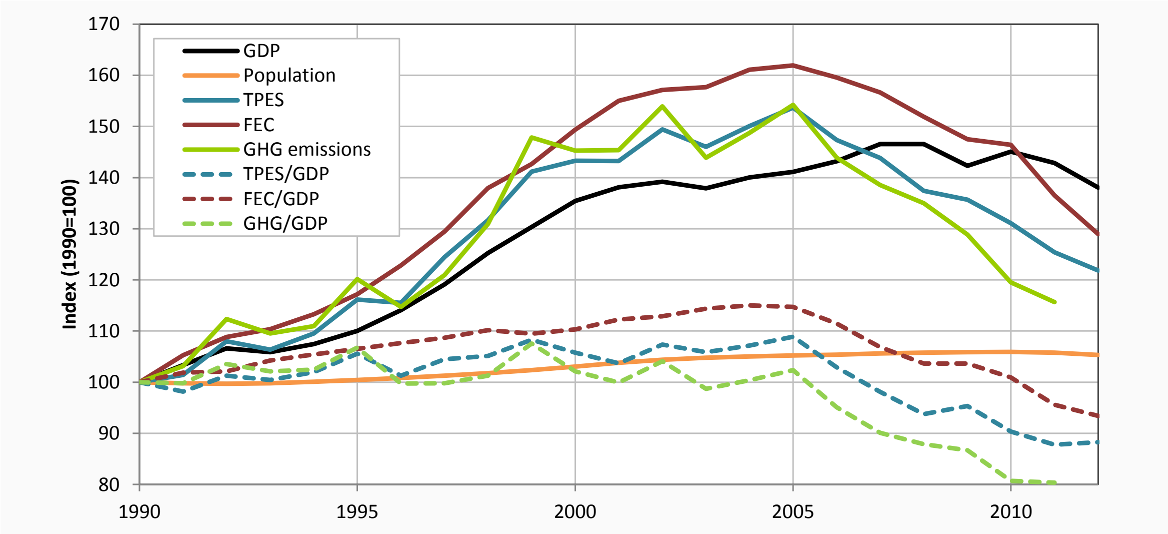


**Figure 1.6** | Socio-economic and energy indicators evolution for Portugal (Note: TPES – Total primary energy supply; FEC – Final energy consumption). *Source:* author's own elaboration based on (DGEG, 2013a; IEA, 2013c; Eurostat, 2014a).

Over the years, electricity generation has been largely depended on fossil fuels and hydro (Figure 1.8). The latter was a significant inter-annual variation due to variable rainfall, causing changes in the energy supply and GHG emissions. Nevertheless, the past decade has seen a growing investment in other renewable capacity, mostly wind power, spurred by national support schemes. In 2000 wind represented 1% of the total Portuguese power capacity, while today represents 22% – the second main national renewable capacity after hydro (51% share of total capacity). Due to the high sunshine rate, since 2007 Portugal has also been investing on solar PV, although this energy source still represents only 1% of national power capacity. This commitment on renewables has been reflected in the national power production. In 2006, an average hydrologic year, the electricity generated from renewable sources was 31% of power generation, while in 2012, a dry year, it represented 49%.

The national RES potential and its market deployment made Portugal one of the EU members with the most ambitious target for the share of RES in final energy consumption (31%). However, since the beginning of the economic crisis, the national RES consumption has been kept almost constant (around 25%), and Portugal did not achieve its NREAP interim-targets for 2011 and 2012. Currently, the country is with the half of the EU member states with the largest distance from its 2020 objective. The situation that can become more critical if the 34.5% RES national goal is considered.

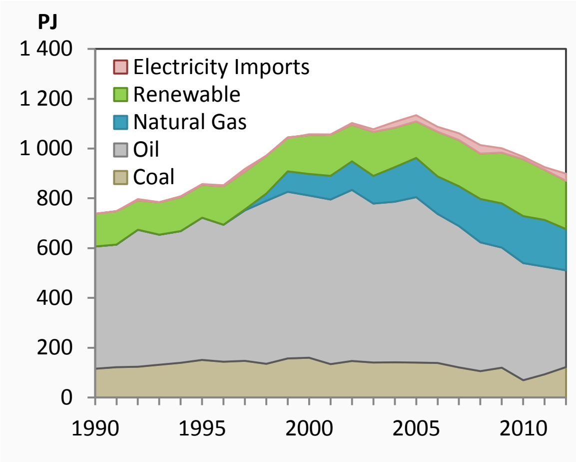


**Figure 1.7** | Portuguese primary energy supply pathway per energy source. *Source:* author's own elaboration based on (DGEG, 2013a).

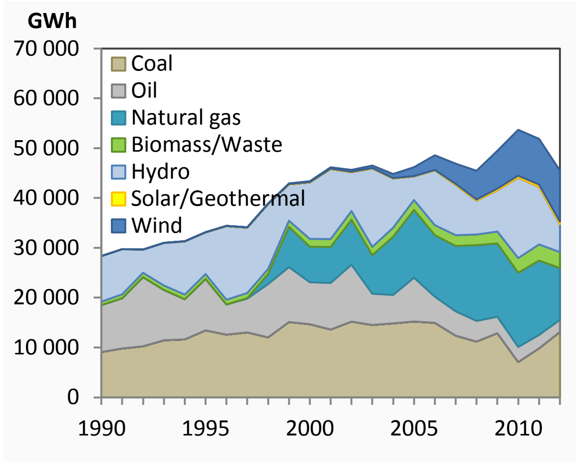


**Figure 1.8** | Portuguese power generation pathway per energy source. *Source:* author's own elaboration based on (IEA, 2013c).

In 2011, the Portuguese GHG emissions represented 116% of the 1990 levels (Figure 1.9). The decline registered after 2005 (around 5% per year) was not enough to overcome the marked rise of GHG emissions in the preceding years, especially until the late 1990s. Currently, it is estimated that, Portugal is 0.32% above the ceiling of GHG emissions established by the first commitment period of Kyoto Protocol: 2008-2012 (CAC, 2014). The majority of the national emissions are from fuel combustion in energy industries and transport sectors representing 49% of the total GHG emissions. Regarding the effort sharing decision, Portugal is one of the EU countries well below its emission allocation limit – currently 10% beneath the 2020 cap (EEA, 2013).

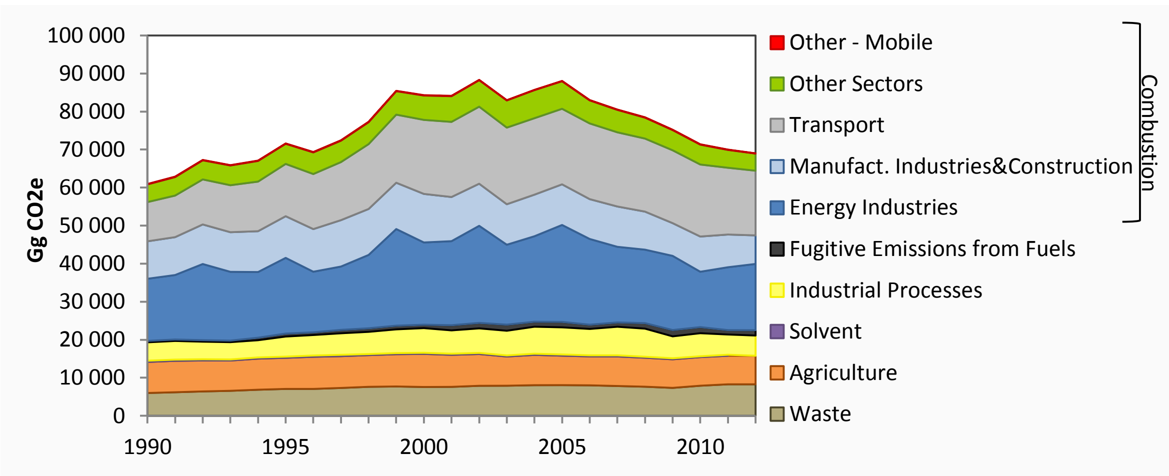


**Figure 1.9** | Portuguese GHG emissions pathway per source category (Note: Land Use, Land-Use Change and Forestry not included). Source: author's own elaboration based on (APA, 2013).

Since the mid-2000s, the final energy and carbon intensity (measured per unit of GDP) have been decreasing, representing today 93% and 80%, respectively of 1990 values (Figure 1.6). Although, it seems that Portugal has been following a pathway towards a more sustainable energy system, these indicators remain above the EU28 average, reflecting the Portuguese economy's lower productivity and competitiveness and indicating that there is enough room to improve energy efficiency (OECD, 2011; APA, 2014) and decarbonise the economy.

In the light of the aforementioned points, Portugal is a relevant case study. The challenges faced by this small, open economy are common to several other countries. Understanding the kind of strategies that can be used for shifting the Portuguese energy system towards a sustainable path is crucial.

> *To what extent can Portugal reduce its energy related GHG emissions and what are the associated economic impacts?*

> *What are most cost-effective energy technologies that Portugal should promote and up to what point can Portugal improve its energy efficiency and renewable energy consumption?*

> *Are the national policy goals supported through EU models and assumptions in line with the national potential?*

## 1.5 RESEARCH QUESTIONS AND THESIS OUTLINE

A future low carbon economy demands major changes on the energy system. Scenarios and integrated assessment models are key tools to explore alternative futures and support energy and climate policy decisions.

This dissertation aims to advance on energy-environment-economy modelling and on GHG emissions scenarios development, to better understand how a transition to a more sustainable energy system and low carbon economy can be achieved. In particular this dissertation has the following objectives:

I. Explore and quantify of the uncertainties associated with the modelling tools and the assumptions behind the generation of low carbon energy scenarios, in order to increase the knowledge about their importance within the energy-climate policy context;

II. Develop an approach to integrate the vision and expectations of different stakeholders (storylines) in the energy modelling framework, in order to provide a consistent support to modelling assumptions and improve scenarios comprehensibly;

III. Develop an integrated hybrid technological-economic modelling platform for energy-climate policy analysis, combining the strengths of bottom-up and top-down approaches and overcome the limitations associated with each of the modelling tools' concepts.

Moreover, this dissertation explores the strategies for the Portuguese energy system comply with different low GHG emissions pathways, considering a set of different futures, namely, technology development, policy constraints, and economic growth. Thus, this thesis aims to contribute with useful insights for the Portuguese decision-making process, towards a more sustainable energy system.

These overarching objectives and deliverables are associated with the following research questions:

A. *What is the role of exogenous modelling assumptions (e.g. energy prices, technological development, socio-economic growth, energy resource availability) on policy related outcomes? Which are the most significant ones that should be assessed in greater detail?*

B. *To what extent different model structures and characteristics (e.g. technological bottom-up versus economic top-down), lead to different GHG reduction strategies and climate policy recommendations, even when calibrated to a common baseline scenario?*

C. *How can qualitative visions of stakeholders from different fields be integrated in a modelling framework to obtain a hybrid combination of socio-economic storylines and energy modelling outcomes?*

D. *How can technology bottom-up and economic top-down approaches be integrated in a hybrid modelling platform combining extensive technology detail with economic sector disaggregation? What are the advantages of such modelling tool for policy analysis?*

The research questions A and B are associated with objective I, while questions C and D are attached to goal II and III, respectively. These questions are answered in a series of papers which are reproduced from Chapters 2 to 6. The conclusions and discussion of the results with respect to the overall objectives of this dissertation are presented in Chapter 7. A guideline to the following Chapters and its connection with the research questions is outlined below and summarized in Table 1.3.

> *CHAPTER 2: ASSESSING EFFECTS OF EXOGENOUS ASSUMPTIONS IN GHG EMISSIONS FORECASTS - A 2020 SCENARIO STUDY FOR PORTUGAL USING THE TIMES MODEL*

In this Chapter the technology TIMES_PT model is used to generate seven scenarios: six technical scenarios each varying one single assumption, namely, demographic and economic evolution, end-use technology deployment, energy resources availability and the implementation and effectiveness of policy decisions; and a baseline case, which includes a combination of assumptions on all exogenous parameters. The comparison between the scenarios in term of GHG emissions, renewable energy consumption and their compliance with the energy-climate policy package gives insights about the contribution of each exogenous assumption to overall uncertainty, answering question A.

> *CHAPTER 3 - LOW CARBON ROADMAP FOR PORTUGAL: TECHNOLOGY ANALYSIS*

Chapter 3 assesses the specific contribution of the technology deployment in the model outcomes by presenting a detailed analysis of the role of technology development and availability in a Portuguese pathway towards a low carbon economy, thereby answering question A. The TIMES_PT model is used to identify the most cost-effective technologies to achieve an 80% GHG abatement target by 2050, regarding two conditions of the technological development: i) a conservative scenario, assuming that the prospects about technologies technical and economic data will remain constant 2015-2020 onwards and; ii) a technology evolution scenario, considering that emerging technologies will be available in the future and existing ones will become more efficient and cheaper, in line with what is generally set in energy modelling studies (e.g., (EC, 2011b; IEA, 2012a; IEA, 2013b)).

> *CHAPTER 4 – TOP-DOWN AND BOTTOM-UP MODELLING TO SUPPORT LOW CARBON SCENARIOS: CLIMATE POLICY IMPLICATION*

The influence of the modelling tool structure and characteristics (economic vis-à-vis engineering/technology) used to design scenarios and support energy and climate policies, is explored in Chapter 4. The GHG reduction strategies defined by the bottom-up TIMES_PT and computable general equilibrium GEM-E3_PT, calibrated to a common baseline scenario, are confronted using a modified Kaya identity. This Chapter answers question B by evaluating the extent of the differences between the models results and analysing the impact of those outcomes in the climate policy decision.

> *CHAPTER 5 - BRIDGING THE GAP BETWEEN SOCIO-ECONOMIC STORYLINES AND ENERGY MODELLING*

As mentioned in Section 1.3.1 a scenario building process that combines both storylines and models outcomes result in more robust and consistent scenarios. The development of storylines based on opinion of different players of society (e.g. policy makers, civil society, energy companies, economists, environmental researchers, among others) help think more clearly and rationally about the interplay between the scenarios driving forces and the respective modelling input parameters. Base on this and following the conclusions from Chapter 2, regarding the assumptions that contribute most to overall uncertainty in GHG emissions scenarios, this Chapter demonstrates how the qualitative socio-economic scenarios developed by stakeholders visions can be linked in a comprehensive framework with energy modelling to overcome social and economic aspects that are generally ignored by current energy modelling exercises. Chapter 5 thus addresses the problem set in question C, adding also information to question A, in particular the role of technology deployment, through the analysis of results.

> *CHAPTER 6 – INTEGRATED TECHNOLOGICAL-ECONOMIC MODELLING PLATFORM FOR ENERGY AND CLIMATE POLICY ANALYSIS*

Question D is tackled in Chapter 6, which presents the methodological development of an integrated technological, economic modelling platform (HYBTEP), built through the soft-link between the bottom-up TIMES and the computable general equilibrium GEM-E3 models. HYBTEP integrates detailed and extensive technology data with disaggregated economic structure, and 'full-link', i.e., covering all economic sectors. Thus, the hybrid platform combines the technological cost-effective choices with the macroeconomic responses, which is an essential metric for the policy decision support. To assess the advantages of hybrid platform, the response of HYBTEP within three different energy-climate policy scenarios is compared to TIMES outcomes, considering different values for energy service-price elasticities. This chapter also addresses question A, showing the importance of the exogenous assumption – energy service-price elasticities, and question B, by confronting the results of TIMES, a "conventional" technological model with HYTBEP with an economic component.

**Table 1.3** | Overview of the research questions address in each chapter of this dissertation.

| Chapters | Research questions | | | |
|---|---|---|---|---|
| | A<br>Modelling Assumptions | B<br>Modelling concepts (technology vs economic) | C<br>Integrating storylines and energy modelling | D<br>Integrating technology and economic modelling |
| 2 | ✓ | | | |
| 3 | ✓ | | | |
| 4 | | ✓ | | |
| 5 | ✓ | | ✓ | |
| 6 | ✓ | ✓ | | ✓ |

All the Chapters provide, in greater or lesser degree, insights on the strategies that could promote the shift to a more sustainable energy system in Portugal.

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# CHAPTER 2

## ASSESSING EFFECTS OF EXOGENOUS ASSUMPTIONS IN GHG EMISSIONS FORECASTS - A 2020 SCENARIO STUDY FOR PORTUGAL USING THE TIMES MODEL*

* This paper is under review (following referees' reports) as follows: Simões, S., Fortes, F., Seixas, J., Huppes, G. (2014). Assessing effects of exogenous assumptions in GHG emissions forecasts – A 2020 scenario study for Portugal using TIMES model. Technology forecasting and Social Change. (Conditionally accepted in November 2013, under review since February 2014).

## ABSTRACT

Model outcomes are substantially based on assumptions. The challenge of this paper is to quantify the role of specific assumptions on policy relevant modelling outcomes. The development of greenhouse gases (GHG) emission scenarios, using energy-economy-environment models, is fundamental for climate policy. Scenario uncertainty depends on the appropriateness of the assumptions implemented as exogenous parameters. Main causes for uncertainty relate to assumptions on exogenous parameters as demographic and economic development, technology evolution and deployment, and policy decisions. To assess uncertainty it is a common practice to run different scenarios combining several assumptions, making it difficult to assess the role of individual assumptions in overall uncertainty. This paper assesses the individual contribution of different exogenous parameters for scenarios on the Portuguese energy system. The technology model TIMES_PT is used to develop alternative GHG scenarios for 2020. The Baseline scenario includes assumptions on all exogenous parameters. The other six technical scenarios each vary in only one assumption. The more relevant assumptions to overall uncertainty are related to socio-economic development, followed by assumptions on technology deployment. The availability and price of energy resources leads to minor variations on GHG emissions only, less than 2% of the Baseline scenario emissions in 2020.

## 2.1 INTRODUCTION

Energy-economic-environment models such as Markal/TIMES family of models (Loulou et al., 2004; Loulou et al., 2005) but also PRIMES (Capros, 2005) and POLES (Russ et al., 2009), are frequently used to support policy makers in climate change mitigation policy decisions. They are used to develop greenhouse gas (GHG) emission scenarios, exploring possible pathways. Examples are the EU Energy Climate 2020 Package (EC, 2008) and 2030 Policy Framework (EC, 2014) that relied on emission scenarios developed with the PRIMES model (Capros et al., 2008); the French National Climate Change Plan[9] (NCCP) which used GHG scenarios for the electricity sector derived from POLES (DGEC, 2011); the Italian official energy and GHG emission scenarios built with the TIMES Italy model (ENA, 2012); and the United Kingdom's 4th Carbon Budget of the country's Carbon Plan, using the MARKAL model (Hawkes et al., 2011). Such models require a set of exogenous assumptions, such as the rate of demographic and economic development, rate of energy-efficient technology evolution and deployment, the availability and price level of energy resources, and the pace of implementation and effectiveness of policy decisions. The assumptions reflect the different levels of knowledge that energy system models integrate: social-economic-environmental knowledge basis, the range of policy measures, and finally uncertainty and subjectivity in the system (Rotmans and van Asselt, 2001).

Naturally, each of these assumptions has an associated uncertainty, as defined by the Intergovernmental Panel on Climate Change (IPCC) (Field, et al., 2012)[10] and typified in three groups by (Rotmans and van Asselt, 2001) as: technical uncertainty (regarding quality of input data), methodological uncertainty (regarding appropriateness of the modelling tool) and epistemological uncertainty (due to structural uncertainty and variability and managed via improved model completeness). Each of these lead to assumptions on exogenous parameters which will affect the overall degree of uncertainty of each GHG forecast (Moss, 2010; IEA, 2012; DECC, 2012; Strachan, 2011; Pilavachi, et al., 2008). It is common practice to model sets of alternative scenarios (formal scenario analysis) representing different sets of assumptions combined, as interesting pathways

[9] The emission scenarios used in the French NCCP are also an input in other national policies, especially the National Energy Efficiency Action Plan.

[10] In this paper we use the IPCC definition of the term: "An expression of the degree to which a value or relationship is unknown". It can result from many reasons as "quantifiable errors in the data, ambiguously defined concepts or terminology, or uncertain projections of human behaviour" and thus can be represented both quantitatively and qualitatively.

(Riahi, et al., 2007). Each pathway combines two or more sets of exogenous assumptions, resulting in a range of emission scenarios (Rotmans and van Asselt, 2001; Usher and Strachan, 2013). One of the most well-known examples of this approach is in the Special Report on Emission Scenarios (SRES) of the IPCC (IPCC, 2000). For example, the IPCC A1F1 emission scenario considers a pathway that describes a world with fast economic and population growth peaking in 2050, continued use of fossil fuels and moderate deployment of new and efficient technologies. On the contrary, the A2 scenario has continued population growth beyond 2050 but slower economic and technological change (IPCC, 2000). There is good reason to combine different pathways into feasible scenarios, namely avoiding the burden of assessing multiple combinations of assumptions, which might become impossible considering limited time and resources. In that combined process, however, information on the individual role of the different assumptions is lost and it is not possible to assess the contribution of each individual assumption on overall uncertainty of scenario outcomes. In other words, without separately assessing the role of individual assumptions as inputs in highly detailed energy system models, it is not possible to identify which of those are more relevant regarding model outputs and consequently more significant for policy decision that thus should be studied in more detail. An example is that substantial effort might be allocated to define and run different hydro or wind resources variability scenarios or different oil and gas import prices scenarios as part of an energy system modelling exercise when these changes in such prices are not critically influencing model results. On the contrary, assumptions that are not perceived as critically influencing model outcomes and are thus taken as "granted" can be found to have a more important effect in results and thus merit further exploration in their design. This paper is set out to fill this gap in assessing individual relevance of main energy system model assumptions, by making systematic individual variations in model inputs and assessing the different in results regarding climate and energy policy commitments (i.e. GHG abatement and renewable energy consumption targets). The paper's results allow guiding other energy system modelling exercises for climate policy support by highlighting which assumptions should be designed with more care in order to generate model results with more meaningful insights for policy making.

Typically, policy makers and modellers place special emphasis on assumptions on variations of socio-economic growth, on fossil fuel prices and on the availability of key energy technologies (e.g. variable renewable energy resources (RES) or nuclear). Assumptions on the pace of the implementation / decommissioning of planned electricity plants and detailed deployment of end-user energy efficient equipment (e.g. appliances or insulation) are not always perceived as equally relevant for uncertainty, possibly because these are areas that can be more easily controlled by national or regional policy making. Most national and EU GHG emissions scenarios do not explicitly address these two last exogenous assumptions (detailed in the next section), and to our knowledge individual variations to each of the exogenous assumptions was never performed with the TIMES family of models, nor with other energy system models. Although there are several papers relying on the use of TIMES and similar energy system models for a number of climate policy relevant questions (such as Chiodi et al., 2013; Kanudia et al., 2013; Capros et al., 2014; Anandarajah and Strachan, 2010) they do not cover their effective application for GHG emissions scenarios generation for policy support, nor do they analyse the individual roles of the considered exogenous assumptions. Typically, such studies include sensitivity analysis to a few specific assumptions, but not covering the whole range of exogenous model assumptions. Within the field of assessing uncertainty in GHG emission scenarios, the literature mostly deals with improving the methods used to address "epistemological uncertainty" as defined by (Rotmans and van Asselt, 2001). That is, it covers aspects related to trying to improve model completeness to better deal with structural uncertainty and variability, such as variability of climatic conditions. Examples are the work of (Michel, 2009; Labriet et al., 2012; Li et al., 2014). The work of (Strachan et al., 2009) is the closest in the literature to the approach we use here as the authors compared the effect of different assumptions in the MARKAL model for UK. However, the authors combined scenarios developed for different purposes over many years and did not focus on a systematic assessment of each assumption.

This paper further addresses this issue by assessing the contribution of each of a set of exogenous parameters, used in an actual policy support process, considering the Portuguese energy system as a case study. We vary the penetration of end-use energy efficient equipment; socio-economic growth rates; rate of implementation of policy incentives & investments for promotion of renewable electricity; availability of water resources for hydropower; and primary fossil energy import prices. The linear optimization technology model TIMES_PT is used to develop seven alternative GHG scenarios for 2020. One of these is a Baseline scenario which includes a combination of assumptions on all exogenous parameters, while the others have variations in only one of them.

The next section presents an overview of exogenous assumptions in GHG emission scenarios in several European countries in order to illustrate that the analysis of the Portuguese case is also relevant for other countries. This is followed by a section describing the methodology for scenario development in the TIMES_PT model, and finally the analysis of results, discussion of their implications and the conclusions.

## 2.2 OVERVIEW OF EXOGENOUS ASSUMPTIONS IN GHG EMISSION SCENARIOS ACROSS EUROPE

This section presents an overview of major exogenous assumptions in energy and GHG emission scenarios for nine European countries (Table 2.1), with estimates for 2020 and/or 2030. All these scenarios have been used to support national energy/climate change policies and have used highly detailed modelling tools. Of these, the tools used in the United Kingdom, Italy and France are large energy system models very similar to TIMES_PT used in this case-study.

This overview aims to: 1) demonstrate that the case study of the Portugal model and assumptions is relevant for other countries, as they have undertaken similar modelling exercises, with similar approaches to treatment of exogenous assumptions in "combined packages", and 2) set the context for variation of the assumptions within the analysis for the Portuguese case-study by looking into how these were treated in other countries.

We have reviewed the GHG emission scenarios developed for France, Germany, Italy, Ireland, Portugal, Romania, Spain, The Netherlands and United Kingdom, together representing 71% of the EU28 emissions in the annual average 2008-2012 (EC, 2013). The countries' selection was based on relevance for EU28 emissions measured as annual average 2008-2012 (EC, 2013) and availability of information on the methodology and usage of energy models for developing GHG emission scenarios. The biggest eight countries regarding annual average 2008-2012 GHG emissions in absolute terms in EU28 (80% of emissions) are as follows (from bigger to smaller): Germany, United Kingdom, France, Poland, Italy, Romania, Spain and The Netherlands. During this review we could not find detailed information on exogenous assumptions considered for Poland, which is thus not included in the overview presented in this section. Portugal was included as it is the focus of the paper and Ireland was considered as its energy system is much similar to the Portuguese one regarding size and technology profile (including share of RES).

In the reviewed policy support studies no systematic quantitative uncertainty assessments have been performed, with limited exceptions for the United Kingdom, Spain and the Netherlands. All studies include a simplified analysis varying one or more of selected exogenous assumptions. In none of the documents we found indication that a systematic series of variations in one or more of the assumptions was performed as part of the sensitivity analysis. Instead, very specific alternative cases were assessed, e.g. high oil prices relative to a specific oil price or no implementation of a specific policy measure (P&M). The assessed assumptions probably reflect ideas on what is politically acceptable or relevant, regardless of effects on GHG emissions as modelled. This is the case for example in the revision of the German forecasts introducing a nuclear exit option following the Fukushima accident.

We have found that from these nine studied cases only Portugal and Spain have used more than one macro-economic scenario. All forecasts, consider different degree of implementation of existing and planned P&M that can be broadly grouped with having effects on energy intensity via promotion of energy efficiency and on the deployment of renewable electricity (RES-e) power plants. The most common considered P&M are the National Energy Efficiency Action Plans (NEEAP) and the National Renewable Energy Action Plans (NREAP). Not all of the forecasts are developed exclusively with the aim of deriving GHG emissions scenarios or projections, as they are used for national energy planning. Therefore, probably some of the assumptions are relevant for energy policy making and not necessarily for GHG emission mitigation. Nonetheless, when it comes to energy production and consumption these two are closely related enough for considering them in our study.

From this overview we conclude that the exogenous assumptions that we assess for the Portuguese case-study are in line with what is being done in other European countries and that these countries use similar energy system models to TIMES_PT to support national climate policy. Therefore, it becomes clear that the approach we develop in the following sections is not only relevant but replicable for other countries.

**Table 2.1** | Examples of medium term GHG emission scenarios and projections from energy production and consumption and considered exogenous assumptions.

| Study | Methods | Timeline | Major exogenous assumptions[a] |
|---|---|---|---|
| Dutch Reference projection energy and emissions 2010-2020 | 12 combined models including POWERS for wholesale Dutch electricity market and RESolve-E for renewable electricity (ECN/PBL, 2012) | 2020-2030 | Three scenarios with the following policy variants: adopted P&M, adopted plus proposed, and adopted plus "*Lente*" policy package. This entails differences in: level of effectiveness of buildings thermal regulations, deployment of more efficient technologies and installed fossil power capacity in 2020, level of financial incentives to RES power plants (and subsequent RES-E generation), biofuels and deployment of RES technologies for heating and cooling.<br>All scenarios have the same macro-economic assumptions (-0.3% GDP annual growth rate in 2010, 1.7% in 2011-2020), as well as energy and $CO_2$ prices (20 €/t in 2020). However, the uncertainties regarding some of the parameters' assumptions above were translated into uncertainty of energy use and emissions per sector by attributing ranges to energy and $CO_2$ prices. |
| French NCCP | POLES energy system simulation model (DGEC, 2011) | 2020-2030 | Two scenarios, with and without the P&M in the Grenelle policy package (Pre-Grenelle and Grenelle scenarios). This entails differences in: level of effectiveness of thermal regulations for buildings, EU ETS $CO_2$ prices for industry (18 or 25€/t in 2020), type of biofuels in road transport (1st and 2nd generation), deployment of new installed nuclear capacity in 2020 and level of cross border electricity trade.<br>Both scenarios rely on the same macro-economic assumptions (1.5% GDP annual growth rate in 2010-2015, 2.2% in 2015-2020 and 1.6% in 2020-2030) and energy prices (oil price of 100 USD/bbl in 2020 and 115 USD/bbl in 2030). The scenarios mention a preliminary sensitivity analysis on nuclear power capacity. |
| German Scenarios for an Energy Policy Concept | DIME investment and dispatch optimisation model for electricity and CHP and LORELEI optimisation model for renewable electricity integration (Schlesinger et al.,2011) | 2020 (2050) | Five scenarios: reference plus scenarios I - IV, where the reference scenario reflects the extrapolation of observable trends and no $CO_2$ cap. Scenarios I - IV have a 2020 $CO_2$ cap of 40% below 1990 levels, different extension times for existing nuclear power plants and rates for energy efficiency improvements. An update was made in 2011 following the Fukushima accident converging in an "Exit" and "Life Extension" scenarios regarding the nuclear plants.<br>Only one common macro-economic scenario with the following GDP annual growth rates: 0.35% in 2008-2015 and 0.66% in 2016-2020 with oil price of 98 USD/bbl in 2020 and 110 USD/bbl in 2030. The $CO_2$ prices are of 20 or 19-23 $€_{2008}$/t in 2020, respectively for the reference and I – V scenarios. No other explicit sensitivity analysis or variation in assumptions seems to have been made but for alternative retrofit costs for nuclear power plants in the scenarios I – V. |

| Study | Methods | Timeline | Major exogenous assumptions[a] |
|---|---|---|---|
| Irish GHG emissions and energy forecasts | HERMES macro-economic model for the energy sector and IDEM electricity dispatch model (Clancy et al., 2011) | 2020 | Three scenarios with different policy variants: Baseline (all P&M until end of 2010), NREAAP/NEEAP with the P&M in these two plans including +7% RES installed capacity in 2020 than Baseline, and the Exploratory scenarios with two variations: Exploratory Potential with higher RES deployment (+148% installed capacity in 2020 than Baseline) and Exploratory Risk with a more pessimistic view of energy efficiency and RES developments (-1% installed capacity in 2020 than Baseline).<br>All scenarios have the same macro-economic assumptions (3.0% GDP annual growth rate in 2011-2015, 3.3% in 2016-2020), as well as energy (oil price of 111 USD/bbl in 2020) and $CO_2$ prices (33 €/t in 2020). No variations in oil prices or in economic growth are quantified, although discussed. The variations in exogenous parameters are the ones in the scenarios described. |
| Italian GHG emissions and energy scenarios | TIMES Italy energy system optimisation (ENEA, 2012) | 2020-2030 | Three scenarios Reference (P&M in place as in 2009), Current Policies (considers effect of NEEAP and NREAP) and Roadmap (necessary additional P&M to c0mply with GHG target as in EU Road Map 2050).<br>All scenarios have the same macro-economic assumptions (1.0% GDP annual growth rate in 2011-2015, 1.5% in 2016-2020), as well as energy (oil price of 108 USD/bbl in 2020 and 129 USD/bbl in 2030) and $CO_2$ prices (32 €/t in 2020). The variations in exogenous parameters are only the ones in the described scenarios. |
| Portuguese NCCP | TIMES_PT energy system optimisation model (Seixas et al., 2009) | 2020-2030 | Four scenarios combining two different macro-economic scenarios (Tendency and Change) with different level of implementation of P&M as planned in the previous version of the NCCP and NEEAP (from energy efficiency in buildings to deployment of RES power plants and biofuels in transport) and as in the energy policy targets to meet with the RES final energy national target: Business as Usual (only existing policies and RES plants), Tendency Kyoto and Change Kyoto (P&M and RES deployment as in the NCCP and NEEAP) and Road Map RES (high RES deployment).<br>The two macro-economic assumptions scenarios encompass the following GDP annual growth rates: 1.7 – 1.9% GDP in 2006-2010, 1.9 – 2.8% in 2011-2015 and 2.1 – 3.2% in 2016-2020). All consider the same energy prices including an oil price of 84 USD/bbl in 2020, 93 USD/bbl in 2030, and no $CO_2$ prices. Sensitivity analyses were performed for high primary energy import prices and for low and high hydro availability. |

| Study | Methods | Timeline | Major exogenous assumptions[a] |
|---|---|---|---|
| Spanish GHG emissions and energy scenarios | Non identified simulation tool (MINETUR, 2011, MAGRAMA, 2011) | 2020 | In MINETUR (2011) there are three scenarios: Central, High and Low considering a similar degree of implementation of P&M (NEEAP (E4), Spanish Strategy for Climate Change and Clean Energy, NREAP, Strategic Carbon reserve Plan and the Industry Policy Plan (PIN2020)) but different annual rates for the reduction of the final energy intensity in 2010-2020 (respectively 2%, 1.5% and 2.5%), resulting in differentiated final and primary energy consumption. In order to ensure the compliance with the common RES targets a differentiated RES deployment is considered in the Central and High scenarios (22% more RES installed capacity in 2020 in the High scenario).<br>The three macro-economic assumptions scenarios, Low, Central, and High, encompass the following respective GDP annual growth rates: 1.9, 2.2 and 2.9% in 2010-2015 and 1.8, 2.4 and 2.8% in 2016-2020. All consider the same energy prices including an oil price of 111 USD/bbl in 2020, and $CO_2$ prices of 25 €/t in 2020.<br>For the official GHG emission scenarios (MAGRAMA, 2011) a slightly different approach was considered as the three GHG emission scenarios assume different degree of implementation of the P&M above (WoM with only P&M until 2000, WM with the P&M until 2020 and WaM with P&M under discussion). It is developed an uncertainty analysis with subjective probability levels defined by experts to identify upper and lower ranges for economic evolution, energy and material efficiency, emission factors and general uncertainty within a 95% confidence interval. |
| UK GHG emissions and energy projections | DECC Energy and Emissions model (DECC, 2012) | 2020 | Due to the frequent update of the projections only one central scenario is presented, but factors affecting the emission estimates are mentioned when comparing with the previous projections (e.g. changes to savings estimates via implementation of policies, in power plant assumptions or changes to economic long term growth projections). The projection considers the implementation of all current climate change policies.<br>The projections rely on one macro-economic scenario with annual GDP growth rates of 2.5% in 2010-2015 and 2.8% in 2016-2020). The central scenario has an oil price of 118 USD/bbl in 2020 and 128 USD/bbl in 2030 plus a $CO_2$ price of 24 - 27 €/t in 2020 respectively for industry and electricity generation. In addition there are low and high fossil fuel prices scenarios with corresponding $CO_2$ prices. An uncertainty assessment was performed based on Monte Carlo simulation to capture the likely variations in the following key inputs to the projections: fuel prices, GDP, temperatures, policy impacts, power station capital costs, non-$CO_2$ emissions. |

[a] Except if otherwise mentioned all oil prices are in USD 2010 and $CO_2$ prices refer to ETS and are in Euros 2010.

## 2.3 Methods and Model

To quantify the contribution of different exogenous assumptions on the uncertainty of GHG emission scenarios we have used Portugal and the energy system model TIMES_PT as a case-study. The main motive for using this country and model was the privileged access to information on how the model outcomes were used for policy support, since the authors were involved in this exercise (Seixas et al., 2009). From the previous section and as mentioned before it becomes clear that the assumptions considered for analysis in the Portuguese case study are relevant for other European countries which use very similar methods to generate GHG emission scenarios for their climate policy making.

To assess the effects of each exogenous assumption for Portugal we developed seven scenarios for 2020 using the TIMES_PT model. TIMES_PT is a linear optimisation bottom-up technology model generated with the TIMES model generator from ETSAP[11] of the International Energy Agency. More detailed information on TIMES in general, including basic concepts and equations can be found in (Loulou et al., 2005). The TIMES_PT model uses these same equations representing the Portuguese energy system from 2000 to 2030 (more details in Appendix A). The model considers both the supply and demand sides and includes the following seven sectors: primary energy supply; electricity generation; industry; residential; commercial; agriculture; and transport.

The seven scenarios used to assess the effect of exogenous model assumptions are: Baseline (BASE), Efficiency (EFF); Demand (DEM), Low Renewable Electricity (low RES-e), Low Hydro (LowH), High Hydro (HighH) and High Oil Price (100$). Each of these is detailed in this section. We defined the ranges of the assumptions variations for each scenario together with Portuguese policy makers (Portuguese Environment Agency, Inter-Ministerial Panel for Climate Change and Ministry of Economy) during the development of the Portugal CLIMA 2020 study commissioned by the Ministry of Environment (Seixas et al, 2009).

The BASE scenario was developed considering a number of assumptions on exogenous model inputs, such as on demographic and economic evolution, technology deployment, energy resources availability and on the implementation and effectiveness of policy decisions. In each of the other six scenarios we made a variation in one of the exogenous assumptions. Besides this variation, which is explained in detail below, these scenarios are identical to BASE. None of the scenarios include a GHG cap or $CO_2$ tax.

[11] Energy Technology Systems Analysis Programme

### 2.3.1 EFF SCENARIO - PENETRATION OF END-USE EFFICIENT EQUIPMENT IN THE DEMAND SECTORS

Regarding the promotion of end-use energy efficiency & renewable end-use equipment, all scenarios except EFF have the same limited penetration of new equipment for residential, commercial and industry, based on 2000-2005 trends and on the estimated evolution until 2015 (assumed to be maintained until 2020) as in the NEEAP (RCM 80/2008). The EFF scenario does not have any limits on the degree of penetration of end-use efficient & renewable equipment. Thus, it reflects the maximum gains obtained by the full realisation of the national demand-side technological potential. Therefore, this paper only addresses savings due to technological replacement and does not assess energy savings due to reduction of demand for energy services, such as reduction in thermal comfort requirements motivated by environmental awareness (see also Appendix 2A).

If no exogenous limits are imposed to the penetration rate of efficient & renewable equipment, a substitution of existing technologies will happen as this leads to cost savings. As previously mentioned, TIMES_PT is an optimisation model with the ultimate objective of cost reduction. Thus, barriers to the penetration of cost-saving new equipment such as resistance to change, imperfect information, and aesthetics or other subjective preferences are not considered by the model. In order to reflect these “realistic” constraints, exogenous inertia factors are considered in all scenarios. With the exception of EFF, all scenarios have embedded a delay in the penetration rate of new technologies and fuels in the residential, commercial and industry sectors. These factors were defined for the replacement of existing lighting and other electric appliances, for penetration of insulation, and for existing biomass, LPG and diesel technologies for cooking, space heating, and water heating by new more efficient alternatives, but using the same fuels. The main differences in the scenarios regarding end-use efficient equipment are presented in Table 2.2.

**Table 2.2** | Differences between scenarios regarding the penetration of end-use efficient equipment.

| Measure/Scenario | Unit | 2010 | 2020 | |
|---|---|---|---|---|
| | | | **BASE, DEM, low RES-e, LowH, HighH, 100$[a]** | **EFF** |
| Maximum Insulation in existing buildings | % of households and of commercial building area | n.a. | 9% | 50% |
| Maximum double glazed windows in existing buildings | % of households and of commercial building area | n.a. | 18% | 50% |
| Maximum solar thermal water heating | % of households<br>% of commercial building area | n.a.<br>n.a. | 8%<br>1.2% | 100%<br>100% |

| Measure/Scenario | Unit | 2010 | 2020 | |
|---|---|---|---|---|
| | | | BASE, DEM, low RES-e, LowH, HighH, 100$[a] | EFF |
| Maximum heat pumps and efficient biomass heating | % of households and of commercial building area | n.a. | 8% | 100% |
| Maximum efficient lighting (CFL) | % of efficient lamps in total lighting | 15% | 61% | 100% |
| Maximum efficient refrigeration (A+ and A++) | % efficient freezers and refrigerators | 1% freezers 8% refrigerators | 37% freezers 25% refrigerators | 100% |
| Maximum efficient dishwashers and cloth washing appliances (A+ and A++) | % efficient dishwashers and cloth washing | 1% | 25% | 100% |

n.a. – not available; [a] Portuguese NEEAP objectives for 2015, assumed identical for 2020.

### 2.3.2 DEM SCENARIO - SOCIO-ECONOMIC SCENARIOS AND ENERGY AND MATERIALS DEMAND PROJECTIONS FOR 2020

Demand projections drive the whole energy system modelled in TIMES_PT and the effects of a demand variation were studied with the DEM scenario. Despite this variation, all seven scenarios share the same projection methodology used in all scenarios, as follows. The socio-economic scenarios and respective materials and energy services demand projections considered in this paper were generated within the study “PortugalClima2020 - Impact evaluation of the EU climate and energy policy package in Portugal” for the Portuguese Ministry of Environment (Seixas et al., 2009). Under this study two different socio-economic scenarios (and demand projections) were built: Tendency and Change. The first assumes a moderate economic and demographic growth, whereas the latter is more optimistic as it assumes a higher economic growth and an economic shift towards innovation and technology (Ribeiro et al., 2008). For the purpose of this paper, the Tendency scenario was considered in all scenarios except DEM which considers the higher growth of the “Change” socio-economic scenario, as summarised in Table 2.3 and in Appendix 2B.

**Table 2.3** | Differences between scenarios regarding main macro-economic drivers until 2020.

| Parameter | Unit | 2000 | 2005 | BASE, EFF, low RES-e, LowH, HighH, 100$ | | | DEM | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | **2010** | **2015** | **2020** | **2010** | **2015** | **2020** |
| GDP | Meuros (2000) | 122270 | 127490 | 138863 | 152436 | 168729 | 139935 | 160384 | 187933 |
| Private consumption | Meuros (2000) | 73702 | 79420 | 85600 | 93586 | 103327 | 85985 | 97759 | 113330 |
| Population | 1000 inhab. | 10226 | 10549 | 10596 | 10538 | 10420 | 10656 | 10725 | 10740 |
| **Annual average growth rate %** | | | **'01-'05** | **'06-'10** | **'11-'15** | **'16-'20** | **'06-'10** | **'11-'15** | **'16-'20** |
| GDP | | | 0.8% | 1.7% | 1.9% | 2.1% | 1.9% | 2.8% | 3.2% |
| Private consumption | | | 1.5% | 1.5% | 1.8% | 2.0% | 1.6% | 2.6% | 3.0% |
| Population | | | 0.6% | 0.1% | -0.1% | -0.2% | 0.2% | 0.1% | 0.0% |

### 2.3.3 Low RES-e scenario - Implementation of infrastructures and incentives for production of renewable electricity

Regarding the promotion of renewable electricity, the major difference between low RES-e and all other scenarios is the degree of RES in electricity generation and in biofuels consumption in transports as detailed in Table 2.4. All seven scenarios include: i) the *mandatory target set by the European Biofuels Directive* from 2003[12] of a biofuels consumption of 5.75 % of petrol and diesel use for transport in 2010, which is extended to 2020, and ii) *current and on-going investments* on renewable energy supply infrastructures to achieve the indicative target of 39% RES-e on gross electricity consumption by 2010, following the RES- e European Directive from 2001[13]. In addition, in all six scenarios, except the low RES-e, are considered: i) the more ambitious *national target of 10% biofuels* consumption of petrol and diesel use for transport in 2010 (extended to 2020), ii) the *expected but not yet implemented* investments on renewable energy supply infrastructures to achieve the indicative target of 45% RES-e for 2010 and to comply with the national Kyoto Protocol GHG emission target, according to national policy commitments (RCM 1/2008; INAG, DGEG, REN, 2007; MEI, 2007a; MEI, 2007b). This includes the installation of 900 MW of a coal power plant with $CO_2$ capture and storage (CCS) in 2020.

The minimum installed capacity of RES-e technologies were implemented in the model as in Table 2.4. In the BASE, EFF, DEM, LowH, HighH and 100$ scenarios the minimum installed capacities were retrieved from the Ministry of Economy objectives for 2010 to 2020 (MEI, 2007a). In the low RES-e scenario conservative estimates were made for 2020 based in the 2007 installed capacity, on issued permits, and assuming a growth rate similar to the verified in 2000-2007 for the cases of non-CHP

[12] Directive 2003/30/EC on the promotion of the use of biofuels or other renewable fuels for transport.

[13] Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market.

biomass, solar photovoltaic (PV) and biogas power plants. Also reflecting the current energy policies, which include incentives for combined cycle gas turbines (CCGT), the authorised investments for new 3.2 GW of CCGT are included in all scenarios. Of these 1.6 GW were operating in 2010. In the BASE, EFF, DEM, LowH, HighH and 100$ scenarios, 1.6 GW of new CCGT are assumed to function at least at 37% of their capacity. This is the minimum threshold to justify investment in such plants, based on information supplied by the National Energy Directorate (DGEG). In the low RES-e scenario, the new CCGT are installed but are not forced to operate (Table 2.4).

**Table 2.4** | Differences between scenarios in terms of infrastructure and in incentives for RES-E reduction.

| Measure/Scenario | Unit | 2010 | 2020 | |
|---|---|---|---|---|
| | | | BASE, DEM, EFF, LowH, HighH, 100$ | low RES-e |
| Biofuel consumption target | % consumption of petrol & diesel use for transport | Gasoline: 0.0% & Diesel: 0.08%[a] | 10% | 5.75% |
| RES-E installed capacity | GW | 9.41 | 13.43 | 10.42 |
| Hydro | GW | 4.84 | 6.86 | 5.58 |
| Wind-onshore | GW | 3.87 | 5.70 | 4.50 |
| Biogas | GW | 0.01 | 0.10 | 0.05 |
| Solar | GW | 0.13[b] | 0.15 | 0.10 |
| Waste | GW | 0.09 | 0.12 | 0.12 |
| Biomass (non-CHP) | GW | 0.11[b] | 0.25 | 0.05 |
| Waves | GW | 0.00 | 0.25 | 0.03 |
| New Gas CCGT (minimum CCGT activity % of capacity) | GW | 3.04 (34%) | 4.38 of which 3.2 new (37% minimum activity) | 4.38 of which 3.2 new (no minimum activity) |

[a] values for 2009; [b] for solar and biomass the on-going investments at the time the results were generated totalled 0.10 GW and 0.05 GW for 2020, respectively. These were the minimum capacities introduced in the model. However, the most recent official data for 2010 (made available in the end of 2011) show that the figure was exceeded already in that year.

### 2.3.4 LowH and HighH scenarios - Availability of hydro resources

Hydropower plays an important role in electricity generation in Portugal (26.8% of total generated electricity in 2000). However, its contribution depends on each year's hydrological characteristics, which have high annual oscillations (38% of generated electricity in 2003 and only 20% in 2002). For all scenarios, except for LowH and HighH, the available hydro resources considered in the TIMES_PT model replicate an average hydrological year. This means that from 2000 to 2030 all modelled years have identical annual hydro availability (with seasonal variations) which is similar to those available in the year 2000 (an average hydrological year according to (DGEG, 2012)).

In the LowH scenario the availability of hydro resources for power generation replicates 2005 values, a dry year (IPH of 0.336). In the HighH scenario the hydro availability replicates the values of 2003, a wet year (IPH of 1.090). All other five scenarios (BASE, EFF, DEM, low RES-e, 1004 bbl) have hydro availability corresponding to an IPH of 0.885 (as in 2000). The low and higher hydro availabilities of LowH and HighH were modelled in a simplified form by reducing or increasing the availability factors of each (existing and new) hydro power plant technologies. The reduction and increase of availability factors is roughly the same as the difference between average, dry and wet IPH. Thus, the availability factor of the LowH scenario is 62% lower than the BASE & other scenarios, and the AF of the HighH are 23% higher.

### 2.3.5 100$/BBL SCENARIO - PRIMARY ENERGY IMPORT PRICES

For all scenarios except for 100$ scenario the average primary energy imports prices projections, as presented in Table 2.5 for coal, oil and gas, were adopted from the Reference scenario of the PRIMES and GEM-E3 models used by the EU in the preparation of the energy-climate policy package (Russ et al., 2009). The oil prices vector are generated by the global POLES[14] model, considering scenarios of available oil, new oil reserves that might be discovered and the supply and demand laws. The corresponding real gas and coal prices were estimated by (Seixas et al., 2009) considering the annual relationship between oil and other fossil fuels assumed by the IEA in the Reference scenario of the World Energy Outlook 2007 (IEA, 2007).

For the 100$ scenario it was assumed the high oil prices scenario from the study on oil prices developed by the Department of Prospective and Planning and International Relations of the Portuguese Ministry of the Environment (Ribeiro et al., 2008). This national study was based on scenarios developed by IEA and US National Energy Agency and was validated by national energy experts. The corresponding real gas and coal prices were estimated by (Seixas et al., 2009) considering the annual relationship between oil and other fossil fuels assumed by the IEA in the High Growth scenario of the WEO 2007 (IEA, 2007).

**Table 2.5** | Major differences between scenarios regarding primary energy import prices.

| Year | BASE, DEM, low RES-e, EFF, LowH, HighH | | | 100$ | | |
|---|---|---|---|---|---|---|
| | **Oil ($2010/bbl)** | **Natural Gas ($2010/m³)** | **Coal ($2010/ton)** | **Oil ($2010/bbl)** | **Natural Gas ($2010/m³)** | **Coal ($2010/ton)** |
| 2000 | 37.63 | 0.22 | 37.01 | 37.63 | 0.22 | 37.01 |
| 2005 | 60.01 | 0.28 | 69.11 | 60.01 | 0.28 | 69.11 |
| 2010 | 56.21 | 0.23 | 53.39 | 97.94 | 0.41 | 89.29 |
| 2015 | 58.88 | 0.25 | 58.46 | 101.99 | 0.43 | 90.32 |
| 2020 | 61.69 | 0.26 | 61.12 | 106.21 | 0.45 | 91.36 |

[14] http://www.enerdata.fr/enerdatauk/tools/Model_POLES.html

Moreover, the most recent values from the IEA for Europe in 2020 (IEA, 2012) are substantially higher than the Base & Other scenarios (e.g. 97 to 118 $2010/bbl of oil) which might have a significant effect on absolute results. However, the (too) low price estimates still allow for a view on the role of *differences* in oil price levels. It should be noted that in the Energy Roadmap 2050 considers in 2020 89 $ 2010/bbl of oil for the reference scenario and 133.5 $2010/bbl for the high scenario (EC, 2011).

### 2.3.6 SUMMARY OF THE STUDIED SCENARIOS

The seven studied scenarios were designed to integrate in varying degrees the major exogenous assumptions considered in the development of GHG emission scenarios: penetration of end-use energy efficient equipment; socio-economic growth rates; rate of implementation of policy incentives & investments for promotion of RES-E; availability of water resources for hydropower; and primary fossil energy import prices. The scenarios are summarised in Table 2.6.

**Table 2.6** | Synthesis of the modelled scenarios.

<table>
<tr><th>Assumption</th><th>BASE</th><th>EFF</th><th>DEM</th><th>low RES-e</th><th>LowH</th><th>HighH</th><th>100$</th></tr>
<tr><td>Penetration of end-use energy efficient equipment</td><td>Following NEEAP targets</td><td>High</td><td colspan="5">Following NEEAP targets</td></tr>
<tr><td>Socio-economic growth</td><td colspan="2">Tendency</td><td>Change (high growth)</td><td colspan="4">Tendency</td></tr>
<tr><td>Implementation of policy incentives & investments for promotion of RES-E</td><td colspan="3">Extra investments for 45% RES-e & 10% biofuels</td><td>Only current & on-going investments & 5.75% biofuels</td><td colspan="3">Extra investments for 45% RES-e & 10% biofuels</td></tr>
<tr><td>Availability of water resources for hydropower</td><td colspan="4">Average hydrological year</td><td>Dry year</td><td>Wet year</td><td>Average hydrological year</td></tr>
<tr><td>Primary fossil energy import prices</td><td colspan="6">Reference</td><td>High</td></tr>
</table>

Finally, in all seven scenarios the following assumptions are made reflecting the most relevant Portuguese energy policies in place:

i. A ban on nuclear power due to the political unacceptability of this option in the modelled time horizon;
ii. New coal power plants will only be available from 2015 onwards following energy sources diversification policy and support to the use of natural gas. It is assumed that

"conventional" coal power plants without sequestration will not be implemented from 2015 onwards, following expected GHG control policies;

iii. The 2005 tax on oil products, differentiated according to the energy carriers, was included and extended until 2020;

iv. To emulate developments in electricity imports and exports - affected by interconnection capacity with Spain - increasing maximum limits were set from 2000 to 2030, up to a maximum import and export of 46 and 20 PJ in 2020, respectively, and of 60 and 30 PJ in 2030. These are rough estimates since there are no good forecasts at the moment, although they are in line with the national transmission operator studies (REN, 2008). This corresponds to a growth of imports with 255% and of exports with 121%. Thus, trade uncertainty under the liberalised Iberian electricity market is not considered.

## 2.4 RESULTS

This section presents the comparison between the six studied scenarios and the Base case in terms of GHG emissions and renewable energy consumption and their compliance with the energy-climate policy package. The assumptions with a higher % difference from what was considered in BASE (energy prices and low hydro) do not necessarily lead to the higher variations in national GHG emissions from 1990 till 2020 as depicted in Figure 2.1.

The GHG emission estimates of the three scenarios related to costs and availability of primary energy (LowH, HighH and 100$) lead to variations in 2020 total national GHG emissions that are less than 2% different from BASE as shown in Table 2.7 and Table 2.8. Table 2.7 presents the variation in GHG emissions in 2020 for the studied scenarios as well as an indication (in % estimated from the assumptions in BASE) of the magnitude of the variation introduced for each of the exogenous assumptions. Table 2.8 summarises the GHG emissions for all scenarios, aggregated for EU ETS and non EU ETS.

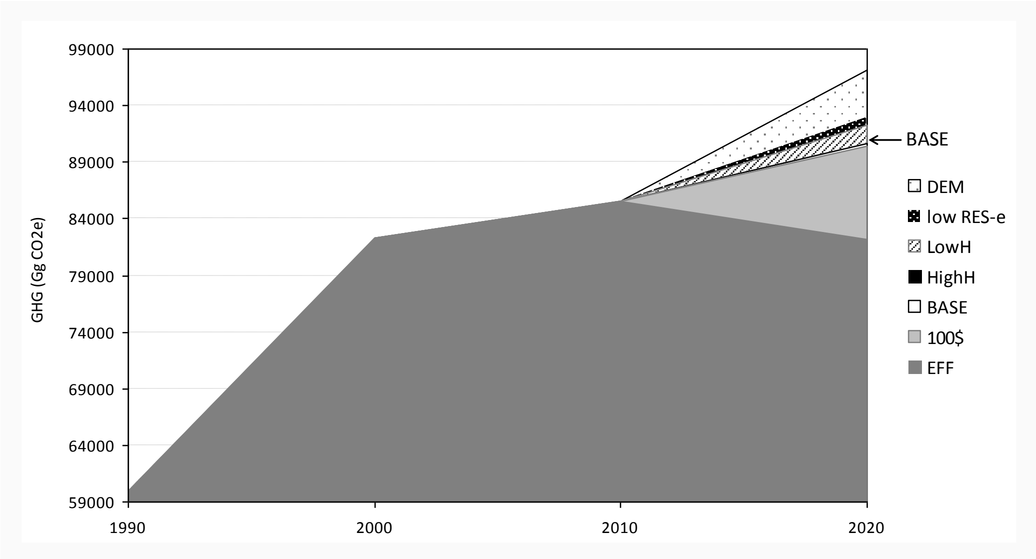


**Figure 2.1** | Variation in GHG emissions from 1990 to 2020 for the modelled scenarios.

The EFF scenario is the one with a higher difference in 2020 emissions from BASE (less 9%), followed by DEM with emissions roughly 7% higher than BASE. The delayed or slower implementation of policy incentives & investments to RES-E leads to an increase in emissions of only 2.5%. In overall terms it seems that the emission changes are not significant. In this analysis it should be remembered that emissions from F-Gases, waste and non-energy agriculture emission sources were not estimated by TIMES_PT and are thus identical in all scenarios (see (Seixas et al., 2009) for a detailed description on how these non-energy GHG emission estimates were made).

**Table 2.7** | Indicative variation in assumptions in 2020 compared to BASE and corresponding variation in GHG emissions.

| Scenario | % variation in assumption input in the model compared to assumption as in BASE in 2020 | % variation in total GHG[a] emissions in 2020 |
|---|---|---|
| EFF | -42% demand for energy services in buildings, since this can be met with more efficient technologies. This is a proxy measure of the variation in the assumption weighting the different assumptions for the different technologies with the weight of the useful energy service demand they can potentially affect (space heating, lighting, refrigeration, etc.) | -9.3% |
| DEM | +5% for energy services demand modelled as useful energy (agriculture, buildings and non-energy intensive industry)<br>+1% for passenger transport and +8% for freight transport<br>-2% for energy intensive industry (modelled as Mt) | +7.1% |
| Low Res-e | -43% RES-e installed capacity | +2.5% |
| LowH | -62% availability factor for hydro plants | +1.7% |
| HighH | +23% availability factor for hydro plants | 0.0% |
| 100$ | +72% oil and gas prices and +49% coal price | -0.3% |

[a] Because the TIMES_PT model deals exclusively with emissions from combustion and productive processes (approximately 81% of national emissions in 2005 (APA, 2008), to verify compliance with GHG targets emissions not estimated in TIMES_PT were also considered (GHG emissions from solvents use, non-combustion agricultural activities, waste management, and f-gases) from (Seixas et al., 2009).

**Table 2.8** | GHG emission estimates for 2020 (Gg CO2e).

| **Sector/Scenario** | **2005** | **2020** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **BASE** | **EFF** | **DEM** | **low RES-e** | **LowH** | **HighH** | **100$** |
| Energy Supply | 28 283 | 31 720 | 32 627 | 31 806 | 30 713 | 31 778 | 31 720 | 31 719 |
| Industry & Solv. | 15 964 | 15 146 | 13 104 | 16 521 | 16 833 | 16 398 | 15 146 | 15 124 |
| Transport | 19 861 | 21 570 | 15 875 | 26 194 | 22 617 | 21 648 | 21 570 | 21 639 |
| Commercial | 3 437 | 2 841 | 940 | 2 868 | 2 891 | 2 891 | 2 841 | 2 828 |
| Residential | 2 652 | 2 512 | 2 787 | 2 874 | 2 989 | 2 628 | 2 512 | 2 239 |
| F-Gases | 799 | 2 137 | 2 137 | 2 137 | 2 137 | 2 137 | 2 137 | 2 137 |
| Agriculture | 9 059 | 9 074 | 9 074 | 8 947 | 9 074 | 9 074 | 9 074 | 9 074 |
| Waste | 7151 | 5 679 | 5 679 | 5 679 | 5 679 | 5 679 | 5 679 | 5 679 |
| National Total | 87 205 | 90 677 | 82 223 | 97 026 | 92 933 | 92 233 | 90 677 | 90 439 |
| t CO2e/Meuros GDP | 684 | 537 | 487 | 575 | 551 | 547 | 537 | 536 |
| | **Total Non EUETS** | **48 535** | **48 535** | **41 106** | **41 106** | **50 875** | **49 384** | **48 535** |
| | **Total EUETS** | **42 142** | **42 142** | **41 117** | **41 117** | **42 058** | **42 849** | **42 142** |
| **% Variation from 2005** | | | | | | | | |
| EU ETS | | 16 | 13 | 19 | 15 | 18 | 16 | 16 |
| Non-ETS | | -4 | -19 | 6 | 0 | -3 | -4 | -5 |
| Total | | 4 | -6 | 11 | 7 | 6 | 4 | 4 |
| **% Variation of total emissions from BASE** | | **---** | **-9.3** | **7.1** | **2.5** | **1.7** | **0.0** | **-0.3** |

In Figure 2.2 is presented the 2020 sector emission variations calculated as % from BASE scenario emissions. The difference in emissions in the EFF scenario is mostly due to less 67% emissions from commercial buildings than in BASE and to a lesser extent to reduced emissions from transport and industry. The causes for these lesser emissions are the faster substitution of existing equipment by more efficient ones. The EFF scenario also has more 42% emissions from CHP than BASE due to the higher activity of new gas CHP plants. The DEM scenario has higher GHG emissions from all modelled sources due to the higher demand for energy services. In the low RES-e scenario, the delay in implementation of RES-e incentives & infrastructures is not translated in an increase in emissions for the power sector. However, the demand sectors do increase emissions as less electricity is used.

Although the overall differences in GHG emissions are never above 10% compared to BASE emissions, they still have an impact in compliance with the energy-climate policy package, especially regarding the RES target of 31% for 2020 (EC, 2009a) (Table 2.9). The RES share of final energy consumption of the BASE scenario is 27% and the different exogenous assumptions can lead to differences of more 4% which allow complying with the target (as happens for the EFF scenario), or less 4% (low RES-e scenario). These differences in RES share are due to changes in all sectors energy profile, depending on the scenario. Regarding the compliance with GHG emissions targets (EC, 2009b) the differences in scenarios (Table 2.9) are more relevant for the non-ETS emissions especially for the EFF scenario (less 19% emissions in 2020 than in 2005).

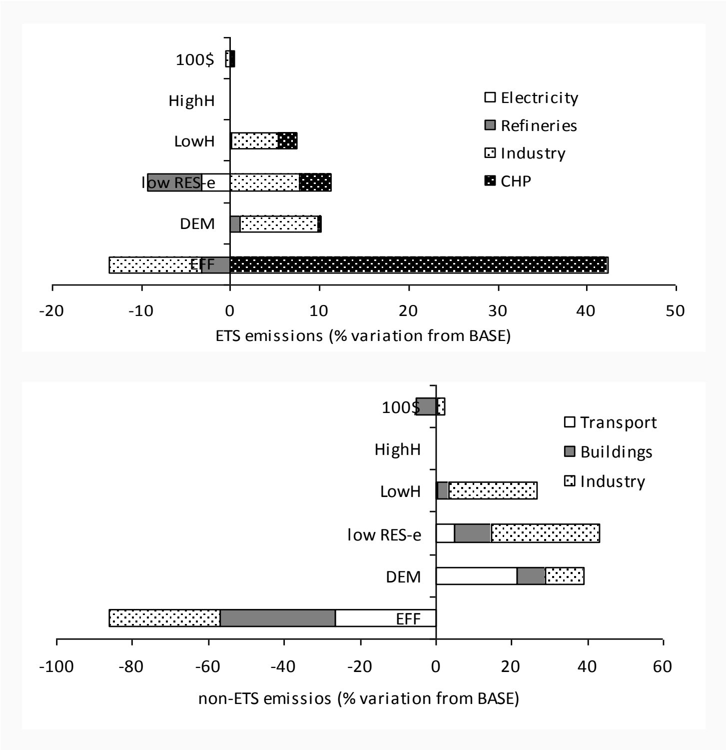


**Figure 2.2** | ETS and Non-ETS GHG emission estimates for 2020 represented as % variation from the BASE scenario.

**Table 2.9** | RES share of final energy consumption in 2020 (PJ).

| Sector/ Scenario | BASE | EFF | DEM | low RES-e | LowH | HighH | 100$ |
|---|---|---|---|---|---|---|---|
| Electricity | 136 | 142 | 145 | 112 | 101 | 147 | 145 |
| Heath & cooling | 100 | 99 | 105 | 101 | 102 | 71 | 76 |
| Residential | 48 | 51 | 49 | 49 | 49 | 24 | 20 |
| Commercial | 10 | 14 | 13 | 10 | 10 | 11 | 13 |
| Industry | 43 | 34 | 43 | 42 | 43 | 36 | 43 |
| Transport | 31 | 26 | 33 | 18 | 31 | 27 | 27 |
| Final Renewable Energy (a) | 267 | 267 | 284 | 232 | 234 | 245 | 248 |
| Total Final Energy (b) | 976 | 866 | 1072 | 974 | 973 | 846 | 853 |
| % Renewables (a/b) | 27 | 31 | 26 | 24 | 24 | 29 | 29 |
| **% diff of a/b from BASE** | | **4** | **-1** | **-4** | **-3** | **2** | **2** |

## 2.5 Discussion

From the results presented before it appears that the most relevant assumptions in a TIMES model for overall GHG variations are the ones related to the socio-economic development (macro-economic and population growth). This view is shared by (ECN, 2010; IEA, 2012; DECC, 2012). The assumptions on end-use efficient technology deployment are the next most important. On the contrary to what is perceived by policy makers, judging by the large number of scenarios and forecasts that look into these (see (van Ruijven and van Vuuren, 2009) for an overview of these), fossil fuel prices and the availability of renewable energy resources present only minor variations on GHG emission (less than 2% of the Baseline).

Several studies as the SRES (IPCC, 2000; van Vuuren et al., 2009; EMF, 2011; Riahi et al., 2007; or Capros, 2014) use multi model approaches allowing to capture and address the range of outcomes from different models using the same or similar assumptions. This was clearly not the approach used in this paper. Although those multi model studies are extremely relevant to better inform science and policy making, the higher time and efforts that they entail are frequently not compatible with the timings and budgets available to national climate policy makers. In that context typically one or two complementary models are used to generate GHG emission scenarios. Acknowledging this 'real life' constraint, we have focused into looking at the range of outcomes of one model only (TIMES_PT), hoping that this simplified pragmatic approach can be more easily adopted in the policy support context.

One of the limitations of the work here presented is that it could be argued that the larger differences in scenarios are caused because we did not use the same range of variation for all the modelled assumption (i.e. we did not model 1%, 5% and/or 10% changes from BASE on oil prices, on demand for energy services, etc.). Nonetheless, we believe our analysis is still valuable since all the assumptions and their variants, from economic growth rates to hydro availability, were developed within an actual climate policy process. They result from the actual discussion with policy makers and national stakeholders while developing the 2020 GHG emission scenarios used by the Portuguese Ministry of Environment. Thus, the different ranges for variation of the assumptions translate the actual expectations and perceptions of policy makers on their plausible variations.

Most emission scenarios used in climate policy consider different degrees of policy implementation, which are typically dealt with via different scenarios, each reflecting a different degree of implementation (usually simply by considering scenarios with and without policies). (ECN/PBL, 2012) has a different approach by assessing the uncertainty in the policies' effects (i.e. their effectiveness) and not on their implementation. According to (ECN/PBL, 2012), the implementation of the P&M is not considered an "uncontrollable external uncertainty" but instead dependant on controllable political will and thus not to be subject to an uncertainty analysis. We do not necessarily agree with this view as it can be argued that the factors affecting political will are so complex that are in practical terms uncontrollable. In fact, in practical terms most uncertainty assessments of GHG forecasts do not make this distinction in policy implementation and their effectiveness. In most of the cases reviewed in section 2.2 it is considered that a policy can be implemented or not, and if it is implemented, then is assumed effective. In our analysis we have used this later approach.

Although our analysis focused on a case-study for Portugal, we believe this methodology can and should be easily replicated for other countries and other national (and even supra-national) energy system models. As a practical implication affecting the work of other modellers and policy makers, we suggest that the definition of the assumptions as model inputs should be thoroughly discussed *a priori* with a view to ensure that their selection lead to model results that have relevant differences and allow providing insights. This has been suggested as relevant in (Rotmans and van Asselt, 2001) and implemented using expert elicitation in (Usher and Strachan, 2013) or using stakeholders workshops in (Treffersa et al., 2005). In particular, based on our analysis, we would suggest that less effort should be spent analysing variations in oil, coal and gas prices and more on the technology deployment associated with different penetration of energy efficiency measures and socio-economic growth (or even lack of it). Finally, we believe that this relatively simple approach to assess impact of individual exogenous assumptions adds substantial transparency to model results which is becoming more and more relevant for climate policy support in a rapidly changing energy system (Pfenninger et al., 2014).

## 2.6 CONCLUSIONS

This paper assesses the contribution of different exogenous parameters for the variations in GHG emissions estimates for the case study of the Portuguese energy system for 2020. This is relevant as these scenarios are used for policy support in many countries, using similar assumptions and models as in the Portuguese case-study. In this paper we have identified which assumptions more critically affect the GHG emission scenarios allowing efficient modelling by allocating more resources to the substantiation of the most critical assumptions. This is important as the development of GHG emission scenarios is a time consuming process, also limited by the substantial running time of complex models. Thus, we believe it is of utter relevance to carefully consider which assumptions are more relevant and to focus on these. In our analysis, seven scenarios were generated for 2020 using the TIMES_PT model: Baseline, Efficiency, Demand, Low Renewable Electricity, Low Hydro, High Hydro and High Oil Price. The Baseline scenario was developed considering a number of assumptions on exogenous model inputs, such as on demographic and economic evolution, technology deployment, energy resources availability and on the implementation and effectiveness of policy decisions. The other six scenarios are identical to the Baseline but for a variation in one of these exogenous assumptions.

The first main conclusion is that key issues in energy supply in Portugal, the availability of water for hydropower and the price of – to be imported – oil hardly have any influence on the outcomes in terms of greenhouse gas emissions in 2020. The GHG emission estimates of the scenarios where exogenous parameters were varied lead to variations in 2020 total national GHG emissions less than 9% different from the Baseline. This has consequences in two directions. Improvement in model quality should not focus on these issues; and policies should not build on these elements. A policy-relevant consequence that should be further explored is the possibility that increasing oil prices, as a policy measure, as through carbon taxes, has a limited effect on overall climate performance.

The second main conclusion is that overall emissions levels as modelled for around two decades from now are very much dependent on general socio-economic development and population growth, and also but to a lesser degree depend on developments in end-use efficiency. Should we then focus at reduced growth for reaching climate targets?

The third conclusion is on what we can learn from this exercise in scrutinizing the TIMES-type partial equilibrium models. Are the conclusions valid beyond the outcomes for Portugal? As they are linear optimization models, they tend to be most sensitive to one driver at a time. The question is: can we be sure that, for example, a carbon tax would have a limited effect? Or would the effect occur only after “all other mechanisms” have worked out, taking more than two decades? Or would the limitation be an artefact of partial equilibrium modelling, with all mechanisms in reality working simultaneously? Nobody can answer these important questions now. We hope that with our primary analysis we have set up a rich field of further study.

## 2.7 APPENDIX 2A – OVERVIEW OF THE TIMES_PT MODEL

TIMES_PT is supported by a detailed database, with the following exogenous inputs: (1) end-use energy services and materials demand, such as residential lighting, machine drive requirements or steel; (2) characteristics of the existing and future energy related technologies, such as efficiency, stock, availability, investment costs, operation and maintenance costs, or discount rate; (3) present and future sources of primary energy supply and their potentials; and (4) policy constraints, such as emission caps. The model finds the optimum combination of energy supply and demand technologies to satisfy the demand, i.e. it designs an energy system with the lowest possible total costs. More information on the details of the TIMES_PT model and its exogenous technology database can be found in (Simoes et al., 2008). The other exogenous inputs are detailed in the following sections.

As a partial equilibrium model, TIMES_PT does not model the economic interactions outside of the energy sector. Furthermore, it does not consider in detail demand curves and non-rational aspects that condition investment in new and more efficient technologies. In fact, the model unrealistically assumes that stakeholders are rational with perfect market foresight. Thus, some of the most important barriers for the uptake of new energy technologies in industry, and the residential and commercial sectors are inherently absent in TIMES_PT. These barriers are exogenously introduced, as described in the section detailing the studied scenarios and in (Simoes et al., 2013).

## 2.8 APPENDIX 2B – ENERGY SERVICES AND MATERIALS DEMAND ASSUMPTIONS IN TIMES_PT

For all seven scenarios the macro-economic drivers in section 2.2 were used to derive a detailed materials and energy services demand for 2020 which is thoroughly described in (Fortes et al., 2008). The demand projections were developed using a bottom-up approach for the residential and commercial sectors and top-down approach for the industry and transport sectors. For the residential and commercial sectors, detailed assumptions were made on: stock of existing and new buildings; evolution of occupancy rate; average building area; evolution of heating and cooling comfort requirements per $m^2$; evolution of per capita water and cooking useful energy requirements, among other. These assumptions consider past statistics and forecasts on: population growth, private consumption and planned touristic developments. The demand for energy services for the residential sector is disaggregated for single urban houses, single rural houses and apartments and considers two climatic regions: South and North of Portugal. For the industry and transport sectors a relationship was assumed between the demand for energy intensive materials (steel, paper, glass, cement, lime, ammonia and chlorine), transport and other energy services required for industry and evolution of sector gross value added (GVA). This relationship includes the effect of a price evolution factor, income and price elasticity of final demand to GAV, and assumptions on the autonomous efficiency improvement in industry (Kanudia and van Regemorter, 2006). Both the socio-economic and the materials demand projections were validated through an extensive stakeholder consultation process during 2008 (Seixas et al., 2009).

The final demand projections are thus differentiated across sectors and scenarios (Table 2.A):

- Industry: i) quantities of steel, paper, glass, cement, lime, ammonia and chlorine ii) Useful energy for the remaining industries (ceramics, chemical, other industry);
- Residential: useful energy demand for hot water, cooling and heating, lighting, cooking, refrigeration, cloth washing and drying, dish washing and other electric appliances;

- Commercial: useful energy demand for hot water, cooling and heating, lighting, public lighting, cooking, refrigeration and other electric appliances;
- Transport: passengers and freight transportation trough road and railway expressed in pkm (passenger-kilometre) and tkm (ton-kilometre) and aviation and navigation expressed in useful energy demand.

**Table 2.A** | Differences between scenarios regarding demand for end-use energy services until 2020 using the index 2000 = 1000

| Demand type | Year/Scenario | 2000 | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|---|
| Heating | BASE & OTHER | 100 | 124 | 140 | 147 | 152 |
| | DEM | 100 | 124 | 141 | 152 | 161 |
| Cooling | BASE & OTHER | 100 | 138 | 165 | 191 | 222 |
| | DEM | 100 | 138 | 165 | 195 | 235 |
| Water Heating | BASE & OTHER | 100 | 122 | 143 | 155 | 163 |
| | DEM | 100 | 122 | 144 | 157 | 167 |
| Chemistry | BASE & OTHER | 100 | 92 | 103 | 121 | 133 |
| | DEM | 100 | 92 | 103 | 121 | 141 |
| Other industry | BASE & OTHER | 100 | 85 | 86 | 91 | 97 |
| | DEM | 100 | 85 | 84 | 87 | 89 |
| Pkm | BASE & OTHER | 100 | 110 | 129 | 145 | 157 |
| | DEM | 100 | 110 | 127 | 143 | 156 |
| Tkm | BASE & OTHER | 100 | 127 | 138 | 157 | 178 |
| | DEM | 100 | 127 | 137 | 150 | 164 |
| Paper | BASE & OTHER | 100 | 97 | 124 | 142 | 156 |
| | DEM | 100 | 97 | 123 | 142 | 155 |
| Cement | BASE & OTHER | 100 | 98 | 106 | 107 | 107 |
| | DEM | 100 | 98 | 103 | 107 | 107 |
| Glass | BASE & OTHER | 100 | 117 | 141 | 169 | 182 |
| | DEM | 100 | 117 | 141 | 169 | 181 |
| Iron & Steel | BASE & OTHER | 100 | 150 | 244 | 375 | 370 |
| | DEM | 100 | 150 | 244 | 375 | 370 |

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# CHAPTER 3

## LOW CARBON ROADMAP FOR PORTUGAL: TECHNOLOGY ANALYSIS*

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## ABSTRACT

The European Union (EU) has endorsed the goal of keeping global warming below 2°C, establishing the objective of reducing its greenhouse gases (GHG) emissions by 80 to 95% in 2050 face to 1990 values. 'The Roadmap for moving to a competitive low carbon economy in 2050' outlines the EU strategy to achieve this target, prompting Member States to develop similar exercises. This paper aims to present an analysis of the cost-effective opportunities in Portugal to achieve an 80% GHG abatement target by 2050. Six scenarios combining different conditions of technological development (frozen and optimistic evolution), GHG mitigation (-80% reduction cap and no additional climate action) and energy prices elasticities (with and without) are generated through the bottom-up model TIMES_PT. The modelling exercise shows that it is feasible for Portugal to achieve a low carbon future, even under a technology frozen (TF) scenario, although higher energy consumption and different technological options are observed. Wave technology in power sector and hydrogen trucks in transports only appear in technology evolution scenario (TE) after 2030, which are replaced by a higher wind offshore power production and ethanol trucks in TF scenario. Electric mobility is anticipated in TE appearing in 2015 through light-duty electric vehicles, while for TF scenario gasoline plug-in vehicles became cost effective in 2040. These technology differences are also reflected in total system costs, which are 54 bn€$_{2011}$ higher in TF scenario. Energy prices elasticities do not changed significantly the technology options, although in terms of total costs a reduction of around 53 bn€$_{2011}$ and 16 bn€$_{2011}$ (about 31% and 9% of the 2011 Portuguese GDP) is observed for TF and TE scenarios, respectively.

## 3.1 INTRODUCTION

There is a growing consensus on the need to reduce significantly greenhouse gases emission (GHG) to keep global warming below 2°C of pre-industrial levels and limit the negative impacts of climate change. This has motived several countries and regions to establish abatements targets (e.g. HMG, 2008; EC, 2011a; MFE, 2011; UNFCCC, 2011) and many studies have been conducted to design decarbonisation scenarios, outlining how the transition to a low carbon economy can be achieved, and evaluating its economic impacts (see Hughes and Strachan, 2010 and Söderholm et al., 2011 for a review on low carbon scenarios).

In 2008, EU made the commitment to reduce its GHG emissions to 20% below 1990 levels in 2020. This pledge, together with a 20% renewable energy target was set into European Union (EU) legislation through the "Climate and energy package" (EC, 2008). Considering the importance of looking beyond 2020 to keep the increase of the average earth temperature below 2°C, the EU has set more recently the objective of reducing its emissions by 80 to 95% in 2050 face to 1990 values. 'The Roadmap for moving to a competitive low carbon economy in 2050' (EC, 2011a) outlines the EU strategy to achieve this target, namely by defining the sectoral reductions potential and the role of technology to achieve it, prompting member states to developed common exercises.

Currently the Portuguese GHG emissions represent only 2% of the total EU27 and Portugal has one of the lowest national GHG emissions per capita – 6.6 $tCO_2e$/hab. vis-à-vis the EU27 average of 9.4 tCO2e/hab (EEA, 2012). However, Portugal is in the top five countries with highest emissions increase since 1990, being the second EU15 country with the biggest rise, only surpassed by Spain. Moreover, Portugal is the only EU27 country that shows a positive variation of the annual final energy intensity between 1990 and 2009 (EEA, 2012). One of the main factors that drive these increases was the rise of road transport supported by strong development of road infrastructure and rapid growth in private car ownership (IEA, 2009). Under the EU Climate and Energy Package policy, Portugal is committed to limit in 1% the increase of its GHG emissions not included in the European Trading Scheme (ETS) by 2020 of 2005 values (EC, 2009a). Although there are no national targets for the ETS emissions as they will be implemented at EU level (-21%) on a sector basis (EC, 2009b), several Portuguese energy and manufacturing industries are also included in this demanding reduction goal. The same Package sets for Portugal one of the most ambitious national renewable energy sources (RES) targets: 31% share of RES on the final consumption of energy by 2020, including 10% share of biofuels of energy consumption in transports (EC, 2009c).

Supported by the EU climate policy and low carbon roadmap framework, this paper aims to present an exploratory analysis of the cost-effective opportunities for Portugal to achieve an 80% GHG abatement target by 2050. As known as key drivers to tackle the climate change (e.g. EC, 2009d; IEA, 2010; IEA, 2011a) the role of low carbon technologies will be evaluated, taking into account the uncertainty associated with its development, namely on its cost curves. Therefore, assuming two different technology development scenarios, this paper presents a Low carbon roadmap for Portugal up to 2050 identifying sector mitigation options (potential and technology choices) and giving insights about the necessary  targets, namely RES consumption to achieve such ambitious mitigation goal.

This chapter is organized as follows: section 3.2 describes the methodology for scenario development, section 3.3 analyses and discusses the results and section 3.4 presents the main conclusions.

## 3.2 METHODS

To design low carbon futures for Portugal, and contribute with insights on future energy technology pathways in different realities of the technological development, six scenarios were generated up to 2050 using the technological bottom-up TIMES_PT model. This section presents TIMES_PT model, followed by the major assumptions considered in each scenario.

### 3.2.1 TIMES_PT MODEL

TIMES (The Integrated MARKAL-EFOM system) is a linear optimisation bottom-up model generator developed by ETSAP[15] of the International Energy Agency (IEA). The ultimate objective of TIMES is the satisfaction of the energy services demand at the minimum global cost (*i.e.,* minimum total discounted net present value of all costs included in the model), subject to technological, physical and policy constraints. The model makes simultaneous decisions about equipment investment and operating, primary energy supply and energy trade considering its "perfect foresight" characteristic. More information about TIMES model can be found in Loulou et al. (2005).

TIMES_PT maps the entire chain of the Portuguese energy system up to 2050, from energy supply, namely energy imports and production, to end-uses consumption and energy trade, including in the middle energy transformation and distribution. It models in detail the primary energy supply (oil refineries, bio-refineries, and synthetic fuel and hydrogen production plants) and electricity

[15] Energy Technology Systems Analysis Programme

generation, as well as final energy consumption sectors, namely, industry, residential, services, agriculture and transport sectors and respective sub-sectors (Simões et al., 2008).

Currently, TIMES_PT technological database has more than two thousands of existing and future energy related technologies, with detailed information such as efficiency, capacity factor, availability, technical lifetime, investment, operation and maintenance costs, etc. It comprises more than 50 power plant technologies (existent and available for future investments), including more than 20 renewable and several fossil generation technologies, some of which with carbon capture and storage (CCS). The transport sector covers cars, light-duty and heavy-duty trucks, buses, coaches, rail, aviation and marine technologies such as conventional gasoline, diesel, LPG and hybrid vehicles, and biofuel, synthetic fuel, plug-in hybrids, battery electric and hydrogen fuel cell vehicles. Buildings (residential and services sectors) possess more than one thousand heating, cooling, water heating, cooking technologies as well as lighting and electric equipment' (e.g. refrigerators, washing, drying and dish washing machines) divided per type and/or efficiency classes. Industry sector in TIMES_PT is divided in iron &steel, other non-ferrous metals, paper, glass, cement, lime, ceramics, ammonia, chlorine, nitric acid, other chemical, and other industry, and its technology database contain fuel kilns, process heat, machines, cogeneration and specific sector processes, like clinker production or pulp production in cement and paper industry, respectively, as well as other processes technologies.

The original TIMES_PT technology database was obtained from the European NEEDS Project[16] and have been validated and updated over time, namely by national stakeholders within several initiatives (EU RES2020[17] and COMET[18] projects; Seixas et al., 2008; Seixas et al., 2010). For illustrative purposes the economic assumptions behind selected power sector technologies are presented in Table 3.A (in Appendix).

[16] NEEDS - New Energy Externalities Developments for Sustainability (www.needs-project.org).

[17] RES2020 – Monitoring and Evaluating the RES Directives implementation in EU-27 and policy recommendations.

[18] COMET – $CO_2$ transport and storage (http://comet.lneg.pt/).

## 3.3 SCENARIOS DEFINITION

Six scenarios combining two conditions of technological development, GHG mitigation and energy prices elasticities were developed and analysed to explore the role of technology in a low carbon future for Portugal up to 2050, as described below and summarized in Table 3.1.

Due to the uncertainty associated with the development of energy end-use and supply technologies, we establish two assumptions:

- Technology frozen (TF), assuming a conservative technological development, where the prospects about technical and economic data will be remain constant from 2015-2020 onwards. Technologies that are expected to be in a commercial phase after this period will not be available, such as CCS;
- Technology evolution (TE), assuming that emerging technologies will appear in the future and existing ones will become more efficient and cheaper as set in TIMES_PT database.

Figure 3.1 presents an example of the differences between the two scenarios regarding the investment cost and long distance efficiency for some private cars technologies. Other technical and economic data, namely availability, process emissions factors, operation and maintenance costs, are also subject to the same type of assumptions.

These assumptions are combined with two other conditions regarding GHG mitigation post 2020:

- Baseline scenario (BASE) describing the potential development of the Portuguese energy system if no additional climate action is undertaken up to 2050. Portugal implements the climate and energy package in 2020 and extends its commitments until 2050, but no additional targets are assumed.
- Low carbon scenario (CAP), considering a national action after the 2020 climate commitments, leading to a reduction of GHG emissions[19] of 80% by 2050 comparing with 1990 levels.

Both scenarios assume for 2020 the following climate and energy package limits: i) an increase of 1% of non ETS emissions; ii) a reduction of -21% of ETS emissions due to the lack of information about the objective that will be imposed to Portuguese installations; iii) the RES directive targets of 31% for the total final consumption and 10% for the energy consumption in transports.

[19] Energy and industrial processes $CO_2$, $CH_4$ and $N_2O$ emissions. Halocarbons production and consumption emissions, as well as non-energy emissions such as the one associated with solvents, agriculture, land use and waste are not considered.

Two additional scenarios assuming energy price elasticities were also modelled (CAP.ELAS) to assess the importance of energy services demand reduction (induced by energy price increase) in technology choices. It was assumed a price elasticity of -0.3 for all demands categories except for commercial cooking and public lighting, whose values were -0.2 and residential cooking and industry with an -0.1 price elasticity. Most of these elasticities were supplied by Katholieke Universiteit Leuven (Simões et al., 2008) and are generic for EU countries.

**Table 3.1** | Overview of the scenarios assumptions.

| Scenarios | 80% GHG emission target (compared to 1990) | Technology assumption | Energy price elasticities |
|---|---|---|---|
| BASE_TE | No | Evolution | No |
| BASE_TF | No | Frozen | No |
| CAP_TE | Yes | Evolution | No |
| CAP_TF | Yes | Frozen | No |
| CAP.ELAS_TE | Yes | Evolution | Yes |
| CAP.ELAS_TF | Yes | Frozen | Yes |

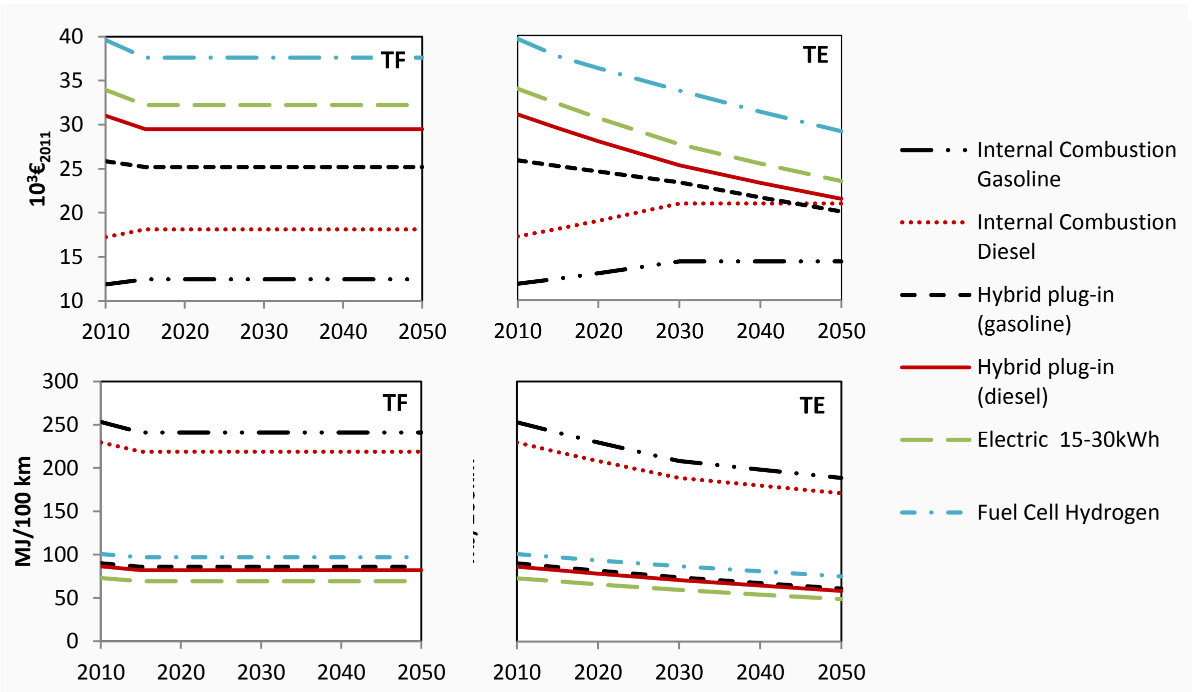


**Figure 3.1** | Investment costs (upper charts) and long distance efficiency (lower charts) for some private car technologies in TF and TE scenarios. *Source of TE scenario*: Adapted from (Kampman et al., 2011).

### 3.3.1 Socio-economic assumptions

The socio-economic development and its respective demand projections are the driving forces of the whole energy system modelled in TIMES_PT. In this paper all the modelling scenarios adopt the same socioeconomic growth, generated within the project $HybCO_2$[20]. In the project, two scenarios for the Portuguese economy were developed (Alvarenga et al., 2011): 'Welcome', outlining that Portugal is not able to successfully set structural changes in its economy with exception of the promotion of the health cluster; 'We cannot fail' assuming that Portugal performs a number of structural changes capable of stimulate innovation, creativity and technological improvement, moving the economy up in the value chain. For the purpose of this paper just 'We cannot fail' scenario was considered since it assumes a higher economic growth, representing the more demanding situation in terms of GHG abatement.

Table 3.2 summarizes the main socio-economic drivers of 'We cannot fail' scenario and the respective demand growth considered in TIMES_PT. The energy and materials demand was generated according to the methodology presented in (Seixas et al., 2010) supported by a top-down approach for industry, services and agriculture sustained by the sector value added growth and bottom-up calculations for buildings and transport. The bottom-up method depends on several drivers, namely the number and characteristics of the dwellings, occupancy rate, transport typology, population, average travel km, among other parameters.

**Table 3.2** | Macroeconomic drivers and respective energy services, materials and mobility demand annual average growth (%).

| | Driver | 2010-2020 | 2021-2030 | 2031-2040 | 2041-2050 |
|---|---|---|---|---|---|
| Socioeconomic drivers[a] | GDP | 0.9 | 2.0 | 2.9 | 2.9 |
| | Population | 0.0 | 0.1 | 0.1 | 0 |
| | GVA Agriculture, forestry and fishing | 0.8 | 2.1 | 2.1 | 2.1 |
| | GVA Industry and Construction | 0.5 | 2.5 | 2.7 | 2.8 |
| | GVA Transports | 0.8 | 2.5 | 2.5 | 2.5 |
| | GVA Services | 1.4 | 2.9 | 2.9 | 3.0 |
| | GVA Energy | 1.7 | 4.0 | 4.1 | 4.2 |
| TIMES_PT demand[b] | Energy services demand in residential building | 0.9 | 1.0 | 0.9 | 0.7 |
| | Energy services demand in services | 0.4 | 1.8 | 0.9 | 0.9 |
| | Energy services demand in industry | -0.4 | 0.8 | 0.9 | 1.0 |
| | Materials demand in industry (iron & steel, paper & pulp, cement, lime, glass) | 2.1 | 0.7 | 0.7 | 0.5 |
| | Passenger.km mobility | 1.1 | 1.9 | 1.1 | 1.1 |
| | Tonnes.km mobility | 2.5 | 1.5 | 1.4 | 1.4 |

[a]Source: Alvarenga et al. (2011)

[b]Own calculations based on Seixas et al. (2008)

[20] Hybrid approaches to assess economic, environmental and technological impacts of long term low carbon scenarios – The Portuguese case (http://hybco2.cense.fct.unl.pt/)

### 3.3.2 OTHER MODELLING ASSUMPTIONS

Besides the socioeconomic drivers the modelling scenarios consider other common exogenous assumptions, which are briefly outlined:

i. 9% discount rate for centralized electricity generation, 8% for buses and trains; 12% for commercial, industry, decentralized electricity generation, CHP and freight transport; and 17.5% for residential, cars and motorcycles (EC, 2011b);
ii. Fossil fuel import prices adopted from Current Policies Scenario of World Energy Outlook 2011 (IEA, 2011a) and extended up to 2050 through a linear trend, namely 115.9–126.2 $\$_{2010}$/tonne for coal, 134.5–157.9 $\$_{2010}$/barrel for crude oil and 12.6–14.3 $\$_{2010}$/MBTU for natural gas, respectively, for 2030 and 2050.
iii. No nuclear energy option, due to current Portuguese political options;
iv. Subsidies or feed-in tariffs are not considered in the modelling exercise;
v. Electricity trade under the liberalised Iberian electricity market is not considered. It was set, according to national transmission operator a maximum net export of 9.3 and 4.4. TWh for 2015 and 2020 respectively. 2025 onwards it was assumed a zero exports and imports net balance (Seixas et al., 2010).
vi. Technical potential of national RES sources supported by several national studies and expert opinion (Table 3.B in Appendix), according to (Seixas et al., 2010).

## 3.4 RESULTS

This section presents and discusses the main results of the low carbon scenarios for Portugal, namely the GHG emissions reduction per sector and the respective mitigation options, regarding the electricity production profile, end-use sectors energy consumption and technological choices. BASE scenarios results are also shown as they set a benchmark on which the results of the CAP_TE and CAP_TF scenarios can be compared. However, due to the scope of this paper higher attention is given to the decarbonisation scenarios (CAP). At the end is presented and analysed the role of energy service demand reduction to achieve a low carbon future by confronting the results of CAP.ELAS scenarios with respective CAP scenarios.

### 3.4.1 GHG EMISSIONS

CAP scenarios show that it is feasible to reduce the Portuguese GHG emissions in 80% by 2050 comparing to 1990 levels and fulfilling at the same time the national energy/materials and mobility demand, even in a scenario with lower technology development. The only exception is related with clinker, which cannot be produced nationally in the CAP_TF scenario in 2050, being necessary to import this raw material to accomplish such aggressive mitigation cap and satisfy cement demand.

Figure 3.2 and Table 3.3 presents respectively, the GHG emissions per sector and the corresponding abatement reduction effort for CAP and BASE scenarios, but as explained before no significant focus will be given to the former. In fact, although BASE scenario continue the current climate and energy package lines for Portugal even achieving more ambitious targets (e.g., -1% for non EU-ETS vis-à-vis the +1% cap) they are not enough to achieve a relevant GHG abatement in 2050, which stays around +38% (by 1990 values).

In the CAP scenarios, decarbonisation is foremost in power and heat production. By 2030 power sector reach reductions above 50% comparing with 1990 levels and in 2050 for CAP_TE this sector presents almost zero emissions with a decrease of 94%. As the stringency of the cap increases over time, major reduction efforts are also required from other sectors. In absolute terms is industry that has the second biggest mitigation potential in 2050, more than 8 Mt $CO_2$e reduced (face 1990) in all CAP scenarios.

In CAP_TE part of the emissions abatement is associated with CCS, reducing 61% of the gross industry GHG emissions. In transport, the increasing trend of GHG emissions is maintained up to 2030. However in 2050 the sector suffers significant reductions, especially in CAP_TE scenarios, where the technology evolution allows it to achieve a reduction above 8 Mt $CO_2$e (-86% comparing to 1990 levels). Despite the significant reductions of these two sectors (i.*e.* industry and transports), no long-term full decarbonisation is achieved and in 2050 they represent the main contributors of national GHG emissions. On the contrary, in 2050 buildings (residential and services) is the sector with the lowest emissions. This sector is almost completely decarbonised (less than 1 Mt $CO_2$e), supported mainly by a shift to electricity consumption, in both scenarios. Relevant reductions are also verified in petroleum refining. This energy supply industry will decrease its activity to around one third of the current levels, mostly due to the significant reduction of oil products by transports.

The main differences between CAP_TE and CAP_TF scenarios are related with the allocation of the ETS and non-ETS emissions abatement potential. In the technology evolution scenario, the main abatement effort is associated with the non-ETS emissions (-31.8 Mt $CO_2$e.), mostly associated with mitigation in transport, while in CAP_TF (without technological evolution), ETS sectors have the most cost-efficient reductions (-33 Mt $CO_2$e.) sustained by energy and manufacturing industries.

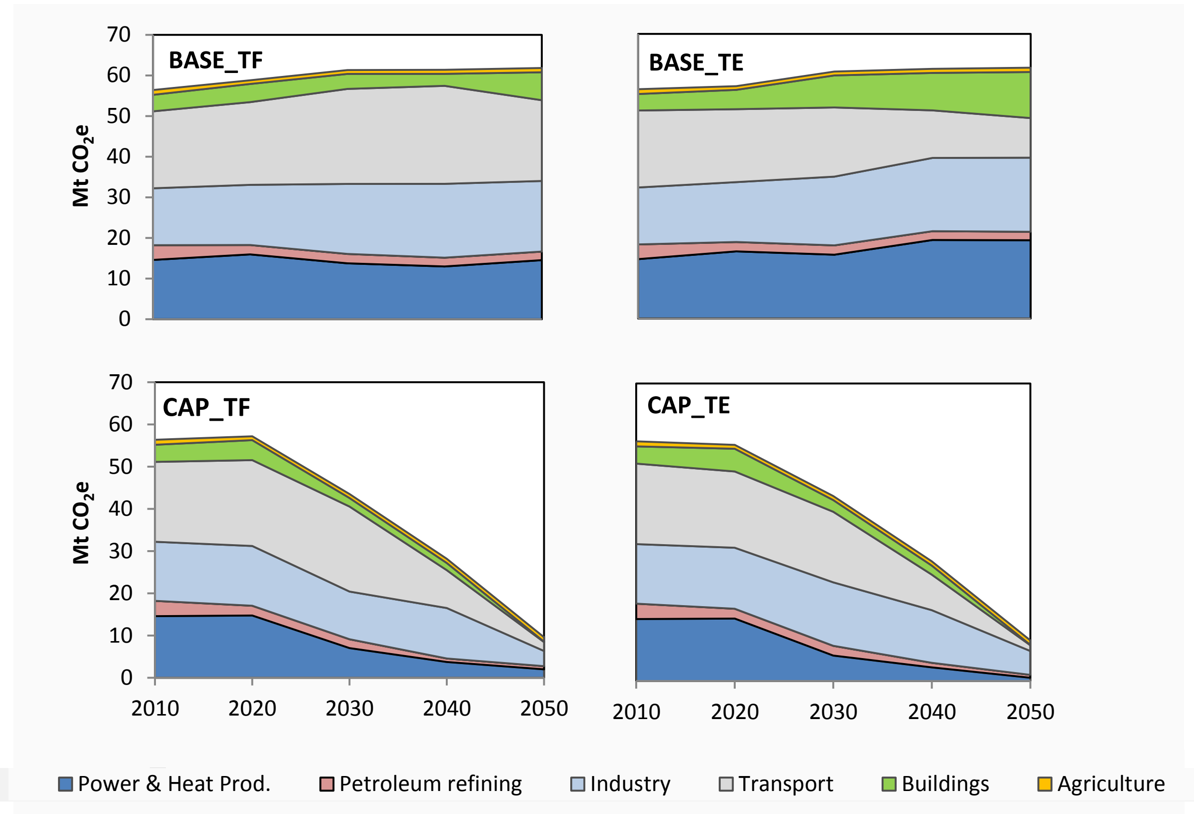


**Figure 3.2** | Sector GHG emissions (Mt $CO_2e$) over time in the different scenarios.

**Table 3.3** | Sector GHG emissions abatement per scenario and selected years (%).

| | | **1990 (Mt)** | **BASE_TF** | | **BASE_TE** | | **CAP_TF** | | **CAP_TE** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **2030** | **2050** | **2030** | **2050** | **2030** | **2050** | **2030** | **2050** |
| **% of reduction face to 1990** | Power & Heat Prod. | 14.0 | -2 | 4 | 12 | 37 | -50 | -86 | -57 | -94 |
| | Petroleum refining | 2.1 | 10 | 0 | 9 | -1 | 0 | -64 | 10 | -68 |
| | Industry | 13.9 | 24 | 25 | 21 | 31 | -19 | -74 | 7 | -60 |
| | Transport | 10.1 | 133 | 98 | 69 | -3 | 100 | -79 | 65 | -86 |
| | Buildings | 2.8 | 32 | 145 | 181 | 304 | -28 | -97 | -2 | -97 |
| | Agriculture | 1.8 | -48 | -42 | -48 | -42 | -48 | -42 | -48 | -42 |
| | **Total** | ***44.7*** | **37** | **38** | **36** | **38** | **-3** | **-80** | **-3** | **-80** |

| | | **2005 (Mt)** | **BASE_TF** | | **BASE_TE** | | **CAP_TF** | | **CAP_TE** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **2030** | **2050** | **2030** | **2050** | **2030** | **2050** | **2030** | **2050** |
| **% of reduction face to 2005** | EU-ETS | 37.4 | -23 | -23 | -23 | -23 | -49 | -88 | -46 | -74 |
| | Non -ETS | 31.0 | -3 | -1 | -5 | -1 | -28 | -85 | -33 | -103 |
| | **Total** | **68.5** | **-14** | **-13** | **-15** | **-13** | **-39** | **-87** | **-40** | **-87** |

### 3.4.2 ELECTRICITY GENERATION

As shown in Figure 3.3, electricity generation increases during 2010-2050 period in all scenarios. In BASE_TF and BASE_TE it grows 25% to 33%, respectively, while for CAP_TF and CAP_TE it increases more expressively (70% and 94%) as the decarbonisation efforts lead end-use sectors to shift to electricity.

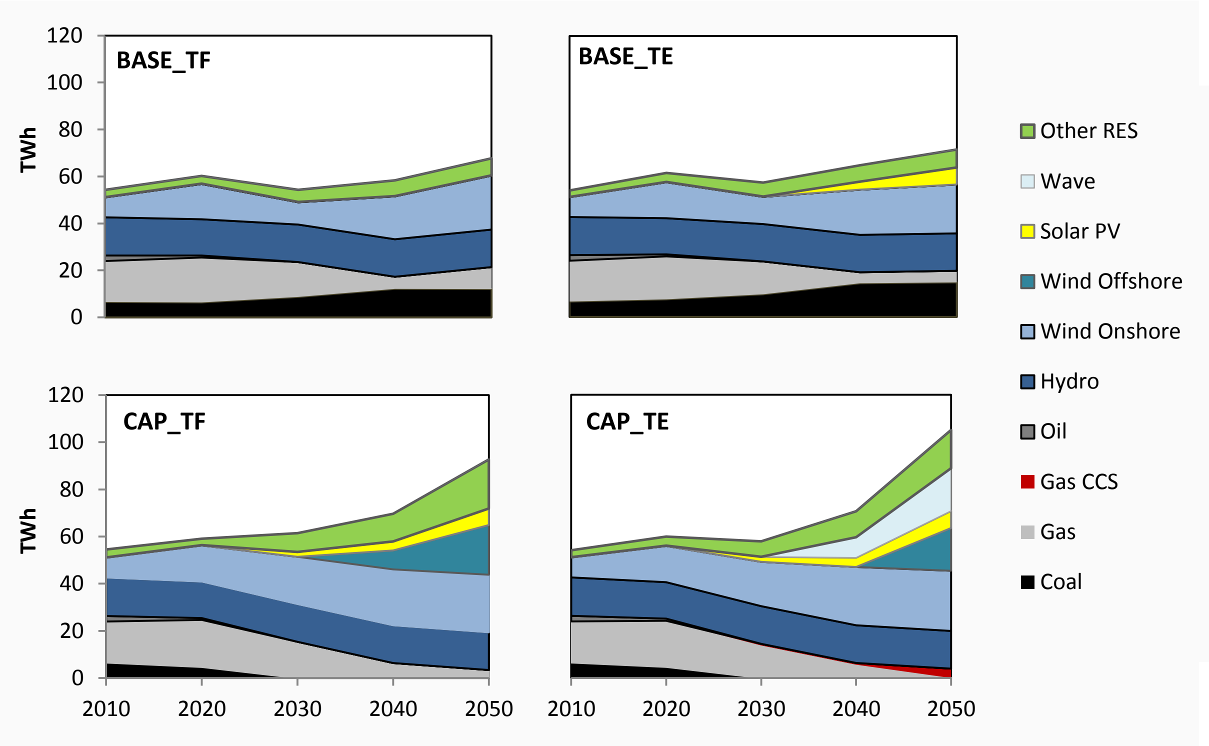


**Figure 3.3** | Electricity generation (TWh) per technology over time.

In the absence of a significant GHG cap, high-carbon-content coal remains a relevant energy source in electricity generation, contributing in 2050, to 18% and 21% of the total electricity generation in BASE_TF and BASE_TE scenarios. However, in CAP scenarios with the decommission of the current coal power plants, no new capacity is installed, which is replaced by RES sources, reaching 75% and 96% of the power production mix technologies in 2030 and 2050, respectively, for both CAP_TE and CAP_TF scenarios.

In the CAP scenarios, hydro, wind onshore and solar photovoltaic (PV) are the most cost effective technologies for Portugal, achieving their maximum potential in both scenarios. Although CCS is available in CAP_TE scenario, the technology does not have a relevant role in electricity generation, since it is applied in only 4% of the total production.

The main difference between the low carbon scenarios is associated with wave and wind offshore technologies. Wave technology only appears in CAP_TE in 2035, while floating wind offshore just becomes an option after 2040. In CAP_TF by contrast, wind offshore is selected as a cost-efficient technology early in 2035. While currently the investment cost for wave energy technology is nearly three times higher than offshore wind, experts envisage (Seixas, et al., 2010) for the long term a reduction of the cost gap between the two technologies, and an increase of wave efficiency – factors that are not captured by CAP_TF scenario.

### 3.4.3 ENERGY DEMAND AND TECHNOLOGY CHOICES IN END-USE SECTORS

An increase in final energy consumption is observed in all the scenarios, associated with the rise of energy services demand. Technology evolution scenarios present lower final energy consumption growth as the continuous technology development lead to higher efficiencies – 8% and 16% of increase between 2010 and 2050 for BASE_TE and CAP_TE respectively, vis-à-vis 26% and 24% for BASE_TF and CAP_TF (Figure 3.4).

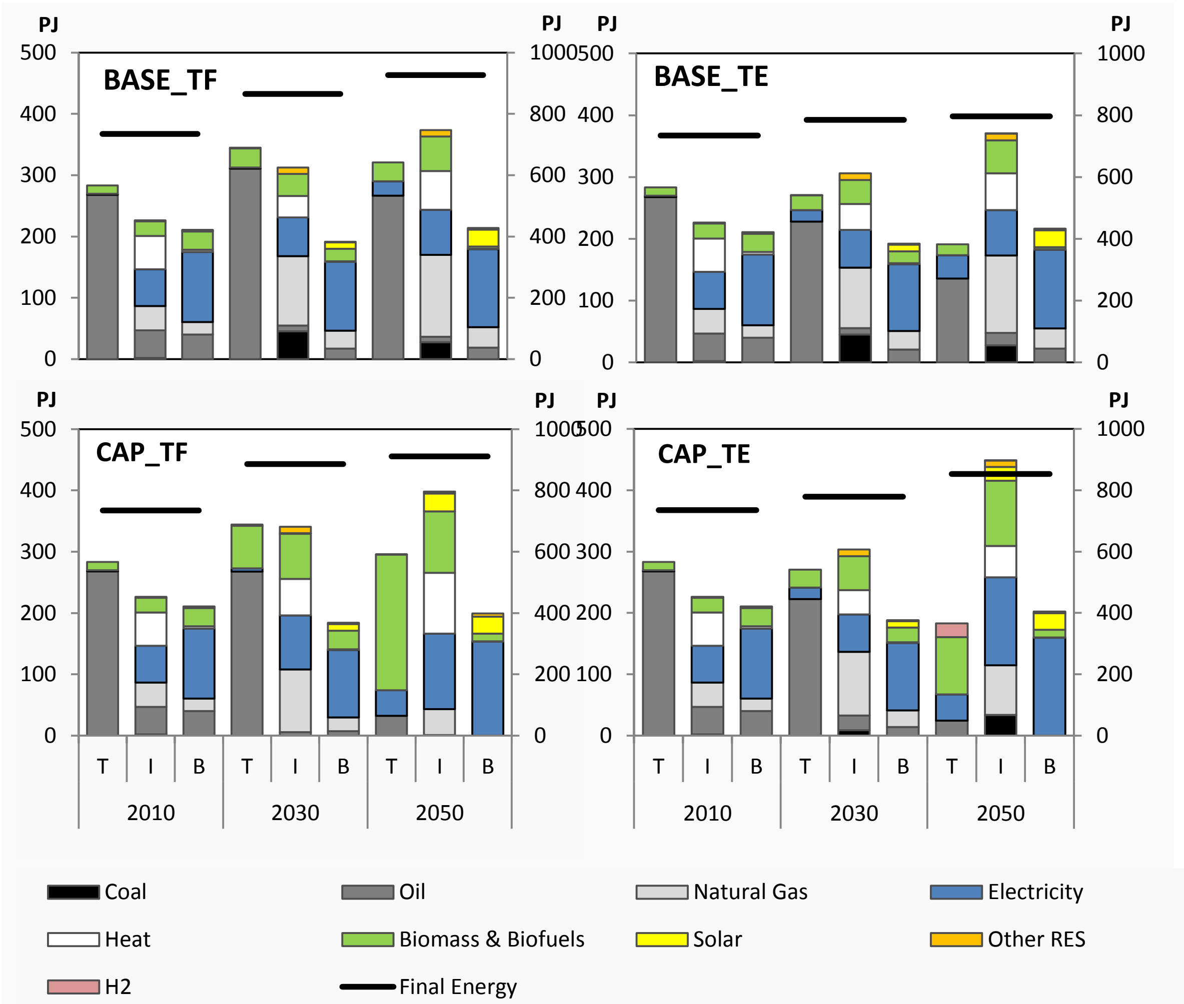


**Figure 3.4** | Energy consumption per sector and energy carrier (PJ) for selected years 2010, 2030 and 2050 [T: transport, I: industry, B: buildings]

Oil products are the dominant fuels in 2010, as well as in 2030, accounting for more than one-third of final energy demand in all scenarios. However, for most scenarios this leading position is replaced by other energy sources, namely by electricity (BASE_TE and CAP_TE) and biomass (CAP_TF), driven largely by transport energy choices.

Through the medium term (2030) the consumption of natural gas increases over time for all the scenarios. This growth continues up to 2050 for BASE scenarios (doubling from 2010 values). However, for CAP_TF and CAP_TE natural gas consumption suffers a decrease required to achieve a low carbon target, reaching a lower consumption by 2050 in CAP_TF of -40% comparing to today.

Electricity represents 24% of the total final energy demand in 2010, but its share increases continuously throughout the analysed period, reaching by 2050 35% and 40% in CAP_TF and CAP_TE, respectively. For the same year and scenarios, the total RES consumption (including renewable electricity and heat) achieve 81% and 77%, more than a double of the current Portuguese target of 31% for 2020.

In the absence of an aggressive GHG emissions cap (BASE scenarios) and with increasing energy services and materials demand, industry replaces higher cost oil products by cheaper coal and natural gas energy carriers. For the CAP scenarios the mitigation strategy is associated with the replacement of oil base technologies by low carbon ones, namely biomass and electricity. This leads to no oil products consumption by 2050 in industry. The coal demand observed in the BASE scenarios is also seen in CAP_TE. However, in this scenario the consumption is related with CCS technologies installed after 2040 in cement industry. Moreover, for the same period some investments are made by the chemical industry in natural gas carbon capture technologies. In CAP_TF due to the unavailability of CCS, solar heating and more efficient technologies (*e.g.* more efficient kilns already in the market) are preferred, explaining the lower energy demand (11% less than CAP_TE in 2050) and the higher solar heating share (7% in CAP_TF versus 5% in CAP_TE). In fact, CCS also plays an important role in global energy demand, being responsible for a high percentage of fossil consumption in total final energy, 18% in CAP_TE in 2050 vis-à-vis 10% in CAP_TF.

Following recent trends, the electrification of the building sector will remain in the long term, being more intense in the CAP scenarios. In 2050 electricity represents around 77% and 79% of buildings energy demand for CAP_TF and CAP_TE respectively, versus the 54% of 2010 and 59% of the BASE scenarios in 2050. The decarbonisation of Buildings is also supported, in both CAP scenarios, by an increase of its energy performance (use of highly efficient heat pumps and insulation measures), and the use of solar equipment's both for space and water heating. In 2050, insulation measures suppressed around 30% of the gross heating and cooling energy needs, at the same time that solar thermal satisfy around 40% of buildings heating and water heating energy consumption.

With the extension of the current EU climate and energy police up to 2050 (Base scenarios), transports will continue to rely on petroleum-based fuels, with a moderate contribution of biofuels, which is maintain as a result of biofuels policy obligation. The increasingly growth of oil crude price induce however the appearance of electric mobility, especially for motorcycles. Moreover, even in a technology frozen scenario, where plug-in road vehicles have significantly higher investment costs comparing to conventional internal combustion gasoline and diesel technologies, they become cost-efficient after 2040 due to their higher efficiency.

In CAP scenarios, transports suffer significant GHG reduction, driven by the use of biofuels and the increase of energy efficiency due to electric and plug-in vehicles. In CAP_TE electric mobility appears earlier in 2015 through light-duty electric vehicles, and later in 2040 through passenger gasoline plug-in cars. For CAP_TF electric mobility is only confined to private cars, namely gasoline plug-in and electric vehicles that became cost effective in 2040 and 2050, respectively (Figure 3.5). In 2050, electricity base vehicles satisfy 65% to 83% of road mobility (vehicles.km), including passengers and freight transport, in CAP_TF and CAP_TE scenarios. For the same year and scenarios, biofuels, mainly biodiesel, are responsible for 35% to 7% of the road mobility.

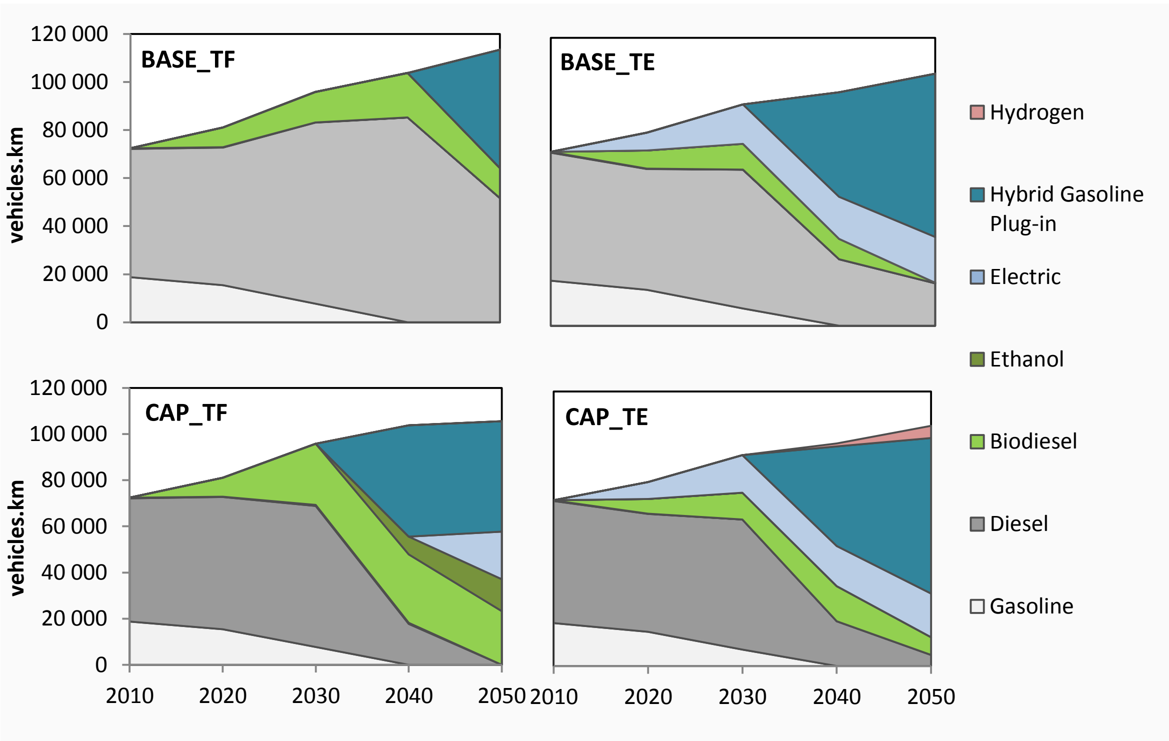


**Figure 3.5** | Road transports mobility (vechiles.km) over time.

The main differences between CAP scenarios are related with heavy road freight and passengers mobility. In CAP_TE, together with biodiesel, hydrogen trucks are the main option to reduce GHG emissions of road heavy freight in 2040, while in CAP_TF due to limited technology development are ethanol trucks that together with biodiesel contribute to this mitigation goal. Moreover, in CAP_TE hydrogen buses and coaches also became a competitive alternative after 2040, while in CAP_TF heavy passengers mobility in the long term (2050) is sustained by biodiesel.

### 3.4.4 ECONOMIC ANALYSIS

The additional total global cost needed to achieve an 80% GHG reduction by 2050 in Portugal is around 77 to 23 bn€$_{2011}$ for CAP_TF and CAP_TE respectively, compared with BASE scenarios. This represents an increase of 6% to 2% of the total energy system costs to go from a rise of around 38% of GHG emissions in 2050 to a reduction of 80% relative to 1990 levels. These values represent around 45% to 13% of the Portuguese 2011 GDP, which corresponds in average 0.8%/p.a. to 0.3%/p.a. of the GDP during the period 2010-2050 (assuming no impact on the economic variables presented in Table 3.2). The main share of the system costs is related with investment. CAP_TF and CAP_TE are responsible for an increase of around 49 to 14 bn€$_{2011}$ of investment costs comparing to BASE_TF and BASE_TE scenarios.

The significant differences between CAP scenarios costs reflect the importance of technology development in a low carbon scenario. Although Research, Development and Demonstration (RD&D) expenses are not included in this analysis, according to IEA statistics (IEA, 2011b) Portugal is one of the Organisation for Economic Co-operation and Development (OECD) countries with the lowest RD&D budget per GDP, being traditionally a technology price taker. However, in the last years RD&D budget have been growing (257% from 2001 to 2010), representing in 2009 (before the current economic crisis) around 3.6M€$_{2011}$, just 0.002% of the national GDP.

### 3.4.5 ENERGY DEMAND REDUCTION IMPACTS

In addition to the increase of energy efficiency, to the switch to low carbon fuels and the installation of CCS equipment's, the decline of energy, materials and mobility demand can also play an important role in GHG emissions reducing, which is modelled trough exogenous energy services price elasticities. The total demand for the 2021-2050 period (differences in the time length) is respectively 5% and 2% lower in CAP.ELAS_TF and CAP.ELAS_TE then for the corresponding scenarios without elastic demand. These minor differences have not significantly changed the electricity generation fuel mix, although the total production reduces in 2050, 8% and 12% for

CAP_TF_ELAS and CAP_TE_ELAS, respectively compared with the CAP scenarios without price elasticities. The same applies to final energy, which maintains a similar energy consumption structure, including the share of RES consumption, although the absolute total consumption reduces by 16% - 4% for CAP_TF_ELAS and CAP_TE_ELAS.

Concerning sector GHG abatement (1990 base), the opposite situation between the CAP.ELAS scenarios is observed in 2050 (Table 3.4): i) in CAP.ELAS_TF industry reduces less its emissions compared to CAP_TF once the higher reduction in agriculture give a margin to the model; ii) by contrast in CAP.ELAS_TE, industry reduces more its emission comparing with CAP_TE, resulting in less reduction for power & heat production and buildings. However, it should be underlined that these differences in both CAP.ELAS scenarios represent less than 3% of the total abatement (-35 Mt $CO_2$e.).

**Table 3.4** | GHG emissions reduction (Mt $CO_2$e.) compared to 1990 values.

| | CAP_TF | | CAP.ELAS_TF | | CAP_TE | | CAP.ELAS_TE | |
|---|---|---|---|---|---|---|---|---|
| | **2030** | **2050** | **2030** | **2050** | **2030** | **2050** | **2030** | **2050** |
| Power & Heat Prod. | -7.0 | -12.0 | -7.0 | -12.2 | -8.0 | -13.2 | -8.1 | -12.7 |
| Petroleum refining | 0.0 | -1.3 | 0.0 | -1.4 | 0.2 | -1.4 | 0.2 | -1.4 |
| Industry | -2.6 | -10.3 | -2.3 | -9.5 | 1.0 | -8.3 | 0.6 | -9.3 |
| Transport | 10.1 | -7.9 | 9.9 | -8.1 | 6.5 | -8.7 | 7.1 | -8.7 |
| Buildings | -0.8 | -2.7 | -0.8 | -2.7 | -0.1 | -2.7 | -0.1 | -2.0 |
| Agriculture | -0.9 | -0.8 | -1.0 | -1.3 | -0.9 | -0.8 | -1.0 | -1.0 |
| **Total** | **-1.2** | **-35.1** | **-1.2** | **-35.1** | **-1.2** | **-35.1** | **-1.2** | **-35.1** |

The model choices lead to a decrease of 1.2% and 3.7% of the total energy system costs for CAP.ELAS_TE and CAP.ELAS_TF, respectively, comparing with its homologous scenarios without energy price elasticities. This corresponds to around 16 bn€$_{2011}$ – 53 bn€$_{2011}$, about 9% and 31% of the 2011 Portuguese GDP, although the economic cost of such demand reduction namely associated with a reduction of, for example, industry production with impacts on employment was not considered.

## 3.5 CONCLUSIONS

This paper outlines a low carbon roadmap for Portugal up to 2050, identifying the role of low-carbon technologies in a different set of scenarios to achieve an 80% reduction of GHG emissions compared to 1990 level. Even in a conservative technological development scenario, it is feasible to achieve this strict target, although the additional costs when compared with the baseline, are substantially higher than in a technological evolution scenarios (77 bn€$_{2011}$ versus 23 bn€$_{2011}$). Depending on the technological development, the low-carbon technology roadmap for Portugal can present some differences, namely in transports, whose electric mobility option can become cost-efficient earlier or in industry due to CCS technology. Regarding power sector, and due to the Portuguese RES potential, RES technologies are always the most cost-effective option, although wave technology is just cost-efficient in technology evolution scenario.

To achieve such a GHG reduction (i.*e.* 80%) in 2050, higher efforts than the 2020 climate and energy package targets should be applied for ETS and non-ETS emissions, in some cases more than 80% reduction. The same happens with RES directive goal, which should increase from 31% in 2020 to more than 77% in 2050.

## 3.6 APPENDIX

Table 3.A and Table 3.B presents the costs of selected power sector technologies within TIMES_PT database and the national primary renewable energy potential, respectively.

**Table 3.A** | Investment, operation and maintenance cost of selected power sector technologies within TIMES_PT technological database

| Technology/ Parameter | Investment Costs (€$_{2011}$/kW) | | | Operation and maintenance costs | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Fixed costs (€$_{2011}$/kW) | | | Variable costs (€$_{2011}$/GJ) | | |
| | 2010 | 2030 | 2050 | 2010 | 2030 | 2050 | 2010 | 2030 | 2050 |
| Wave | 10 428 | 3 476 | 2 781 | --- | --- | --- | 6 | 6 | 6 |
| Onshore wind | 1 298 | 1 039 | 844 | 21 | 20 | 20 | 1 | 1 | 1 |
| Offshore wind | 4 026 | 3 020 | 2 013 | 77 | 77 | 77 | 0.03 | 0.03 | 0.03 |
| Solar PV [Plant Size Thin Film - PV Roof panel CiSi] | 1 891 - 2823 | 1 249 - 1717 | 1 014 - 1 394 | 19 - 28 | 12 - 17 | 10 - 14 | --- | --- | --- |
| Solar CPV | 4 872 | 3 567 | 2 823 | 49 | 27.82 | 28 | --- | --- | --- |
| Solar CSP | 4 526 | 3 335 | 2 858 | 113 | 65.02 | 71 | --- | --- | --- |
| Conventional Coal [steam turbine - Integrated gasification combined cycle] | 1 051 - 1667 | 1 083 - 1 154 | 1 083 - 1 154 | 44 - 49 | 44 – 42 | 44 – 42 | 0.35 – 0.42 | 0.35- 0.42 | 0.35- 0.42 |
| Coal with carbon capture [steam turbine] | --- | 1 795 | 1 782 | --- | 26 | 26 | --- | 0.58 | 0.58 |
| Conventional natural gas [combined cycle – Solid oxide fuel cells] | 494 - 7 693 | 483 - 1 282 | 465 - 962 | 13 - 423 | 13- 62 | 13- 62 | 0.40 – 4.99 | 0.40 – 4.99 | 0.40 – 4.99 |
| Natural gas with carbon capture [combine cycle] | --- | 1 186 | 1 186 | --- | 13 | 13 | --- | 0.40 | 0.40 |

**Table 3.B** | National primary energy potential. *Source:* Seixas et al. (2010).

| Primary energy | Unit | 2010 | 2020 | 2030 | 2050 |
|---|---|---|---|---|---|
| Hydro | GW | 4.821 | | 9.834 | |
| Onshore wind | GW | 3.566 | 6.50 | 7.00 | 7.50 |
| Offshore wind | GW | 0 | 0.075 | 4.00 | 10.00 |
| Wave | GW | 0.004 | 5.00 | | 7.70 |
| Photovoltaic | GW | 0.096 | | 9.30 | |
| Biomass & Biogas | PJ | 0.48 (GW) | 17.46 | 43.7 | 42.69 |
| Geothermal (conventional and Hot Dry Rock) | GW | 0.023 | 0.179 | 0.179 | 0.98 |
| Crops for ethanol production (PJ) | PJ | - | | 19.50 | |
| Crops for biodiesel production (PJ) | PJ | - | | 9.99 | |

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# CHAPTER 4

## TOP-DOWN AND BOTTOM-UP MODELLING TO SUPPORT LOW CARBON SCENARIOS: CLIMATE POLICY IMPLICATIONS*

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## ABSTRACT

The bottom-up TIMES_PT and the top-down computable general equilibrium GEM-E3_PT models are examined using a common baseline scenario to calibrate them, and the extent of their different mitigation options and its relevant to domestic policy making are assessed. Three low-carbon scenarios for Portugal until 2050 are generated, each with different GHG reduction targets. Both models suggest close mitigation options and locate the largest mitigation potential to energy supply. However, the models suggest different mitigation options for the end-use sectors: GEM-E3_PT focuses more on energy efficiency, while TIMES_PT relies on decrease carbon intensity due to a shift to electricity. Although a common baseline scenario cannot be ignored, the models' inherent characteristics are the main factor for the different outcomes, thereby highlighting different mitigation options, which are significant for climate policy design. Policy makers should carefully select the modelling tool used to support their policies. The specific modelling structures of each model make them more appropriate to address certain policy questions than others. Using both modelling approaches for policy support can therefore bring added value and result in more robust climate policy design. Although the results are specific for Portugal, the insights provided by the analysis of both models can be extended to, and used in the climate policy decisions of other countries.

## 4.1 INTRODUCTION

The need to limit the negative impacts of climate change has motivated several countries and regions to set GHG emissions reduction pledges for the medium (UNFCCC, 2011) and long term (e.g. EC, 2011; HMG, 2008; MFE, 2011). Many studies have been conducted to design decarbonisation scenarios (for reviews of low-carbon scenarios, see Hughes & Strachan, 2010; Söderholm et al., 2011).

Energy-economic-environmental models are being used extensively to outline how the transition to a low-carbon economy can be achieved and to evaluate its economic impacts. Macro-economic top-down (TD) and technological bottom-up (BU) frameworks are the two main modelling approaches, differing in the emphasis they place on energy technologies and the comprehensiveness of endogenous market adjustments (Böhringer and Rutherford, 2008).

Conventional BU models use a partial equilibrium representation of the energy system and describe it with high technological detail. They solve optimization problems by computing the least-cost combination of energy technologies to meet the energy services demand. BU models often ignore the macro-economic feedbacks of different energy system pathways or only deal with them partially through energy services demand adjustments (depending on their endogenous energy costs and exogenous price-elasticities). Some studies suggest that price elasticities capture a relevant part of the feedback effects from the economy to the energy system (Bataille, 2005; Labriet et al., 2010). However, BU models do not include the full macro-economic feedback, as they are not able to represent all the economic impacts of climate and energy policies, e.g. on gross domestic product (GDP), production, and labour.

Conventional TD, computable general equilibrium (CGE) models describe the interaction between the energy system and the economy as a whole, following the Arrow–Debreu paradigm. They represent the energy sector in an aggregated form through the use of production functions, capturing substitution possibilities through elasticities of substitution (Böhringer, 1998), and set energy savings through an autonomous energy efficiency index (AEEI). These are usually estimated from aggregated historical data, and there is no guarantee that they will remain valid in the future (Grubb, et al., 2002). Therefore, CGE models suggest that efforts to change the energy system away from a specific form (e.g. as a response to GHG abatement) tend to be costly (Grubb, et al., 1993; Hourcade, et al., 2006; IPCC, 2001; Rivers and Jaccard, 2005; Wilson and Swisher, 1993).

Some methodologies have been developed to integrate the two modelling paradigms in hybrid models (Hourcade et al., 2006): (1) creating a soft-link between two independent TD and BU models; (2) complementing one model to a reduced form of the other; (3) introducing discrete technologies (mostly electricity generation) in CGE models through a mixed complementary problem; (4) or integrating the two models through a decomposition algorithm that makes use of an iterative procedure (for a detailed overview of the methods, see Labriet et al., 2010; Lanz and Rausch, 2011). The primary difficulty arising from most of these methods lies in the inherent computational challenges. To overcome them simplified forms of the models are assumed, which in turn do not allow to capture the global strengths of both approaches. Thus, in-depth climate policy studies still typically use TD and BU models.

Some earlier studies have compared the results of both approaches for carbon mitigation targets through estimated abatement costs (Grubb et al., 1993; IPCC, 2001; Wilson and Swisher, 1993). More recently, IPCC (2007) and van Vuuren et al. (2009) have assessed the sectoral reduction potential of each approach and have found considerable differences in the level of sector abatement estimated by BU and TD models, with the latter indicating higher reductions for energy supply and industry than the former. However, the models of these studies used different baseline scenarios and, in some cases, even different assumptions. The use of different baseline scenarios limits the usefulness of  comparing the model results, as base case emissions in climate mitigation modelling are one of the factors that can drive model outcomes (in addition to the model's structural characteristics and the climate policy regime that is considered; see Fischer & Morgenstern, 2006). However, most multimodel comparison studies, such as the ACROPOLIS (Das et al., 2007) and ADAM (Edenhofer et al., 2010) projects and the Energy Modeling Forum (Clarke et al., 2009), do not have common baseline emissions, and focus primarily on the analysis of the modelling tools and results. Harmonized baseline scenarios include assumptions about energy consumption and emissions, plus other exogenous factors (e.g. GDP, population, and energy import prices). By setting a common baseline, it can be concluded that different TD and BU outcomes, under similar climate policy regimes, are a result of differences in the models' structures and characteristics (e.g. energy substitution elasticities or technology data). This feature is used in this article to examine to what extend the BU TIMES and the TD CGE GEM-E3 models, applied to Portugal, lead to different abatement strategies, and how possible different model outcomes could result in different domestic climate policy recommendations. To achieve these objectives the models' strategies to reduce sector emissions are compared using a modified Kaya identity.

In Section 4.2, the modelling framework and the baseline calibration process are summarized, and the low-carbon scenarios used are outlined. In Section 4.3, the models' results are presented, and the GHG reductions per sector, carbon mitigation strategies, and marginal abatement costs (MACs) are compared. In Section 4.4, the impact on domestic climate policy is discussed, while in Section 4.5 the key conclusions are provided.

## 4.2 MODELLING FRAMEWORK

The BU TIMES_PT and the TD CGE GEM-E3_PT models were used to generate a baseline and three low carbon scenarios for Portugal up to 2050. Although the TIMES and GEM-E3 models have been widely used to assess the impact of the climate policies of the EU or its member states (Blesl et al., 2003; EC, 2008; Proost, et al., 2009; Russ et al., 2009), the mitigation options provided by these models have never been compared. To ensure that any divergence in the models' results is not due to different reference states and assumptions, the models were initially calibrated to a common baseline scenario.

### 4.2.1 THE GEM-E3_PT MODEL

The GEM-E3 (General Equilibrium Model for Economy, Energy, Environment) is a multi-region, multi-sector, recursive, dynamic CGE model (E3M Lab, 2010). It adopts the quantitative application of the Arrow–Debreu paradigm, computing the equilibrium prices of goods, services, labour, and capital that simultaneously clear all markets, and optimizes the behaviour of economic agents. GEM-E3's production technology is represented by constant substitution elasticity (CES) production functions. The CES function combines primary factors with the intermediate consumption of materials, services, and energy in a four-level nested structure.

The GHG emissions abatement achieved by the production sectors results from three available strategies: (1) switching fuel to low-carbon options (i.e. decreasing carbon intensity, driven by substitution elasticities between energy carriers (e.g. electricity, oil, natural gas, and coal; E3M Lab, 2010); (2) increasing energy efficiency (i.e. decreasing energy intensity) by substituting energy for other production factors such as materials, labour, and capital (note that this can also translate into a shift to renewables, although this cannot be differentiated in the GEM-E3 model); (3) reducing activity levels (e.g. reducing domestic production). On the consumer side, the mitigation options are mainly driven by energy saving via energy demand price elasticities.

GEM-E3_PT corresponds to a single country version of GEM-E3 for Portugal and assumes 18 production sectors (see Appendix 4.7). The 2005 benchmark Social Accounting Matrix and transfers between sectors information were built from Use and Supply IO tables, published by Eurostat (2009) and from the Portuguese National Accounts of the National Statistics Institute (INE, 2008), respectively. Energy consumption was calibrated by crossing the national energy balances (DGGE, 2007) with the energy prices published by the IEA (2008). The GHG generated by each productive sector and category of consumption were computed through the use of aggregated $CO_2$, $CH_4$, and $N_2O$ emissions factors for coal, oil, and natural gas, and the national energy balance, and then validated with the national GHG inventories (APA, 2012). The GEM-E3_PT CES nesting structure differs from the standard GEM-E3 (E3M LAB, 2010) model at the second level where the composite factors of labour, energy, and materials (LEM) are split by the three components. At the third level, CES functions define the substitution between materials types, as it defines (separately) energy substitution between electricity and a fossil fuel aggregate (coal, oil, and natural), which is divided at the succeeding level. The substitution possibilities are set through constant elasticities, from international econometric studies (for details, see E3M LAB, 2010). CES varies from 0.4 to 0.5 up to LEM factors, being the range of elasticities values between the energy sources higher (it is 0.5 between fossil fuels aggregated with electricity and from 0.4 to 0.9 between fossil types for transports and energy-intensive industries, respectively).

### 4.2.2 THE TIMES_PT MODEL

TIMES (The Integrated MARKAL-EFOM) system is a dynamic linear optimization model generator, which simulates regional or multi-regional energy systems (Loulou, et al., 2005). Based on a technology database and external constraints (e.g. GHG emissions caps, fossil fuel import prices, and energy sources potential), TIMES is used to compute the energy supply/demand equilibrium under conditions of perfect foresight. The ultimate goal of TIMES is to satisfy energy services demand at the minimum total system cost, making simultaneous decisions about equipment investment and operation, primary energy supply, and energy trade (Loulou et al., 2005). The TIMES_PT model represents the Portuguese energy system, in particular energy supply (e.g. petroleum refining), power sector, and final energy consumption sectors (e.g. industry, residential, commercial, agricultural, and transportation, which in turn are divided into several subsectors) (see Appendix 4.7). The technology database in the model includes the characteristics of the existing and future energy technologies, namely efficiency, capacity factor, availability, technical lifetime, investment, and operation and maintenance costs. The original technology data was obtained from the European NEEDS Project and has been updated within the EU RES2020 project and from international literature, and validated by national stakeholders.

TIMES_PT is calibrated to 2005 national energy balances (DGGE, 2007) and includes $CO_2$, $CH_4$, and $N_2O$ combustion and process emissions, which are calculated and calibrated using emissions factors per energy carrier and/or sector from national GHG inventories (APA, 2012). As with GEM-E3_PT, the same strategies to reduce GHG abatement are assumed in TIMES_PT: (1) decreasing carbon intensity, by choosing technologies that provide the same service with a less carbon intensive fuel (e.g. substitution of a coal boiler to a gas boiler); (2) reducing energy intensity through more efficient technologies; (3) decreasing activity levels (reduction of energy services demand or mobility) through exogenous demand-price elasticities. A price elasticity of –0.3 for almost all demands categories is assumed in TIME_PT (as supplied by the Katholieke Universiteit Leuven). This is assumed to be a generic value for the EU countries. Although the TIMES model can also reduce GHG emissions through carbon capture and storage (CCS) technologies, this mechanism was not considered (see Section 4.2.3).

### 4.2.3 CALIBRATION METHODOLOGY FOR A COMMON BASELINE SCENARIO

The GEM-E3 and TIMES models have been applied together in several European projects (e.g. NEEDS, RES2020, REALISEGRID) in the following way: GEM-E3 is first used to compute the demand drivers, such as GDP and sector domestic production growth; these are then used to determine the evolution of energy services and materials demand (Step I of the calibration process, described later in this section), used as TIMES inputs (Step II of the calibration process). No further feedback of any kind has so far been considered.

To guarantee that both models are benchmarked to a common baseline scenario, and before considering particular climate mitigation targets, a calibration process was developed based on a soft link between the two models. The link follows an approach close to the one used by Labriet et al. (2010), such that prices and quantity variables (e.g. energy, emissions) are exchanged between the models, which are iteratively solved until similar results (i.e. less than a 10% difference) are reached. The overall calibration framework is depicted in Figure 4.1**.**

The main assumptions of the baseline scenario (BS) in both models include (1) an annual real interest rate of 4%; (2) fossil fuel import prices (adopted from the Current Policies Scenario in IEA (2010) up to 2035 and extended till 2050), of US$$_{2009}$162.0/barrel for crude oil, US$$_{2009}$176.9/BTU for natural gas, and US$$_{2009}$124.5/tonne for coal in 2050; (3) a socio-economic scenario that assumes an annual average GDP and population growth of 2.3% and 0.3%, respectively, between 2010 and 2050 (Seixas et al., 2010); (4) a ban on nuclear electricity generation; and (5) the unavailability of CCS technologies (this is justified by the absence of this option in GEM-E3_PT).

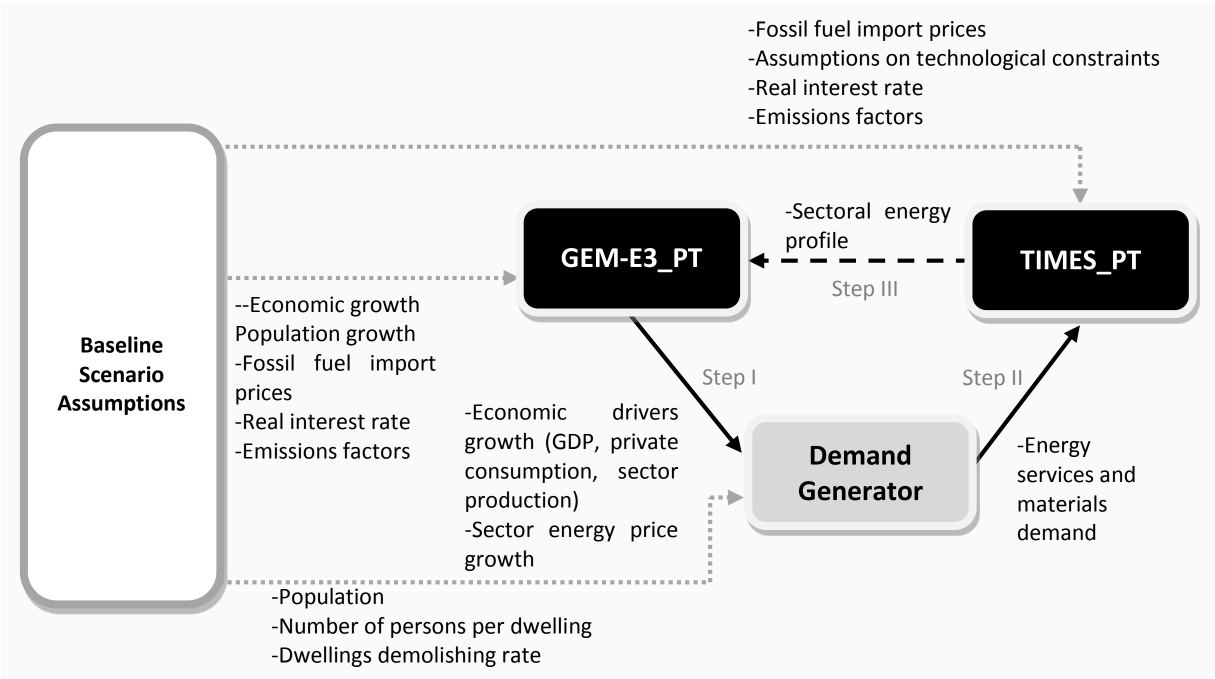


**Figure 4.1** | GEM-E3_PT and TIMES_PT calibration framework (Notes: The dotted grey lines represent Baseline scenario assumptions (e.g. economic and population growth, fossil fuel import prices) or calibration parameters (e.g. real interest rate, emission factor); the black lines represent the iteration process: full black lines are direct inputs/outputs and the black dashed lines represent indirect inputs).

The calibration process between the two models, as depicted in Figure 4.1 proceeded as follows:

- In Step I, the economic drivers and total energy prices by sector, generated by GEM-E3_PT through the optimization behaviour of the economic agents, were used to produce the evolution of energy services and materials demand according to the demand generation equation from Van Regemorter and Kanudia (2006) (as cited in Simões, Cleto, Fortes, Seixas, & Huppes, 2008). The equation assumes that the evolution of the energy services demand is a product of the economic drivers and the total energy prices evolution and autonomous efficiency improvement in industry.
- In Step II, the energy service and materials demand generated in Step I were used as inputs for TIMES_PT, which was then run to compute the least-cost technological profile of the energy system (given in terms of energy consumption, i.e. quantities per sector per energy source, and the corresponding GHG emissions).
- Finally, in Step III, the sectoral energy profile given by TIMES_PT (in terms of both final and primary energy) for the time horizon was included in GEM-E3_PT, where the evolution of energy efficiency is associated with an exogenous AEEI. The goal of this step is to align, in the BS, the models energy consumption and GHG emissions per sector. In most uses of the general GEM-E3 model, AEEI is a fixed value, which is derived from the literature and is identical for all

energy carriers and end-use energy sectors. However, in the present GEM-E3_PT, this parameter was disaggregated per energy carrier and sector and adjusted according to TIMES_PT technological choices in order to ensure consistency between the two models. (See the Appendix 4.7, which presents the 10 sectors considered in the calibration process and its correspondence with the models categories).

Modifications in sector energy consumption can induce changes in domestic production and, consequently, on energy services and materials demand. The three steps were therefore repeated until the energy consumption per energy carrier and calibration sector obtained from TIMES_PT and GEME3_PT models converged, i.e. until there was only a minor difference between the models (less than 10% or 1PJ), relative to the previous iterative process.

## 4.3 LOW-CARBON SCENARIOS

Three low-carbon scenarios, which differ from the BS only in the level of the GHG emissions cap assumed up to 2050, were run in GEM-E3_PT and TIMES_PT: (1) a scenario with a 27% increase in energy-related emissions, relative to 1990 levels (+27S), which corresponds to Portugal maintaining its commitment under the Kyoto Protocol until 2050; (2) a 20% reduction in emissions (relative to 1990 levels) (-20S); and (3) a 60% reduction in emissions relative to 1990 levels (-60S), with a constant annual decrease rate from 2015 onwards for the two latter scenarios (see Figure 4.2). From 2010 to 2015, it was assumed in the three scenarios that Portugal is committed to the caps specified in the Kyoto Protocol, i.e. an increase of only 27% relative to 1990 emissions. The total GHG caps only include energy combustion emissions, which correspond to approximately 97% of the total energy GHG emissions in 2010 (APA, 2012). No emissions' trading among sectors was modelled.

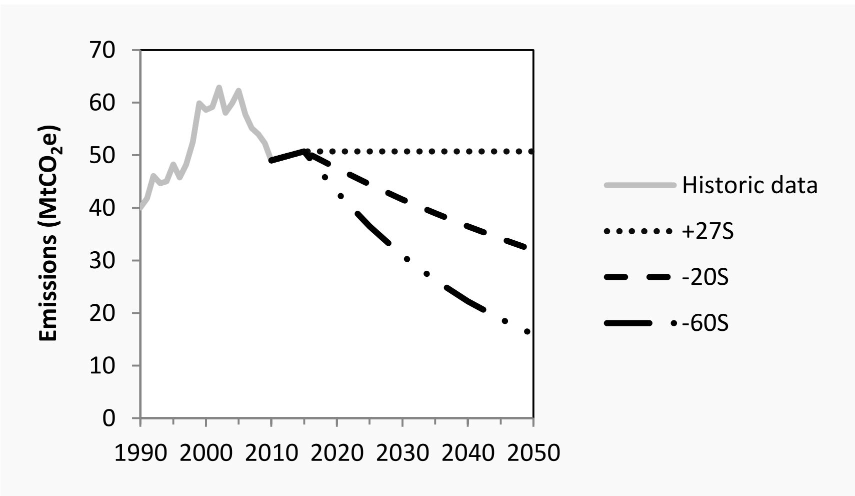


**Figure 4.2** | Low carbon scenarios (+27S, -20S, -60S) (Note: High variability of historical GHG emissions data refers to the variability of hydrologic year. The modelling results rely on an average hydrologic year).

## 4.4 RESULTS

### 4.4.1 BASELINE SCENARIO

High convergence was achieved in the baseline scenarios of both models regarding the consumption of energy and GHG emissions (see Table 4.1). From 2005 to 2050, the final energy consumption in the BS increased by more than 20%. In industry (i.e. ferrous and non-ferrous metals, chemical, energy-intensive and other industries) this increased the most (27% for GEM-E3_PT, 29% for TIMES_PT), and in buildings (i.e. services and residential) it increased the least (13% for GEM-E3_PT and 18% for TIMES_PT). In BS without a GHG cap, the power sector relied on coal, with its relative share increasing from 46% in 2005 to approximately 82% in 2050 due to the fact that this is the cheapest technology/fuel. The consumption of renewable energy was not included in this estimate because it is not an explicit output of GEM-E3_PT (see Section 4.2.1). For both models, energy supply (power sector and refinery) was the leading emitter, followed by transport and industry. The main GHG emissions reduction from 2005 to 2050 occurred in buildings (a reduction of 14%), and the main increase took place in transport (an increase of 22% and 27% for the GEM-E3_PT and TIMES_PT models, respectively).

### 4.4.2 LOW-CARBON SCENARIOS

#### GHG EMISSIONS REDUCTION PER SECTOR

For the sake of simplicity, the following results were assessed by comparing them with the BS. The two models indicate that energy supply will have the highest GHG abatement potential (see Figure 4.3).

Compared to BS, GEM-E3_PT reduced GHG emissions from 24% (by 2020 for +27S) to 90% (by 2050 for -60S), while TIMES_PT reduced emissions from 35% to 82% (for the same years and low-carbon scenarios). In both models, energy supply contributed most to total abatement. However, as the stringency of the cap increased over time and scenario, its relative importance for total abatement decreased, as higher abatement was required from all other sectors. For -60S in 2050, TIMES_PT allocated the biggest abatement to transport (43% of total abatement) due to a shift to biofuels and electricity based technologies. GEM-E3_PT had lower substitution possibilities for this sector. In fact, for private cars, it is not possible to substitute electricity or natural gas for oil, which explains the lower abatement level.

**Table 4.1** | Modelling results for Baseline scenario from GEM-E3_PT and TIMES_PT following the calibration process (renewable energy consumption not included)

| | 2005 | | 2020 | | 2030 | | 2050 | | **Difference between the models (%)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **GEM-E3** | **TIMES** | **GEM-E3** | **TIMES** | **GEM-E3** | **TIMES** | **GEM-E3** | **TIMES** | **'05** | **'20** | **'30** | **'50** |
| Final Energy consumption (PJ) | 654 | 665 | 665 | 684 | 700 | 699 | 802 | 813 | 2 | 3 | 0 | 1 |
| Agriculture | 16 | 16 | 17 | 18 | 18 | 18 | 20 | 19 | 0 | 3 | -1 | -8 |
| Industry | 191 | 191 | 202 | 199 | 202 | 210 | 243 | 245 | 0 | -2 | 4 | 1 |
| Buildings | 184 | 189 | 167 | 170 | 165 | 170 | 217 | 214 | 3 | 2 | 3 | -1 |
| Transport | 264 | 269 | 278 | 297 | 314 | 301 | 322 | 335 | 2 | 7 | -4 | 4 |
| | | | | | | | | | | | | |
| Energy consumption in power sector (PJ) | 294 | 299 | 232 | 234 | 229 | 225 | 241 | 235 | 1 | 1 | -2 | -3 |
| Coal | 136 | 138 | 164 | 166 | 169 | 170 | 196 | 192 | 2 | 2 | 1 | -2 |
| Oil | 69 | 70 | 5 | 5 | 0 | 0 | 0 | 0 | 2 | -6 | 0 | 0 |
| Natural Gas | 90 | 90 | 63 | 63 | 60 | 55 | 45 | 43 | 1 | 0 | -9 | -5 |
| | | | | | | | | | | | | |
| GHG emissions (Gg $CO_2$e) | 62 923 | 63 562 | 57 484 | 59 801 | 60 009 | 60 548 | 65 467 | 67 870 | 1 | 4 | 1 | 4 |
| Agriculture | 950 | 951 | 1 048 | 1 080 | 1 096 | 1 085 | 1 093 | 1 114 | 0 | 3 | -1 | 2 |
| Industry | 9 193 | 9 311 | 9 041 | 9 008 | 9 211 | 9 590 | 11 113 | 11 251 | 1 | 0 | 4 | 1 |
| Energy Supply | 27 025 | 27 087 | 22 046 | 22 971 | 22 238 | 23 232 | 23 995 | 24 765 | 0 | 4 | 4 | 3 |
| Transport | 19 820 | 20 021 | 20 841 | 22 067 | 23 598 | 22 455 | 24 159 | 25 428 | 1 | 6 | -5 | 5 |
| Buildings | 5 936 | 6 192 | 4 509 | 4 676 | 3 867 | 4 187 | 5 107 | 5 312 | 4 | 4 | 8 | 4 |

Industry had the second highest abatement potential (in terms of the percentage of reduction) in both models, with the exception of -60S and -20S in 2050, for which TIMES_PT placed industry after transport and energy supply due to the two latter sectors having considerable electricity and renewable technologies available, respectively.

In TIMES_PT, buildings had the least cost-effective reduction options, with an abatement effort below 55% for -60S in 2050, while in GEM-E3_PT the reduction was 65%. Generally, in the long term, GEM-E3_PT systematically presented higher emissions reductions than TIMES_PT for agriculture, industry, and buildings. For energy supply and transport it was not as easy to highlight major trends between models as the results varied across the scenarios but TIMES_PT mainly gave higher reductions for energy supply than the GEM-E3_PT model. The differences in the models' sector abatement allocations were associated with their abatement possibilities, represented by the technological database in TIMES_PT and the CES function in GEM-E3_PT. Moreover, TIMES_PT results are based on an optimistic perspective about the future, in which current immature technologies will become marketable in the long term. It is assumed by the model that economic agents have perfect knowledge about the future and that their choices are strictly rational. Thus, their investment decisions are not postponed by either uncertain long-term climate policies, resistance to change due to imperfect information, or subjective preferences. By contrast, in GEM-E3_PT the economic agents have imperfect knowledge of the future and that their technological decisions are driven by exogenous substitution elasticities, based on historical data that integrate the just mentioned factors.

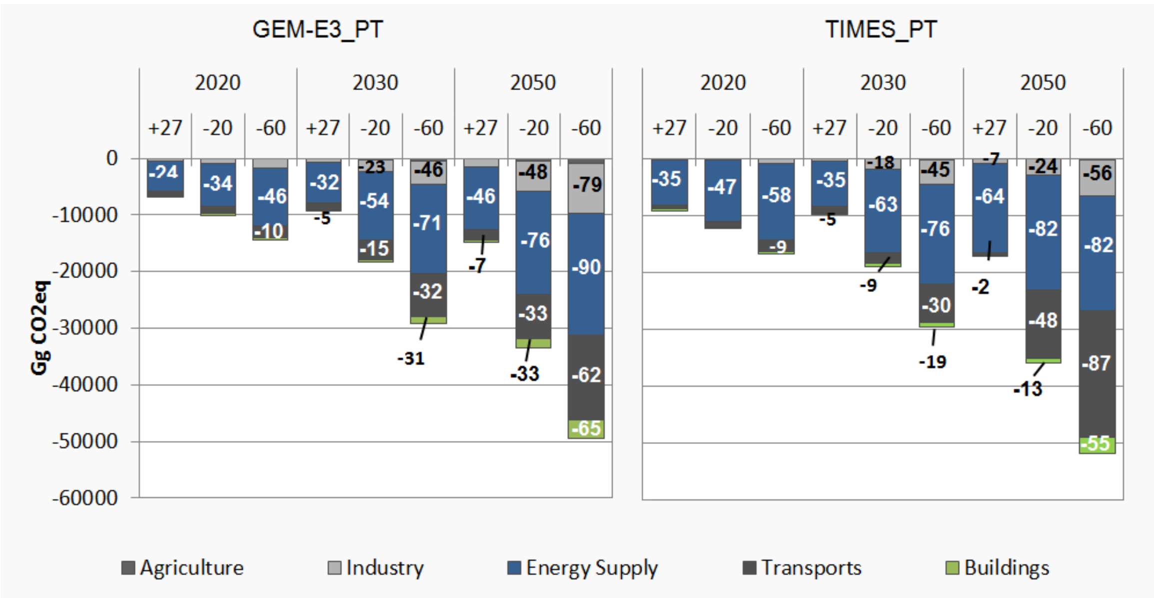


**Figure 4.3** | GHG emissions reduction (Gg $CO_2e$ and percentage inside the bars) for the low carbon scenarios comparing to Baseline scenario (slightly differences in the total GHG emissions abated from the models are a result of the small divergences identify in Baseline).

To illustrate the policy significance of the differences between the model results regarding GHG reduction, the abatement effort was presented using the EU climate and energy package metrics by comparing 2020 results with the 2005 emissions included in the EU Emissions Trading Scheme (EU ETS), and the energy component of the Effort Sharing Decision, which covers non-ETS sectors (see Table 4.2).

**Table 4.2** | Percentage of GHG emissions reduction in 2020 compared to 2005 disaggregated in EU ETS and non EU-ETS for the Low Carbon scenarios.

| Scenario | Sector | GEM-E3_PT | TIMES_PT |
|---|---|---|---|
| +27% Scen. | EU-ETS | -32 | -37 |
| | Non EU-ETS | -6 | -3 |
| -20% Scen. | EU-ETS | -41 | -48 |
| | Non EU-ETS | -8 | -3 |
| -60% Scen. | EU-ETS | -50 | -57 |
| | Non EU-ETS | -12 | -8 |

To simplify matters, it was assumed that the whole energy supply and all energy-intensive industry sectors are included in the EU ETS. The non-ETS sectors include emissions from agriculture, commercial, residential, and transport sectors (including domestic aviation) and non-energy-intensive industry. For all scenarios, TIMES_PT achieved a reduction effort for the EU ETS higher than that of GEME3_PT (by five to seven percentage points), while the latter model defined a higher abatement for non-ETS emissions (by three to five percentage points) compared to the former.

Both models suggest that decarbonisation will occur primarily in the EU ETS sectors, as energy supply and energy-intensive industry have the cheapest abatement options. Although there is no national target for EU ETS emissions, both models found it cost-effective to achieve a reduction in the EU ETS sectors above the EU target of 21% (EC, 2009a) even in +27S. However, in this scenario, only for TIMES_PT is it cost-effective to achieve a –34% reduction target within a conditional increase of the EU's total GHG emissions reduction from 20% to 30% in 2020 (EC, 2010).

Under the Effort Sharing Decision, Portugal must limit its non-ETS emissions to a 1% increase in 2020 relative to 2005 values (EC, 2009b). An EU working paper analysing options that go beyond a 20% GHG emissions reduction (EC, 2012) has indicated that Portugal's non-ETS emissions have a higher reduction potential between 11% and 19%. An 11% reduction was only reached by GEME3_PT in the -60S low-carbon scenario, which is relevant for policy-making and negotiations and demonstrates how important it is to understand the range of modelling tools used.

**ABATEMENT STRATEGY**

The Kaya identity (Kaya, 1990) is widely used to assess the main drivers responsible for GHG emissions and for their abatement. It is possible to understand how GHG emissions are reduced in each of the low-carbon scenarios by comparing the evolution of the various factors of a modified Kaya identity with the BS (see Equation (4.1)).

The original Kaya identity covers the whole economy and defines activity in terms of GDP and population. In the modified Kaya identity, activity is associated with a particular sector, and is generally expressed in terms of domestic production (for GEM-E3_PT) or energy service demand (for TIMES_PT). Although it is not possible to establish a direct comparison between the models' reduction of activity (and consequently energy efficiency) for end-use sectors (as different activity indicators are assumed), the evolution of the various factors allows an understanding of each model's abatement strategy for each sector. The three Kaya factors that correspond to the three main strategies for reducing GHG emissions mentioned above (see Sections 4.2.1 and 4.2.2) are reducing activity, energy intensity, and carbon intensity:

$$CO2\ emissions_s = activity_s{}^* \cdot \frac{Energy\ Consumption_s}{activity_s\ *} \cdot \frac{CO2\ emissions_s}{Energy\ consumption_s} \qquad (4.1)$$

$$\forall s = buildings, industry, transport, power\ sector\ \ldots$$

Note that in GEM-E3_PT, 'activity' comprises sector domestic production by volume ($ME_{2005}$) for industry, services, agriculture, and transport services (i.e. freight and public transport), as well as private consumption (except fuels and power demand) ($ME_{2005}$) for the residential and private transport sectors. In the TIMES model, 'activity' comprises sector energy service demand (PJ) for buildings (residential and services) and agriculture, mobility (pkm, tkm) for transport, and materials and energy demand (tonne and PJ) for industry. In both models, the power sector activity corresponds to electricity production (PJ).

Figure 4.4 illustrates GHG pathways by sector and the evolution of their respective Kaya drivers as compared with the BS. For simplification, the intermediate -20S and agriculture sector are not shown.

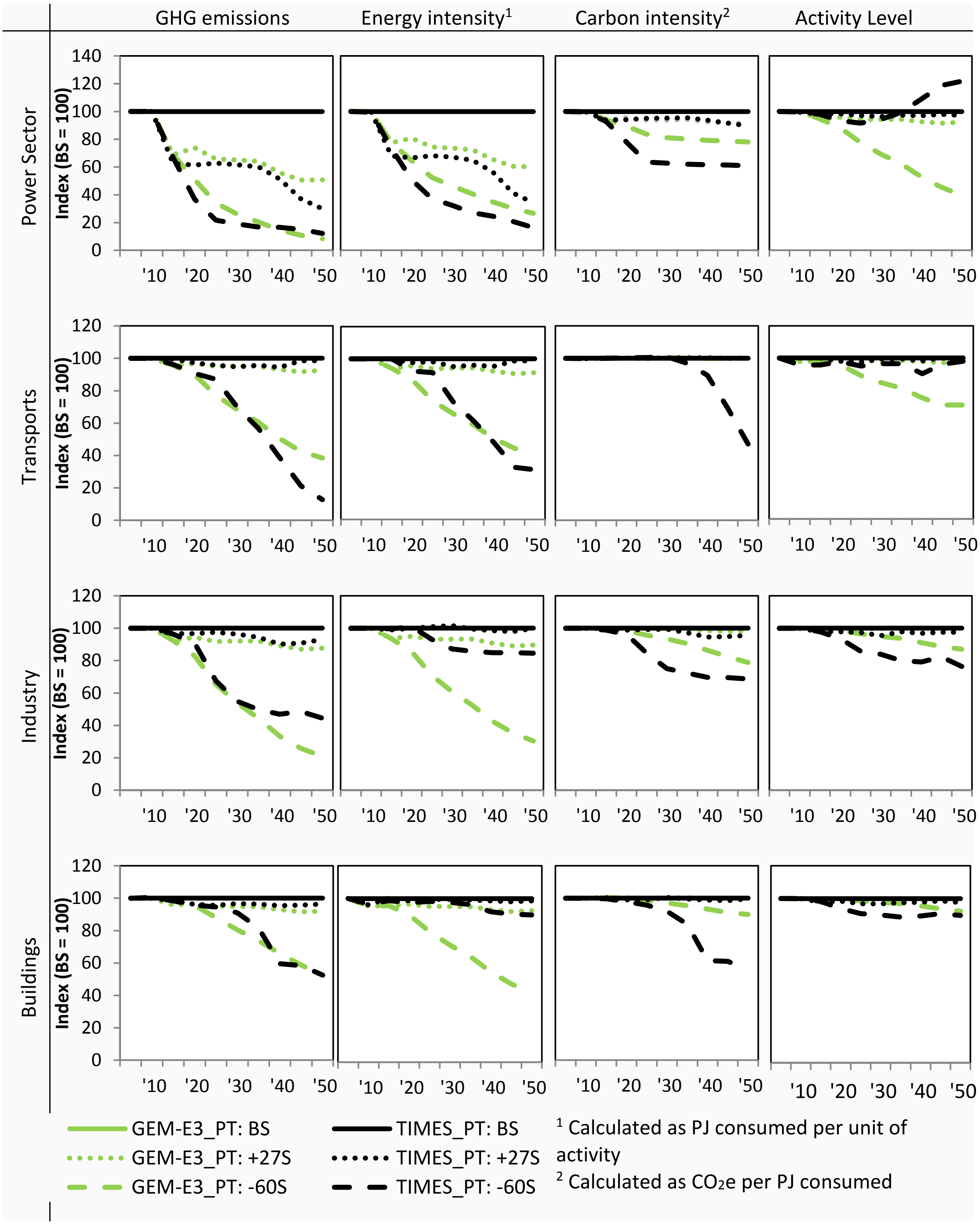


**Figure 4.4** | Comparison between GHG emissions, energy intensity, carbon intensity and activity level across models and scenarios (Baseline scenario (BS) = 100 over time) (excluding renewable energy).

In the power sector, the emissions path and energy and carbon intensity reduction ranges were close in both models. In TIMES_PT, there was a shift from coal to renewables, with fuel carbon intensity decreasing from around 10% to 39% (in +27S and -60S, respectively) in 2050 compared to the BS. In GEM-E3_PT, there was a move from energy consumption to other production factors (e.g. labour, materials, and capital), reflecting investment in renewable energy and more efficient equipment, with carbon intensity decreasing from 8% to 29% (again in +27S and -60S, respectively).

Although the consumption of coal was significantly reduced in the low-carbon scenarios of GEME3_PT (by 37% to 66% relative to the BS) it was still used, which caused a lower reduction in carbon intensity than in TIMES_PT. For the more stringent target, and contrary to the results of the GEME3_PT model, electricity production increased in TIMES_PT and hence end-use sectors could reduce their carbon emissions to a greater extent due to its consumption.

In general, the reduction in emissions by end-use sectors in GEM-E3_PT was associated with a reduction in energy intensity, while carbon intensity and sector activity mainly decreased in TIMES_PT. Total final energy was more reduced in GEM-E3_PT than the share of fossil fuels (see Figure 4.5).

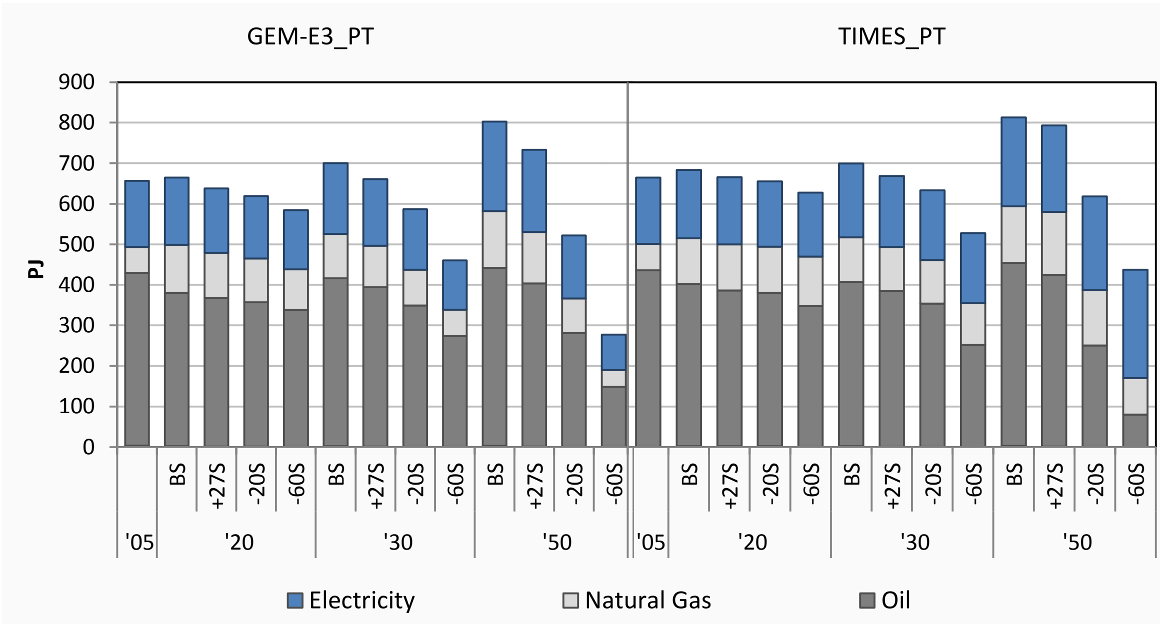


**Figure 4.5** | Final energy consumption by fuel (2005, 2020, 2030 and 2050) under Baseline and Climate Policy scenarios (Renewable energy not included)

In 2050, for -60S, final energy was reduced by approximately 65% compared to the BS, while fossil fuel use was reduced by just four percentage points (from 73% in the BS to 68%). By contrast, the consumption of fossil fuels was more significantly reduced in TIMES_PT (by 34 percentage points, from 73% in the BS to 39% in -60S in 2050) replaced by electricity, than the decrease of final energy consumption (a decrease of 46% in 2050 for -60S compared to the BS).

Because of its technological database, there are several options available in TIMES_PT to reduce power sector emissions (supported by renewable technologies) and to substitute fossil fuels for electricity energy consumption in end-use sectors. The GEM-E3_PT model focuses more on demand-side measures (see van Vuuren et al., 2009), increasing the energy efficiency of end-use sectors through the substitution of energy for other production factors in the CES nest. Accordingly, although electricity consumption was reduced in industry and buildings, its share in the sectors energy consumption increased, which can be explained by a shift from fossil to more efficient electric technologies.

In -60S, when a greater effort is necessary from end-use sectors, transport was an exception amongst these strategies. In addition to a reduction in its carbon intensity in TIMES_PT, there was also a significant reduction in its energy intensity, with the deployment of highly efficient electricity and hybrid plug-in vehicles. In GEM-E3_PT, the reduction in the energy intensity of transport was also accompanied by a reduction of its activity, decreasing by 30% in 2050 in -60S. In fact, transport was the end-use sector where energy consumption reduced the least, maintaining a high share of oil demand across scenarios and through the years. This is reflected in transport constant carbon intensity and represents a limitation on its substitution possibilities.

#### MARGINAL ABATEMENT COST

The GHG emissions reduction potential and abatement strategy defined by each model has a direct impact on abatement costs. MAC curves have been used extensively to assess the cost of particular carbon abatement strategies, and represent the shadow price of mitigation in a given period. MAC curves are also at the centre of the climate policy debate because they rank abatement policies, influencing the decision-making process (Kesicki & Ekins, 2012).

To plot the MAC curve for 2050 from the results of both models (see Figure 4.6), several scenarios for various additional GHG caps were run, representing a linear GHG emissions pathway from 2015 to 2050: 0% (0S), 40% reduction (-40S), and 50% reduction (-50S) of GHG emissions relative to 1990 levels. The other assumptions made in the three original low-carbon scenarios and the BS were maintained.

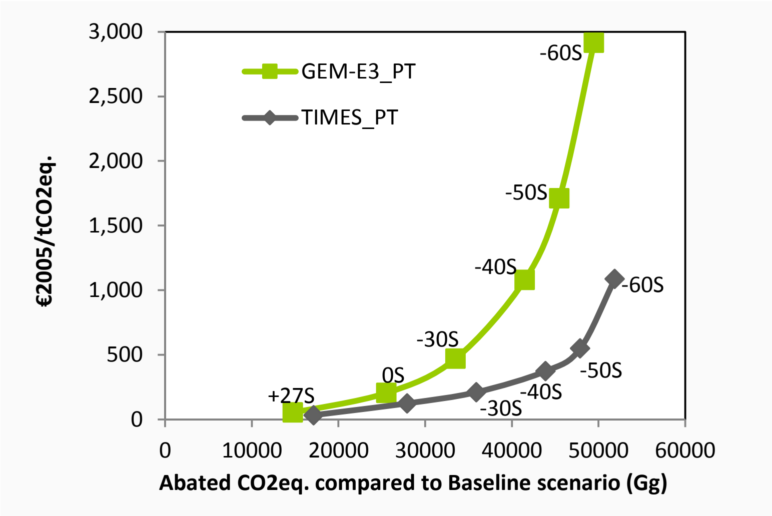


**Figure 4.6** | Marginal abatement cost curve for the year 2050

As some authors have already observed (e.g. Jaccard et al., 2003; Hourcade et al., 2006; IPCC, 2001; Rivers and Jaccard, 2005), the MAC curve from TD models is higher for the same level of reduction than from BU models. The increase in the carbon reduction target from a 27% increase to a 60% decrease led to a corresponding increase in the carbon price from 54€$_{2005}$/t$CO_2$e to 2 915€$_{2005}$/t$CO_2$e in GEM-E3_PT, and from 34€$_{2005}$/t$CO_2$e to 1 075€$_{2005}$/t$CO_2$e in TIMES_PT. For higher GHG abatement levels, the relative difference between the MACs was higher, which can be explained by different reduction strategies and sector potential. Historical substitution elasticities (as in GEM-E3_PT) lower the economy's willingness to change the energy system away from GHG-intensive technologies (Jaccard et al., 2003), resulting in higher abatement costs. By contrast, in BU models, when technology costs are converted into present value through a social discount rate (e.g. 4% used), many technologies that provide the same energy service and reduce GHG emissions appear to be profitable (Bataille, Jaccard, Nyboer, & Rivers, 2006), like the widespread use of electric and hybrid plug-in vehicles observed in TIMES_PT for -60S. The greater financial risk of new technologies, the fact that they may not be perfect substitutes (to consumers), and the availability of capital are not usually considered, resulting in lower mitigation costs from BU models. Moreover, TIMES_PT does not include the full economic feedback represented in GEM-E3_PT (e.g. the impact of the change in economic activity due to GHG policies).

## 4.5 Discussion of Policy Considerations

BU and TD models are two of the most common tools used to support climate policy design, providing insights about the strategies required to meet a GHG emissions cap. However, they have mostly been used independently of one another and without assuming harmonized baselines. Initial runs of the models were performed without considering either a common baseline scenario or any cap. There were significant differences between the models outcomes (e.g. the GHG emissions of GEM-E3_PT were 13% to 48% higher than in TIMES_PT for the years 2020 and 2050, respectively). Thus, the abatement effort required according to each model to achieve GHG emission reduction differed. The results for -60S with and without a common baseline also showed relevant differences, especially in GEME3_PT for the buildings, agriculture, and industry sectors. For example, comparing with the baseline year the difference in the abatement effort required in industry by the non-harmonized GEM-E3_PT and TIMES_PT models was higher (maximum of 38% in 2050) than when the baselines of the models were harmonized (28% in 2050). These results show that although common baseline emissions are not the decisive driver for different outcomes, they cannot be ignored.

Assuming the same baseline emissions, the models yielded close results for sector abatement given moderate emissions caps. However, as the stringency of the cap is increased, the abatement effort and the strategy required to reduce emissions increasingly diverge.

The relevance and usefulness of the findings are derived not so much from the accuracy of the numbers but rather from the insights they provide regarding how and where climate policies should be applied to meet a GHG cap. By allocating significant emissions reductions in one sector rather than another, the models indicate where the cost-effective mitigation policy opportunities are, which might influence, e.g. the potential for emissions trading. For example, the emissions reduction set by TIMES_PT in transport was higher than in industry, which suggests that it will be less cost-effective to reduce industry emissions than transport emissions. By contrast, this was not suggested by the GEM-E3_PT model.

The main strategy in TIMES_PT to reduce GHG emissions (relative to the BS), was to decarbonise the power sector through renewable-based technologies, and to shift the energy consumption of end-use sectors to electricity. This suggests that the most cost-effective solution will be the adoption of low carbon technologies, which are typically promoted by carbon taxes, financial incentives, or regulations.

In GEM-E3_PT, the strategy to reduce end-use sector emissions relied mainly on energy savings, which is also reflected in the decline of electricity production. This indicates that demand side energy efficiency policies will be relevant for example technology or buildings efficiency standards and incentives.

The main difference between the strategies observed in the models is related to the transport sector, which is currently responsible for 30% of the GHG emissions in Portugal (APA, 2012). Based on TIMES_PT, transport can play an important role in the decarbonisation of the economy, with approximately 87% emissions reduction in –60S in 2050 relative to the BS, thanks to the use of biofuels and highly efficient electricity-based technologies (e.g. electric and hybrid plug-in vehicles). Technology choices will be the main drivers for GHG abatement, while behavioural changes will have a modest contribution (as shown by the lower reduction of activity level; see Figure 4.6). Based on GEM-E3_PT, the key driver to reducing transport emissions will be decreasing its energy intensity. This can be achieved by the use of both efficient oil technology options and a reduction in activity. Therefore, TIMES_PT results suggest that technology-oriented policies should be developed as incentives for purchasing electric vehicles, for example, while the conservative vision of GEM-E3_PT suggests that road transport will not move away from using oil and that policies to reduce this activity may be necessary.

Confronted with different results, decision makers should consider ranges of abatement potentials and costs rather than just one model outcome. Policy makers can reasonably create incentives for promoting the technological shifts suggested by the BU models, while taking into account the macroeconomic impacts defined by TD models. However, models are simply tools to explore the technologies and policies (and related possible costs) that could make a specific scenario attainable. Model cost effective results should be just one input among others (e.g. the acceptance of a given technology by the public) used to inform the policy decision process. Thus, the adequacy and significance of the model outcomes should be discussed inter alia with industry stakeholders and consumer associations.

## 4.6 CONCLUSIONS

The abatement strategies of a top-down (TD) and a bottom-up (BU) model were analysed and compared, given a common baseline scenario (BS), to explore potential domestic climate policy-making options. The TIMES_PT and GEM-E3_PT models provided close outputs when harmonized to a common BS, and the results suggest that energy supply has the largest mitigation potential.

However, there are differences in both the effort levels required for each sector, especially for more stringent caps, and the strategies used to reduce GHG emissions, which could lead to different policy designs. The GEM-E3_PT model privileged energy efficiency, as it tends to focus more on the demand side, while the TIMES_PT model relied on the reduction of carbon intensity by shifting energy consumption in end-use sectors to electricity and promoting renewable electricity, thus suggesting that policy makers should provide incentives to promote low-carbon technologies.

Common baseline assumptions for defining an equal reduction global abatement effort cannot be ignored. However, the models' characteristics and the implicit substitution possibilities are the decisive factors responsible for the different results. The constant substitution elasticity (CES) function and consumer demand equations in GEM-E3_PT resulted in a smoother reduction path, while TIMES-PT results reflect the explicit penetration of technologies (ignoring their financial risks or the available capital).

These factors, combined with the fact that TIMES_PT does not include the full economic feedback like GEM-E3_PT, account for the differences in the marginal abatement cost (MAC) curves of the two models and as described in the literature, the TIMES_PT model estimates lower costs than the GEME3_ PT model.

The fact that GEM-E3_PT does not include direct renewable energy (as does TIMES_PT) is one of the major limitations of this study (although renewable energy consumption is excluded from the comparison of the models' results). Still, it should be emphasized that renewable technologies can be indirectly chosen in the CGE model when increasing capital to reduce fossil and electricity consumption.

Moreover, as a perfect foresight model, TIMES_PT anticipates decisions regarding GHG reductions, while due its recursive dynamic character, the economic agents in GEM-E3 are surprised by the GHG caps. These observations, and the fact that the models do not consider the same activity indicators, tend to limit any comparison. However, the goal of this analysis was not to assess divergences of perfectly comparable models, but rather to compare the outcomes of two 'real-life' models extensively used in EU climate policy analysis.

Despite the stated limitations of the analysis, the results suggest that decision makers should consider carefully the modelling tool that is being is used to support their policies. Climate policy design should ideally be supported by the two modelling approaches, and the assumptions and limitations associated with each tool should be clearly stated. The complementary use of both models can bring added value and result in more robust climate policy making once its specificities make them more appropriate to address certain policy questions. Thus, TD CGE models (such as GEM-E3) better handle questions about the policy instruments (economic instruments, standards, recycling strategy) that should be used, while BU models (such as TIMES) are more appropriate for evaluating which instrument is more cost-effective in reducing GHG emissions and which technologies should be promoted.

Integrating TD and BU modelling approaches is relevant to climate policy design. Further work is currently being undertaken to develop a hybrid modelling platform, supported by a soft link between TIMES_PT and GEM-E3_PT, to ensure consistency between their implicit substitution possibilities.

This approach has the advantage of being a transparent process, and maintains the integrity of each model and their respective strengths. Taking the calibration process presented in this article as a starting point (and based on the methodology presented in Labriet et al., (2010)), the structure of the CES function in GEM-E3_PT will be changed to introduce new energy carriers and to replicate the energy system profile, as defined by TIMES_PT for both a baseline scenario and further different policy scenarios.

## 4.7 APPENDIX

Table 4.A provides a characterization of the models' sectors and their correspondence to those considered in the calibration process.

**Table 4.A** | GEM-E3_PT and TIMES_PT sectors and its respective correspondence in the calibration process.

| GEM-E3_PT productive sectors | TIMES_PT sectors | Calibration sectors |
|---|---|---|
| Agriculture | Agriculture | Agriculture |
| Oil | Oil Refinery | Non electricity energy supply |
| Coal; Natural Gas | Other energy supply | |
| Electricity | Electricity | Electricity |
| Ferrous and non-ferrous metals | Iron and Steel; Non-ferrous metals | Ferrous and non-ferrous metals |
| Chemical | Ammonia; Chlorine; Other chemicals | Chemical |
| Energy intensive sector | Cement; Lime; Glass; Other non-metallic minerals; Paper | Energy intensive industries |
| Electric and Other equipment goods; Transport equipment; Other Industries; Consumer Goods Industries; Food and textile; Construction | Other industries | Other industries |
| Land transport; Other transport; Households operation of transport associated with transport equipament (consumption expenditure category) | Transports (road freight, rail freight; buses, Intercity coaches, heavy rail passengers, subway, road car, moto, aviation, navigation) | Transports |
| Services of credit and insurances; Other Market Services; Non Market Services | Services (space heating and cooling, water heating, cooking, refrigeration, electric appliances, public lighting) | Services |
| Households Fuels and power associated with Heating and cooking appliances (consumption expenditure category) | Residential (space heating and cooling and water heating, refrigeration, cooking, electric appliances) | Households |

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# CHAPTER 5

## BRIDGING THE GAP BETWEEN SOCIOECONOMIC STORYLINES AND ENERGY MODELLING*

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## ABSTRACT

The development of scenarios to explore energy and low carbon futures has been widely applied. Although some studies combine qualitative scenarios with quantitative outcomes from modelling exercises, the two approaches have been extensively and separately used. Many energy scenarios are sustained only by the results of the models, which allow great technological details but neglect the interaction with social and economic factors. Using Portugal as a case study, this paper presents a framework to link socio-economic storylines, sustained by national stakeholders' workshops, with the development of quantitative energy scenarios through 2050, generated by the technology-based TIMES_PT model. The storylines highlight different visions of the country's development, including the energy system. A comparison between the energy profile from the storylines and the energy modelling outcomes was performed to assess the extent of their differences. This analysis revealed generally similar visions, with the exception of the importance of some technologies, which may affect future energy planning. We conclude that a combined method that links socio-economic storylines and energy modelling increases the robustness of energy scenario development because providing a coherent context for modelling assumptions allows better reasoning, which is most valued for the decision-making process.

## 5.1 INTRODUCTION

In a world that is in constant change, forecasting the future can be a Sisyphean task. In this context, scenario analysis has appeared as a means of characterizing the future and its uncertainties through a structured and imaginative process (Rounsevell and Metzger, 2010). Scenarios help explore the what, how and/or if in future pathways and allow to understand how different key driving forces might lead to different outcomes. However, scenarios are not predictions or forecasts but rather are a collection of futures that establish the boundaries of uncertainty and the limits within plausible futures (Wilson, 2000).

Since the sixties, scenario analysis has gained increasing importance in future planning. Back then, scenarios arose as a military planning tool, evolving later into the context of public policy and as a strategic management tool for the business community (Bradfield et al., 2005). With the use of scenarios by the Royal Dutch/Shell group (Wack, 1985), the approach was diffused to a wider group of audience and became a popular and recommended method to address uncertainty and to improve decision making (Varum and Melo, 2010). Currently, scenario analysis is associated with an extensive variety of users and disciplines, ranging from policymaking, to business planning, to local management, and to global environmental understanding (Kok et al., 2011). Because of this broad use, a wide range of scenario methodologies and classifications have emerged, as indicated by the extensive scenario planning literature (e.g., van Notten et al., 2003; Bradfield et al., 2005; Börjeson et al., 2006; Bishop et al., 2007; Wilkinson and Eidinow, 2008; Amer et al., 2013).

A common classification is related to the type of questions to which scenarios respond. Explorative (or descriptive) scenarios answer what can happen and explore plausible futures, whereas normative scenarios show how a specific goal can be accomplished and identify the conditions that must be fulfilled to achieve the goal. Moreover, some authors consider the existence of forecasting scenarios (Berkhout et al., 2002; Börjeson et al., 2006), which answer what will happen, and assume that the past trends will continue for the future. Scenarios can also be classified according to the nature of their data: qualitative or quantitative (Rotmans et al., 2000; van Notten et al., 2003; Alcamo, 2008). The former represents visual symbols or narrative stories ("storylines"), creating images of the future and expressing the drivers of change without issuing numerical figures. Qualitative scenarios are generally a result of stakeholders workshops, interviews or other participatory methods and play an important role in situations with high levels of uncertainty or when the information cannot be entirely quantified, such as human values, emotions and behaviour (van Notten et al., 2003). However, qualitative scenarios are often criticized for being "unscientific" because most of their assumptions are derived from stakeholders' thoughts and are not documented, resulting in an irreproducible developmental procedure (Alcamo, 2008). Quantitative scenarios, however, describe the future with numerical figures. These values are generally obtained by complex modelling tools, requiring assumptions and simplifications that tend to highlight the research team's own expertise (Varho and Tapio, 2013). Since the models and their assumptions are often published, quantitative scenarios are more subject to scientific scrutiny. However, the exactness of their numbers can give the illusion of certainty, which contradicts the fact that models only capture a part of "reality", providing a narrow view of the future (Alcamo, 2008b).

The development of scenarios to explore alternative energy pathways and low carbon futures has been widely applied (e.g., Nakicenovic et al., 2000; Ghanadan and Koomey, 2005; Treffers et al., 2005; EC, 2011a; Söderholm et al., 2011; IEA, 2012a). One of the most well-known energy and greenhouse gas (GHG) emission scenario exercises, which combines both qualitative and quantitative approaches, is the *Special Report on Emissions Scenarios* (SRES) from the Intergovernmental Panel on Climate Change (Nakicenovic et al., 2000). The SRES was composed of four storylines, each exploring different economic, technological, environmental and social realities. These were translated into quantitative scenarios through integrated assessment models, illustrating how divergent realities may influence energy consumption and GHG emissions. The SRES attempt to bridge qualitative and quantitative scenario approaches was not entirely successful, since they kept developing in a great extend separately (Wilkinson et al., 2013), existing little evidence of the combination of narratives and modelling on energy and low carbon scenario development (Söderholm et al., 2011). Many energy scenarios result from "desk research" (van Notten et al., 2003), and thus essentially represent quantitative outputs of model runs (e.g., (Syri et al., 2008; EC, 2011a; Söderholm et al., 2011; IEA, 2012a)). Although some studies, such as the EU *Roadmap for moving to a competitive low carbon economy* (EC, 2011b) and the *Energy Roadmap* (EC, 2011a), had a consultation process, these studies do not clearly show how this procedure influenced the final outcomes, nor describe the storyline behind each scenario.

Qualitative scenarios from a participatory process embody the views of different stakeholders/experts and generally focus on describing social, political and cultural developments (Söderholm et al., 2011) that have influence on energy and emissions scenarios. Yet, most of the energy scenarios do not consider all these aspects. They show great technical details, but neglect the entire interaction between social, economic and technological factors. To accommodate the uncertainty that is associated with socio-economic development, some scenario exercises assume different population and/or gross domestic product (GDP) growth paths (e.g., EC, 2011a)). However, these socioeconomic figures are enclosed in a higher structure of economy and society with impact on the entire energy system, such as the economic profile (e.g., energy intensive industries versus energy extensive services), territorial organization (associated with lower or higher mobility demand), and social behaviour (e.g., higher or lower demand for energy services), which are not generally considered, causing these quantitative energy/emissions scenarios to capture only a narrow view of how the future may unfold.

To explore plausible futures for Portugal, a participatory process with national stakeholders was conducted within the research project $HybCO_2$[21]. Two distinct qualitative socio-economic scenarios were designed, in which crucial fields for national development, i.e., the evolution of the economy and its specialization profile, social capital, educational system, spatial planning, environment and energy, were identified. Thus, the two storylines have highlighted different visions for the country's economic and social development, including the evolution of the energy system with its key technologies and energy sources. For both scenarios, quantitative socio-economic indicators, i.e., population, GDP and sectoral gross value added (GVA), were also built, characterizing the alternative country development pathways. Driven by these indicators and sustained by selected assumptions of the storylines, i.e., social and environment behaviour, two quantitative energy scenarios for Portugal through 2050, were generated using the energy model TIMES_PT.

This paper has a threefold objective: (i) to present the participatory process that was used to build qualitative scenarios for Portuguese socio-economic development and the resultant future images of the energy system; (ii) to demonstrate how the qualitative socio-economic scenarios can be linked in a comprehensive framework with energy modelling to overcome social and economic aspects that are generally ignored by current energy modelling exercises; (iii) and to assess to what extend the energy profile outcomes from narrative storylines and quantitative modelling match or diverge, identifying the strength and weakness of each approach and their impact on energy planning.

The next section presents the scenario development framework, including the design of storylines, an overview of the TIMES_PT model and the link between the qualitative socioeconomic scenarios and energy modelling. The quantitative energy scenarios and their comparison with the narratives are analysed in Section 5.3, followed by a discussion of these results in Section 5.4, and by the conclusions in Section 5.5.

[21] $HybCO_2$ Project: "Hybrid approaches to assess the economic, environmental and technological impact of long term carbon reduction scenarios – the Portuguese case-study" (http://hybco2.cense.fct.unl.pt/)

## 5.2 METHODOLOGY

The two visions for the Portuguese energy system were constructed by a scenario approach framework composed of three main steps (Figure 5.1): i) the development of socio-economic storylines that were supported by workshops with stakeholders; ii) the quantification of socio-economic indicators and the translation of selected issues of the storylines into comprehensible numerical modelling assumptions; iii) the development of quantitative energy scenarios using the TIMES_PT model, considering the previous quantitative parameters. Because the evolution of the energy system was identified as a crucial field by the national socio-economic storylines, a comparative analysis between its qualitative visions and the quantitative energy scenarios was performed to assess the differences/similarities between the stakeholders' perspectives and the modelling results.

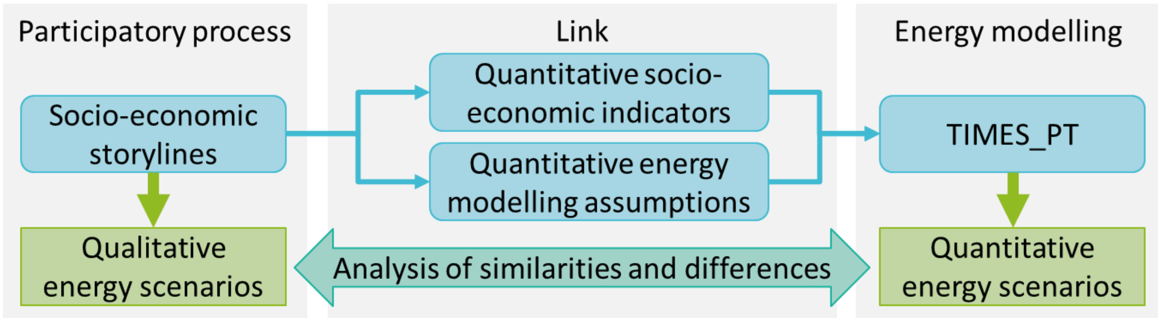


**Figure 5.1** | Scenario approach framework: Link between socio-economic storylines and energy modelling.

### 5.2.1 PARTICIPATORY PROCESS TO DESIGN SOCIO-ECONOMIC STORYLINES

To create plausible visions for the evolution of the Portuguese economy, a scenario-building process was designed supported by the participation of more than twenty-five national stakeholders from different areas of knowledge, namely: business managers, university professors, policy makers and national experts in the fields of economics, energy, design, science, environment, foresight, spatial planning, automotive, tourism, international affairs, strategy and competitive intelligence.

The analysis of international and national literature regarding scenarios (Carvalho et al., 2011a, 2011b) initiated the process and provided the basis for the preparation of the "Global Scenarios to 2050" Workshop. Through a co-creative process with the selected national stakeholders, the following four main critical uncertainties in world development were identified: 1) the emergence of a new techno-economic paradigm (disruptive or incremental), 2) religion (coexistence or conflict), 3) globalization (total or mitigated), and 4) rule(s) settings (participatory democracy – "western ideas" or new paradigm). Considering the selected uncertainties, a set of world scenario structures was also built by the workshop's attendees. With the objective of identifying and making available to discussion the major challenges, patterns and key issues for the future of the Portuguese economy, the following further internal work occurred: i) drafting the global scenarios; ii) analysing their implications for Portugal; and iii) developing a timeline of the major events that had an impact on the Portuguese economy in the global context. These elements supported the organization of two "Scenarios for Portugal 2050" workshops, where, with the involvement of the stakeholders, the following ten national critical uncertainties were chosen and explored: 1) the specialization of the economy; 2) financial sustainability; 3) political system and state configuration; 4) institutional capacity building; 5) cultural values and the ability to generate social capital; 6) strategic leadership and pro-activity of the economic agents; 7) the evolution of the social cohesion model; 8) the typology and role of the cities; 9) generational uncertainty, i.e., how the next generation will interact with the older generation; and 10) the evolution of the education and training systems. Considering these national critical uncertainties, possible structures of the Portuguese scenarios were built by the stakeholders. Finally, two scenarios with differentiated socio-economic paths were drafted by the scenario building team, under the designation "Welcome" and "We cannot fail". In spite of the financial crisis context, it was intentionally planned that none of the scenarios would be catastrophic, with both showing some capacity for managing one of the most serious crises that Portugal faced in both the short- and long-term.

To emphasize the main aspects of the narratives of each scenario, the following six crucial areas were analysed to confront the challenges of sustainable growth, where intangible capital, i.e., skills, institutions, governance, was decisive for exploiting network benefits and for progressing in spatial planning and in environmental sustainability: i) evolution of the Portuguese economy specialization profile; ii) strategic leadership, institutional capacity building and social capital; iii) scientific potential and educational and training systems; iv) spatial planning and the role of the cities; v) digital and physical connectivity; and vi) energy and the environment. A brief characterization of the two scenarios is presented below (Box 5.1). A more comprehensive description of the scenarios and their building methodology, including the workshops participative process, attendees, and outputs (e.g., uncertainties and scenario structures that were selected), can be found in (Alvarenga et al., 2011).

**Box 5.1 – Scenario Storylines**

**Scenario "Welcome"**

The "Welcome" scenario develops in an unstable world, with Europe facing cyclic crises and Portugal seeking to benefit from the intensification of the flows of international services and to gain efficiency in collective strategies. Portugal is able to implement important changes to improve the functioning and positioning of its economy, i.e., the containment of its external deficit and the ability to plan and organize its territory. However, the country is not able to make significant structural changes, maintaining its inability to attract foreign investment capable of leveraging change in the production profile. The exception is the promotion of the health cluster in niche markets that are driven by tourism to accommodate the elderly population of developed countries, who are more demanding of health care. The economic course of action is characterized by proximity and by quick return investment in activities and sectors where Portugal has comparative advantages with poorly skilled, yet specialized, labour.

**Scenario "We cannot fail"**

This scenario, hereafter called Cannot_Fail, develops in a world in expansion, based on knowledge-intensive activities and cooperating in response to global challenges, such as climate change. Portugal invests in major structural changes and manages to participate in the new technological and innovation waves that supply a globally integrated and highly dynamic economy. Macroeconomic and microeconomic policies simultaneously stimulate innovation, creativity and technological improvement, advancing the economy in the value chain. Portugal has the ability to use its "endogenous" resources and skills to attract strategic foreign investment. In this scenario, a reindustrialization of the Portuguese economy arises with the development of new activities, i.e., in the high-tech domain (bio, cogno, nano…) and in intensive knowledge services.

### 5.2.2 ENERGY MODELLING

Energy models are commonly used to generate quantitative energy scenarios that capture the full complexity of the energy system. They model the interactions between energy and the environment, defining, for example, alternative configurations of the energy system to reduce GHG emissions or to assist in planning alternative energy configurations to increase the security of the energy supply.

TIMES (The Integrated MARKAL–EFOM System) is a dynamic linear optimization bottom-up model generator that was developed by ETSAP[22] of the International Energy Agency (IEA). The ultimate objective of the TIMES model is the satisfaction of the energy services demand at the minimum total system cost (i.e., net surplus maximization), subject to technological, physical and policy

[22] Energy Technology Systems Analysis Programme (www.etsap.org/)

constraints. The model computes the energy demand/supply equilibrium by making simultaneous decisions regarding equipment investment, primary energy supply and energy trade. More technical information about TIMES is available at (Loulou et al., 2005). The TIMES bottom-up approach has been largely applied to analyse and to develop energy and greenhouse (GHG) mitigation scenarios at global (Remme and Blesl, 2008; Syri et al., 2008; Labriet et al., 2012), regional (Blesl et al., 2012; Mccollum et al., 2012) and national levels (Assoumou and Maı, 2011; Chiodi et al., 2013).

TIMES_PT maps the entire chain of the Portuguese energy system, from the energy supply (fuel mining, production, imports and exports), to energy transformation (including power and heat production) and distribution, to end-use demand in industry, residential, services, agriculture and transport and its respective sub-sectors.

As depicted in Figure 5.2, TIMES_PT embraces the following four key inputs: i) the demand for energy services (representing the services that energy carriers satisfy, i.e., the needs for heating, cooking, and lighting, among others); ii) technology data (including technical and cost information), iii) resources data (potential and prices) and iv) policy scenarios (e.g., energy or environmental policies, or specific policy instruments). The main model outputs include energy flows, installed capacity and activity of each technology, resultant GHG emissions, final energy prices and energy system costs.

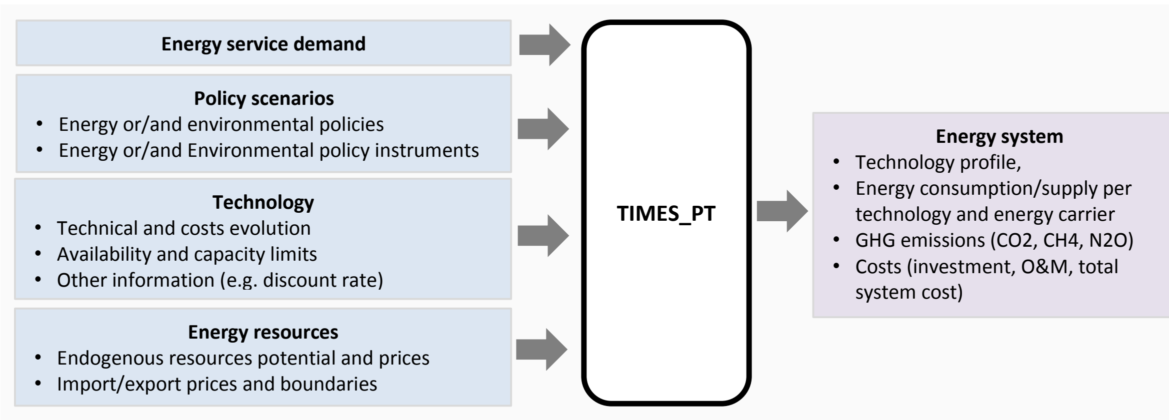


**Figure 5.2** | TIMES_PT inputs and outputs flow.

A detailed description of TIMES_PT key inputs is presented below, as along with some of the data that were generally used and considered in the present research:

i. End-use energy services, materials and mobility demand projections are the driving forces of the entire energy system that is modelled in TIMES_PT. The model includes more than 60 demand categories, divided among 5 main end-use sectors. The demand is quantified exogenously through the evolution of specific socio-economic indicators (e.g., population, sector gross value added, private consumption), demand elasticities and autonomous energy efficiency improvement in industry, as presented in equation 5.1 (adapted from (Chiodi et al., 2013)). TIMES_PT demand categories and their associated socio-economic indicators are provided in the Appendix 5.6, Table 5.A.

$$DEM_{i,t} = DEM_{i,t-1} \cdot \left(1 + DRGR_{i,t} \times \mathrm{ELAS}_{i,t}\right)^{period\ lenght} \cdot (1 - \mathrm{AEEI}_i) \qquad (5.1)$$

Where:

$DEM_{i,t}$ is the energy, materials or mobility demand for each category (i) in each period (t). For the base year (2005), the energy demand was developed considering the historic national data;

$DRGR_{i,t}$ is the annual growth rate of the socio-economic indicator that is associated with the demand category (see Table 5.A);

$ELAS_{i,t}$ is the demand elasticity for each demand category (i) in each period (t);

$AEEI_i$ is the autonomous efficiency improvement factor in industrial sectors.

For residential heating, cooling and hot water, in addition to private consumption per household, energy service demands are projected considering the characteristics of the dwellings (rural, urban and multi-apartment), their age (existent and new, considering the impacts of new building code regulations) and their respective stock, which are calculated from the population, family dimension, demolishing rate evolution and base year stock distribution (see (Simões et al., 2008; Gouveia et al., 2012) for more detailed information regarding residential heating, cooling and hot water energy service demands).

ii. The TIMES_PT technological database has more than two thousand mature and emergent energy-related technologies from both supply and demand. This database has been validated and updated over time by literature reviews (e.g., E-TechDS – Energy Technology Data Source (ETSAP (Energy Technology Systems Analysis Program), 2010), EU SET-Plan (Tzimas et al., 2011), IEA technology roadmaps (e.g., (IEA, 2009, 2010a, 2010b)), and national/international experts' opinions within several European (NEEDS[23], RES2020[24] and COMET[25] projects) and national initiatives (Seixas, et al., 2008, 2010, 2012). The database contains technical (e.g., efficiency, lifetime, availability, emission factors) and economic data (e.g., investment, operation and maintenance costs and discount rates) and their respective evolution over time. In the present research, TIMES_PT considered differentiated discount rates across sectors to accommodate market risk (12% for industry and services technologies, 9% for the power sector, 17.5% for private individuals, including dwellings and private vehicles, and 8% for public transport (EC,

[23] NEEDS - New Energy Externalities Developments for Sustainability (www.needs-project.org).

[24] RES2020 – Monitoring and Evaluating the RES Directives implementation in EU-27 and policy recommendations.

[25] COMET – $CO_2$ transport and storage (http://comet.lneg.pt/).

2011a). Some technology constraints were also set to consider specific aspects of the energy system, such as a minimum share of 15% of fossil fuel and hydroelectricity at the base load, to minimize intermittent renewable power and to guarantee the security of the supply (communication of the National Transmission Network Company in (Seixas et al., 2012)) and the average annual hydrological conditions (with seasonal variations) for all periods from 2010 onwards.

iii. The energy resource information in TIMES_PT is composed of all the physical and economic information regarding energy resources that are available to satisfy demand, including those resources from imports/exports and from domestic production (renewables and fossil mining). As a single country model, energy trade cannot be modelled endogenously, and some exogenous assumptions are adopted, in particular, fossil fuel import prices and electricity trade bounds to reflect the Iberian electricity market. Portugal's renewable energy potentials are estimated from national studies and are validated by national experts, which constitute a boundary for the endogenous primary energy supply (see (Seixas et al., 2012) for more information regarding the Portuguese endogenous energy potential that was considered).

iv. A wide range of climate mitigation and energy policies and policy instruments can be modelled in TIMES_PT, such as decarbonisation and renewable targets, $CO_2$ and energy taxes, and subsidies to specific technologies, among others. In the present research, the Portuguese policies that were considered for the medium term (until 2020) were based on the current legislation derived from the EU climate-energy package, as follows: GHG emissions reduction, an increase in renewable energy consumption and an improvement of energy efficiency. According to the EU Effort Sharing Decision, Portugal can increase by 1% in 2020 (from 2005 values), its GHG emissions not included in the EU Emissions Trading System (EU-ETS) (EC, 2009a). For the EU-ETS emissions, the objective is to reduce the entire EU emissions by 21% with reference to the 2005 values (EC, 2009c), which are allocated to national emitter units based on benchmarks. In the absence of national information, a -21% cap for EU-ETS emissions by 2020 was assumed. The Renewable Energy Directive (EC, 2009b) determines a national target of 31% of renewable energy sources (RES) consumption on final energy demand and at least 10% of RES in final energy consumption in transport in 2020. Although the EU Directive on energy efficiency (EC, 2012a) sets national binding targets of 20% for primary energy savings in 2020, Portugal has defined a reduction of 26% according to the National Energy Efficiency Action Plan (NEEAP) (RCM 20/2013) (i.e., a maximum of 925.3 PJ of primary energy consumption). Although the current exercise did not include the measures that were presented in the NEEAP, the primary energy consumption in 2020 was considered an upper bound, ensuring compliance with the national goal. No other policies, i.e., market deployment initiatives, such as the feed-in tariffs that are currently paid, were assumed in the present research, allowing the model to define the most cost-effective technology mix per scenario.

### 5.2.3 LINKING SOCIO-ECONOMIC STORYLINES TO ENERGY MODELLING

Developing energy scenarios with a bottom-up model as TIMES_PT, requires an extensive set of quantitative inputs, which are not specified in storylines, although these inputs are qualitatively or implicitly considered. The current section elaborates on the link between the storylines and energy modelling by presenting the quantification of the socio-economic indicators and by outlining how the storylines were translated into additional modelling assumptions.

#### QUANTIFYING SOCIO-ECONOMIC EVOLUTION

For each storyline, a set of socio-economic indicators was quantified (Table 5.1) and used as input values for energy service estimates, showing the scale of difference between the scenarios. The quantification was performed based on existent national studies and forecasts and was supported by experts' best guess judgment according to the narratives that have been drawn.

**Table 5.1** | Socio-economic annual growth rate (%) per scenario [Source: (INE, 2009a; Alvarenga et al., 2011), short term indicators updated according to the most recent forecasts (OECD, 2012)]

| | Welcome | | | | Cannot_Fail | | |
|---|---|---|---|---|---|---|---|
| | **'05-'10** | **'10-'15** | **'15-'20** | **'20-'50** | **'10-'15** | **'15-'20** | **'20-'50** |
| GDP | 0.51 | -0.91 | 0.18 | 1.52 | -0.7 | 1.2 | 2.9 |
| Population | 0.17 | -0.08 | -0.14 | -0.34 | -0.1 | 0.1 | 0.0 |
| Priv. Consumpt. | 1.30 | -2.74 | 0.09 | 1.41 | -2.7 | 0.7 | 2.7 |
| GVA Agriculture | 0.3 | -0.6 | 0.2 | 1.5 | -1.1 | 0.8 | 2.1 |
| | | | Specialty agriculture connected to tourism | | | Focus on the technological conversion and on the progress of the value chain | |
| GVA Services | 1.2 | -0.5 | 0.3 | 1.2 | -0.5 | 1.4 | 2.9 |
| | | | Impelled dynamism by Tourism/ hospitality | | | Evolution of the business services, information and communication technologies (ICT's), and financial services | |
| GVA Transports | 2.3 | -0.3 | 0.5 | 1.6 | -1.0 | 0.8 | 2.5 |
| | | | Development associated with tourism evolution | | | Development associated with merchandises, benefiting the flow of products by sea | |
| GVA Industry | -1.5 | -1.4 | -0.5 | 1.2 | -1.4 | 0.5 | 2.7 |
| Chemical | 0.4 | 0.0 | 0.8 | 2.0 | -0.8 | 1.1 | 3.0 |
| | | | Dynamism of the pharmaceutical industry, impelled by health tourism | | | Innovation resulting from intelligent plastic materials is a push to the sectorial GVA | |
| Iron & Steal | 5.8 | -0.3 | 0.5 | 1.0 | -0.8 | 1.1 | 3.0 |
| | | | Maintenance of its economic weight | | | Growing impelled by the equipment and apparatus and transport equipment sectors | |

| | Welcome | | | | Cannot_Fail | | |
|---|---|---|---|---|---|---|---|
| | **'05-'10** | **'10-'15** | **'15-'20** | **'20-'50** | **'10-'15** | **'15-'20** | **'20-'50** |
| Energy Intensive Industries | -0.8 | -0.3 | 0.6 | 1.5 | -1.4 | 0.5 | 1.8 |
| | | Dynamism associated with construction materials with the revitalization of the cities | | | Associated with the development of more intelligent building materials after 2020 | | |
| Other industry (incl. construction and mining) | -1.9 | -1.7 | -0.8 | 1.1 | -1.4 | 0.5 | 2.7 |
| | | Lose of competitive capacity in traditional manufacturing industries | | | Dynamism associated with equipment for renewable energy and with the reconfiguration of the automobile and auto related industries after 2020 | | |

The economic growth (represented by GDP) has a differentiated trend between the two scenarios after 2014 (until 2014, the OECD forecasts 2012) were considered), assuming a more favourable evolution for the Cannot_Fail scenario. Until 2028 a private consumption annual growth rate that was lower than that for the GDP was assumed in both scenarios (although with a progressively reduced gap) because of the current political measures (associated with the Memorandum of economic and financial policies between Portugal and the International Monetary Fund (IMF, 2011)), that aim to reduce the public deficit and restricts the growth of families' disposable income. After this period, the GDP and private consumption indicators followed an equal evolution rate. Regarding GVA, the differentiation of the growth rates between the various sectors translated the characteristics of the storylines (which were explicitly mentioned – see Table 5.1] and included the current investments (more details in (Alvarenga et al., 2011)). For both scenarios, and in line with the current trends, the decrease in the population in the short-term was projected, which then followed a natural evolution rate according to the most representative National Statistic Office predictions (INE, 2009a). This projection resulted in a slight population increase for the Cannot_Fail scenario and a continuous population decrease for the Welcome scenario (Table 5.1).

#### ENERGY SCENARIO MODELLING ASSUMPTIONS

A set of parameter values, intelligible in the context of each storyline, was defined by interpreting selected aspects of the narratives. The qualitative statements regarding energy system outcomes, including the representativeness of particular technologies and energy sources, the increase of energy efficiency or the decrease of energy dependence, were not considered, allowing the model to be "free" to define the most cost-effective technologies and energy carriers per scenario. Table 5.2 illustrates how the two storylines were linked to energy modelling input assumptions. The data that were gathered in this process were derived from national and international studies based on the modelling team's knowledge.

**Table 5.2** | Overview of the linkages between selected issues from socio-economic storylines and energy modelling inputs

| **Welcome scenario** | |
|---|---|
| **Socio-economic storyline** | |
| **Key areas** | Global framing: "There is strong competition between powers in an atmosphere of international instability and risk, (…) latent and open regional conflicts and difficulties in terms of global regulation, for instance in the environmental and financial domains, bearing in mind the existence of quite different economic and political models".<br>Portuguese economy profile: "No significant change in the pattern of activities or in the structural deficit in economic growth. Dual model (coexistence of industries/undifferentiated product sectors with low margins and high value-added products and competitive intensity). Clear concentration on the Tourism/hospitality sector and community care sector".<br>Digital and physical connectivity:<br>- "Postponement of important works regarding connectivity with international networks, such as the new Lisbon airport, while the TGV project was replaced by a set of high performance railway lines".<br>- "For the transport network and internal mobility, the development of ICT (…) allowed a relative reduction in the pressure on urban mobility, but this did not include a break with traditional mobility".<br>Spatial planning and role of the cities: "The phenomenon of extensive urbanization is in this scenario replaced in a progressive way by a paradigm focused on urban rehabilitation and planning".<br>Energy and Environment:<br>- "Change of the population's habits and behaviours, both by the progressive (but slow) use of less polluting domestic equipment and by a more intensive use of collective transport".<br>- "The investment in natural gas exploration in the Algarve basin had some visible results after 2020, contributing to a decrease in energy dependence".<br>- "The expansion of the national electricity production system suffered major delays at the beginning of the period due (..) to the economic slowdown that limited the demand for electricity and, (…) the lack of ability in solving the remaining problems in terms of trans-European electric grids between the Iberian Peninsula and the rest of Europe, limiting the possibility of exporting electrical energy". |
| ***Rationale*** | In a world of international instability and regional conflicts, i.e., in terms of environmental decisions, no international climate mitigation commitment is defined. EU meets its 20-20-20 policy package goals in 2020 and continues its policy, although no additional targets are undertaken after 2020, other than the annual reduction of the ETS cap, which continues to decline until achieving a 50% reduction in 2050 (EC, 2011b). Without a global climate mitigation commitment the fossil fuel world demand continues to increase sharply, leading to a significant growth in its prices. Technology will continue to improve, reducing its costs from increased learning and deployment (IEA,2012a). However, no additional $CO_2$ price will render low carbon technologies more attractive. This scenario is consistent with the 6D scenario of the Energy Technology Perspectives 2012 (ETP2012) (IEA, 2012a) and with the Reference scenarios of the EU low carbon and energy roadmaps (EC, 2011a, 2011b). |

| | |
|---|---|
| **Welcome scenario** | |
| **Link to modelling inputs** | |
| **Energy services demand** | - The energy services demand was estimated (Eq.5.1) according to Portuguese economy profile that was reflected in the socio-economic drivers (Table 5. 1).<br>- Continued trending decrease in household size: 2.7 persons/dwelling in 2010 to 2.3 in 2050 (DPP, 2009) (consistent with the smooth growth of private consumption).<br>- Demolishing rate of 0.05%/year (value before to the economic crises) (INE, 2009b), considering that the spatial planning vision do not have a significant impact on the gradual replacement of existing dwellings per new ones with lower heating/cooling needs.<br>- Mobility evolution: although personal mobility (measured as the average annual distance travelled by passenger) was not reduced, a mode shift from private to public transport was assumed ("more intensive use of collective transport"). Public transport representatives increased from 16% in 2010 to 19% in 2030 (close to Spain and Italy indicator) and 24% in 2050 (Austria data) (EC,2012). |
| **Policy constraints**[1] | No international climate mitigation commitment:<br>- Portugal extends the current national targets for non-ETS emissions (+1% compared with 1990) and renewables (minimum of a 31% share in the final energy consumption and at least 10% in transport) through 2050.<br>- Portugal follows the EU trajectory for ETS emissions (EC, 2011b), reducing by 50% in 2050/compared with 1990.<br>- No additional climate mitigation policies were assumed. |
| **Technology** | - Mature energy technologies: no changes in the TIMES_PT technology database.<br>- Less mature and experimental energy technologies (wind offshore, wave, solar photovoltaic and concentrated solar power (CSP), CCS, electric, hybrid plug-in and fuel cell hydrogen vehicles): a decrease in their costs according to their learning rates[2] and world installed capacity evolution in the 6D scenario (IEA, 2012a) (Figure 5.3 left shows the investment cost of selected technologies). |
| **Resources** | - Fossil fuel imports prices from the 6D Scenario (IEA, 2012a): 149$\$_{2010}$/barrel for oil, 14$\$_{2010}$/Mbtu for natural gas and 126$\$_{2010}$/t for coal in 2050.<br>- Biomass and biofuels import prices were indexed to the world consumption of the 6D scenario (IEA, 2012a), which resulted in an average annual growth of approximately 2.0% for biofuels and 1.4%for biomass.<br>- After 2020, an endogenous Portuguese natural gas resource was considered with a cumulative potential of 2 012.2 PJ (Costa e Silva, 2010).<br>- Power trade was not modelled, considering the Portuguese energy system as a stand-alone system after 2015 due to the electric grid limitation between the Iberia Peninsula and the rest of Europe ("limiting the possibility of exporting electrical energy"). |
| **Cannot_Fail scenario** | |
| Socio-economic storyline | |
| **Key areas** | Global framing: "Context strongly marked by four big global forces in a powerful interaction: geo-economics, technology, demography and environment/sustainability. Sustainability and the environment were, through the use of different mechanisms, progressively incorporated in the economic processes for defining costs/prices".<br>Portuguese economy profile: "Portugal managed to significantly improve its economic performance. In fact, not only the rates of growth in output showed important increases but also the diversification to sectors and clusters more intensive in knowledge, I&DT, innovation and creativity".<br>Digital and physical connectivity: "Technological development was essential for internal mobility (…) communications and the development of the "virtual reality" (for instance, of tele-presence) contributed to reducing the urban mobility".<br>Spatial planning and role of the cities:<br>- "The development of the railway was (…) associated with the significant growth in the transport of merchandise abroad, in a close connection with Portuguese ports and Spanish logistic platforms".<br>- "The extensive urbanization phenomenon was, in this scenario, replaced in a progressive way by a paradigm essentially focused on compacting and, in the new construction, on building more adequate to the increasing needs for energy efficiency".<br>Energy and Environment: "Stalemate of the beginning of the period was overcome, regarding the European electric networks and the connection from the Iberian Peninsula to the rest of Europe". |

| **Cannot_Fail scenario** | |
|---|---|
| ***Rationale*** | Global action is undertaken to reduce GHG emissions and to maintain global warming below 2 °C and thus, the EU endorses the objective of reducing Europe's GHG emissions by least 80% in 2050. The world's consumption of fossil fuels does not continues its sharply growth, resulting in a smoother price increase. A more rapidly deployment of renewables and other low carbon technologies (e.g., CCS or electric mobility) is translated into a faster reduction in its costs. This scenario is broadly consistent with the 2D scenario of ETP2012 (IEA, 2012a) and with the decarbonisation scenarios of the EU Roadmaps (EC, 2011a, 2011b). |
| **Link to modelling inputs** | |
| **Energy services demand** | - Energy services demand was estimated (Eq.5.1) according to the Portuguese economy profile that was reflected in the socio-economic drivers (Table 5.1).<br>- Reduction of household size from 2.7 in 2010, to 2.1 in 2050 (Eurostat, 2010), which is consistent with what is seen in the northern EU countries (greater private income leads to early residential independence for young people and consequently the reduction in household size).<br>- Increase in the demolishing/retrofitting rate to 0.08%/year (Åström et al., 2011) after 2020 to represent a faster replacement of existing dwellings per new ones "more adequate to the increasing needs for energy efficiency" i.e. with lower heating and cooling needs.<br>- Mobility evolution: reduction of "urban mobility"(private car short distance, BUS and metro), after 2020, i.e. decrease in the average urban annual distance that is travelled by passengers in -0.3%/year (the average national reduction verified between 2005 and 2010, which was associated with various factors, including the increase in the unemployment rate and, consequently, a reduction in the work/home trips (EC, 2012b)). |
| **Policy constraints[1]** | Global climate mitigation commitment:<br>- National GHG emissions cap trajectory consistent with the EU emissions reduction. i.e., The annual GHG emissions reduction in the decarbonisation scenarios of the EU Roadmaps (EC, 2011a, 2011b) ( in-5.1%/year between 2020 and 2050) was assumed. This assumption was translated into a GHG emission cap of approximately -70% in 2050 compared with the 1990 values.<br>- No additional renewable or efficiency targets. |
| **Technology** | - Mature energy technologies: no changes in the TIMES_PT technology database.<br>- Less mature and experimental energy technologies: a decrease in their costs according to their learning rates[2] and world installed capacity evolution in the 2D scenario (IEA (Figure 5.3 right, shows the investment cost of selected technologies). |
| **Resources** | - The fossil fuel imports from the 2D scenario (IEA, 2012a): 87$\$_{2010}$/barrel for oil, 8$\$_{2010}$/Mbtu for natural gas and 60$\$_{2010}$/t for coal in 2050.<br>- Biomass and biofuels import prices were indexed to world consumption in the 2D scenario (IEA, 2012a), which resulted in an average annual growth of approximately 3.6% for biofuels and 2.7% for biomass<br>- No natural gas potential was set (due to the large investment in RES, no significant effort to explore fossil resources was considered).<br>- Power trade was modelled considering the increase in the electricity interconnection between the Iberian Peninsula and the rest of Europe. Electricity import price: 136.4€$_{2008}$/MWhe in 2030, 123.2€$_{2008}$/MWhe in 2050 (power price of the decarbonisation scenario "Diversified supply technologies" from (EC, 2011a). Export price: model outcome. A conservative bound trade was also defined: imports could not be higher that 10% of the power that was produced (equivalent to 2010, wet hydrologic year) and exports could not be bigger than 13% of the gross electricity that was generated by the main producers (average percentage of the current main electricity exporters in EU: France and German) (Eurostat, 2012). |

[1]These policy constraints were only assumed after 2020, until this date the policy assumptions that are described in point (4) of section 5.2.2. were applied for both scenarios.

[2]The learning rate corresponds to the percentage capital cost reduction with each doubling of the installed capacity (IEA, 2012a).

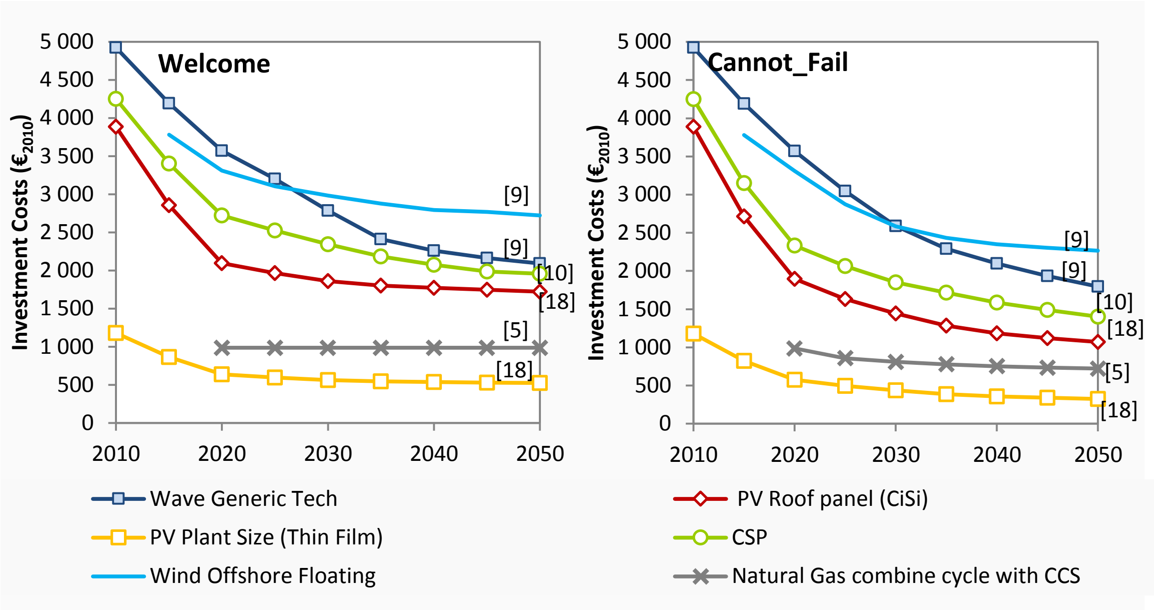


**Figure 5.3** | Investment costs (€2010/kw) and respective learning rate of some power sector technologies that are considered in each scenario. (Learning rates from ETP2012 (IEA, 2012a) in square brackets)

## 5.3 RESULTS

This section presents the quantitative energy scenarios for Portugal through 2050 that were generated by TIMES_PT and outlines the differences and similarities between the model outcomes and the energy configurations from the qualitative scenarios[26]. The analysis is composed of fundamental areas for the Portuguese energy system, i.e., the energy supply and security, power sector, final energy consumption, with a focus on the transport sector, and efficiency. The role of renewable energy and the impact of the energy system on GHG emissions are also evaluated. Notably, not all the qualitative visions are presented in the following section, only the visions that can be compared with the TIMES_PT results and with major relevance for the national energy system.

### 5.3.1 ENERGY SUPPLY AND IMPORT DEPENDENCY

Since 2005, the Portuguese total primary energy supply (TPES) has been decreasing at approximately -3% per year because of energy efficiency improvements in end-use and power sectors, as well as lower losses in electricity transmission and distribution and the reduction in private purchasing power in recent years. In both the Welcome and Cannot_Fail scenarios, the decline of TPES continues through 2020 (Figure 5.4), generally reflecting the decrease in the country's GDP and, consequently, in the energy demand. After this period, TPES increases over time

[26]All the storylines statements in section 5.3 are expressed in quotation marks.

in the Cannot_Fail scenario, reaching +13% in 2050 compared with 2010, whereas in the Welcome scenario, lower economic growth leads to a stabilization of the TPES, resulting in the 2050 values 13% below the current ones.

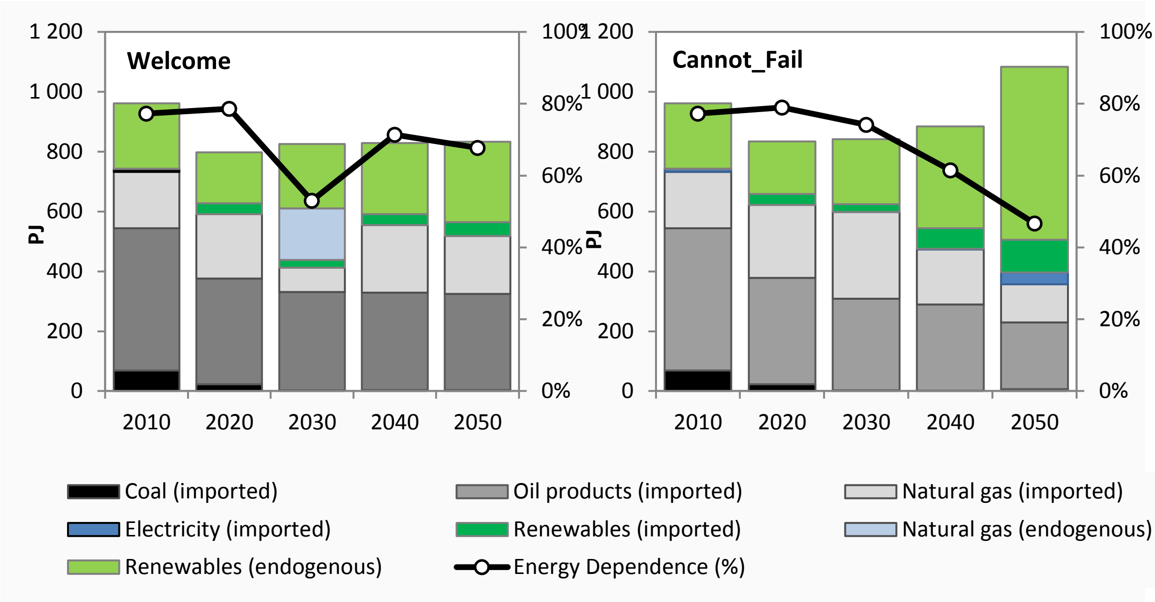


**Figure 5.4** | Primary energy supply (PJ) per energy source and energy dependence (%)

The dependency of Portugal on energy imports has always been high due to fossil fuels and to the limited exploitation of endogenous resources. The high share of fossil fuel in the overall primary energy consumption in 2010 (76%) explains an energy dependence of 75% (Figure 5.4). In that year, 31% of the fossil dependency was for power and heat production (mostly coal and natural gas), and 37% was associated with oil demand for transports.

In recent decades, the RES share in TPES has been growing, from approximately 17% in the 90's to nearly 23% at present. In the Cannot_Fail scenario, where global action is undertaken to reduce GHG emissions, Portugal shifts to RES primary energy supply, which is mostly endogenous, reaching nearly 63% in 2050, whereas fossil fuels decline to a minimum of 33%. This shift, associated with technology changes in power and end-use sectors, as explained in the following sections, causes the country's energy dependence to decrease to 47% in 2050 (almost half of the current values). As mentioned in the Cannot_Fail storyline "the national energy bill was drastically reduced", although the idea that "Portugal tends to be self-sufficient in energy terms", can be optimistic considering the expected energy prices, technology developments and, in particular, the estimated endogenous energy potential. In fact, the optimized energy scenarios show biomass imports (16% of the total RES consumption), indicating that the endogenous potential is not enough or is not cost-effective. The Cannot_Fail storyline also mentions the "transformation of Portugal into an exporter of green energy". However, this green exporter feature is not associated with power energy because the quantitative results show that Portugal is an electricity importer in 2050, which is currently the case.

In the Welcome scenario, in which no significant additional measures are undertaken to reduce GHG emissions, the RES primary energy supply continues its smooth increase,  as already has been observed in recent years. In 2050, the share of fossil energy does not decrease below 62%, in line with the statement “Portugal is still strongly dependent on fossil fuels” from the storyline. Oil remains the most used fuel in all periods and reaches a share of 39% in 2050. The discovery of natural gas in the Algarve basin has visible results after 2020, contributing to the reduction in energy dependence to 53% in 2030. Nevertheless, this endogenous potential of natural gas in Algarve only satisfies the national needs for approximately 15 years (2025 to 2035), and in 2040, the country energy dependence presents values above 70%.

### 5.3.2 POWER SECTOR

Over the last decade (2001-2011), Portuguese electricity production has grown at an average of approximately 1.2% per year. This growth has been accompanied by a rise in renewable electricity (RES-E), reaching 45% of the total power supply in 2011, an average hydrological year. Hydropower plays a crucial role in the Portuguese renewable electricity mix (49% of the RES-E in 2011), although wind onshore has also gained relevance in the last decade (37% of the RES-E in 2011), attenuating the relation between RES-E production and inter-annual hydrological conditions. In both scenarios (Figure 5.5), the existent coal power plants are decommissioned at approximately 2020, and no additional coal capacity is installed, resulting in fossil electricity production that is only sustained by natural gas. In 2020, imported fossil fuels are responsible for 50% and 45% of the electricity generation in the Welcome and Cannot_Fail scenarios, respectively.

A significant differentiation in the power generation structure occurs after 2040 in the Cannot_Fail scenario due to the large penetration of new renewables, such as wave and wind offshore (floating). As mentioned in the Cannot_Fail storyline, Portugal “acquired strong competences in the production of renewable energies, particularly in market niches, in photovoltaic energy and in wave energy”. In fact, “the wave pilot experience in S. Pedro de Moel was a lever for the promotion of an industrial cluster related to sea activities in Portugal and the acquisition of strong competences in the production of energy from the sea waves was translated into international acknowledgement of the country as one of the world ocean energy centers of excellence, namely in wave and deep off-shore wind technologies”. The energy modelling supports this expectation for the long-term because wave and wind offshore energies are responsible for 31% of the national electricity supply in 2050. Solar technologies, i.e., PV and CSP, increase their share in the power supply from 0.5% in

2011 to 13% in 2050, which is consistent with the growth that is foreseen by (IEA, 2012a) for OCDE countries. The significant increase in renewable technologies results in a RES-E share above 80% after 2035 in the Cannot_Fail scenario.

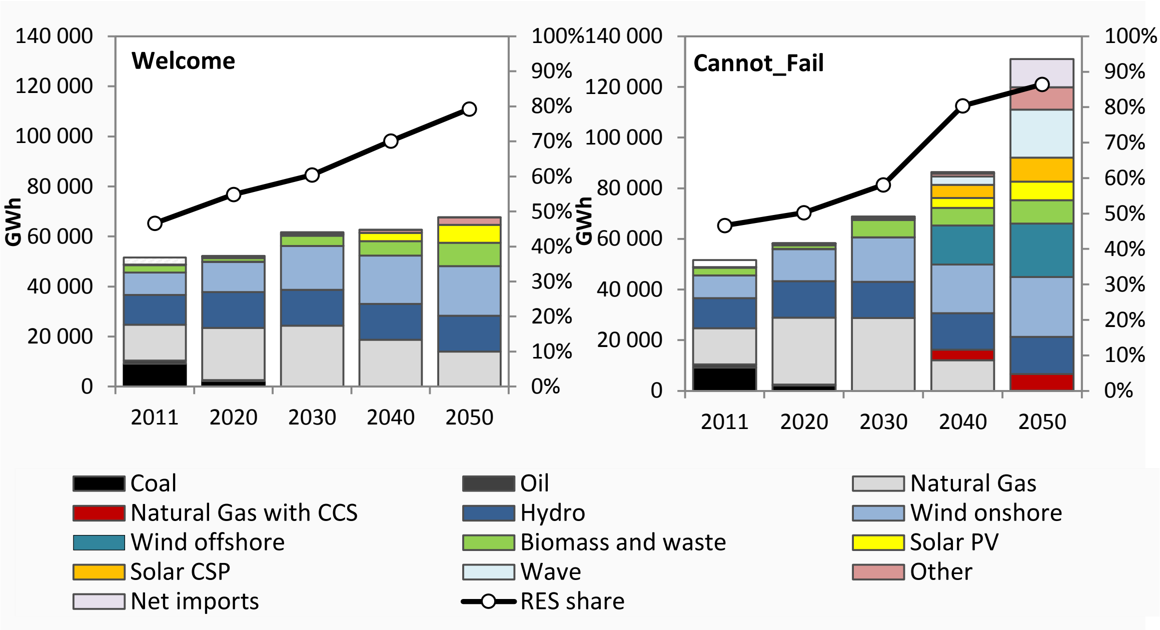


**Figure 5.5** | Electricity supply per source/technology (GWh) and renewable energy share (%)*

*(Due to the temporary character of the national 2011 energy consumption statistics and the inexistent of official values for GHG emissions, all the charts in this paper present 2010 as the most recent historic year. The only exception is the electricity generation chart, primarily because the wet character of 2010 makes it an unrepresentative year in power production composition).

"Portugal also managed to position itself in carbon capture, becoming part of international projects". By 2040, natural gas combined cycle and cogeneration with $CO_2$ capture became one of the technologies of the power production profile, responsible for approximately 5% of the total electricity supply. The cost-effectiveness of natural gas technologies with CCS is due to the severe GHG reduction that is imposed on the energy system. This situation is consistent with (Gouveia, 2012) results, where the $CO_2$ capture in the power sector is associated with gas and not with coal power plants due to the remaining $CO_2$ emissions (efficiency of capture technologies of 85%). "The evolution in the sector of energy transformation was characterized by an increase in competition between the gas and decentralized electricity suppliers, and the centralized producers. This increase in competition was based on the technological evolutions in terms of the platforms, with a rapid expansion not only of the cogeneration of electricity/heat [which almost triples the electricity production from 2011 to 2050 according to TIMES_PT results] but also of the ability for decentralized electricity production using renewable energies". Although micro-generation increases over time, its importance in total electricity generation does not go beyond 4%, reflecting a decentralized electricity importance that is not as expressive as mentioned in the storyline.

Consistent with the Welcome storyline (“the expansion of the national electricity production system suffered major delays at the beginning of the period”), the quantitative scenario shows a stagnation of the electricity supply through 2020, increasing afterwards in a smooth pattern (approximately 0.9% per year from 2020 to 2050) (Figure 5.5). Natural gas-based electricity expands from 28% in 2011 to 40% in 2030; it then declines and is replaced by renewables that provide 64% of the electricity in 2050. Increasing gas import prices is the main explanation for the shift in the power sector. “The large investment in infrastructures for wind power and photovoltaic production, in the first decade of the XXI century, (…) did not achieve a considerable reduction in dependence on external energy through renewable energy [as shown in the previous section] nor allow for a substantial and sustainable growth of an industrial cluster around these energies”. The TIMES_PT results reveal that the investments in wind offshore and in CSP are not continued and that no additional capacity beyond the pilot experiences is installed. However, a significant increase in wind onshore energy and in centralized solar PV is shown, reaching more than 7 GW of installed capacity each in 2050.

### 5.3.3 TRANSPORT MOBILITY

According to the Cannot_Fail storyline, a switch in the mobility paradigm is expected, where “the diffusion and implementation of networks for the supply of electric or hydrogen vehicles, associated with the important changes in terms of population habits and behaviours, contributed very significantly to the sustainable change in the profile of energy consumption in transports”. This expectation of the expansion of low emission vehicles, including electric and hydrogen fuel cells, is achieved by the TIMES_PT model (Figure 5.6). Diesel and gasoline are gradually replaced by biofuels, electricity and hydrogen, decreasing the proportion of oil products in transport’s final energy consumption by a minimum of 37% in 2050. Electric mobility is primarily associated with gasoline hybrid plug-in, and electric vehicles start to show some visibility in 2020, representing almost 10% of the light duty vehicle fleet. By 2050, electric mobility signifies 61% of the light duty fleet, corresponding to 23% of transport’s final energy demand. Mobility electrification leads to a reduction in energy consumption through high efficiency gains. Supporting the Cannot_Fail storyline, hydrogen vehicles, more precisely, hydrogen heavy trucks became a cost-effective technology in 2040, representing 5% and 19% of the heavy truck fleet by 2040 and 2050, respectively. These changes in the technological profile of transport sector result in a significant increase in RRES consumption, rising from the mandatory share of 10% in 2020 to approximately 60% in 2050, close to the percentage that is presented by the decarbonisation scenarios of (EC, 2011a).

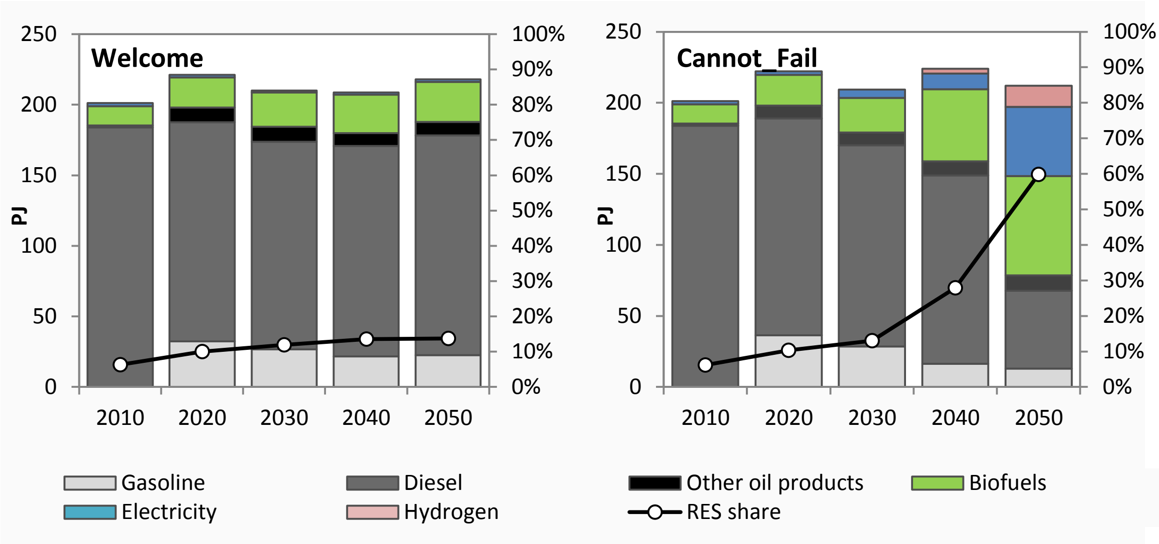


**Figure 5.6** | Energy consumption (PJ) in transport sector per energy source and the share of RES consumption (%)

In contrast, according to the Welcome storyline "was not possible to move, in a significant and fast way, to the adoption of the electric vehicle. (…) Electric vehicle did not make it, at least until 2030". The modelling results are more conservative than the respective storyline once electric mobility is negligible during the modelling period (Figure 5.6). Transports remain strongly dependent on fossil fuels, although decrease its share on energy consumption due to the RES obligation (EC, 2009b). Renewables, comprising mostly biodiesel, increase slightly over time until reaching a maximum of approximately 14% in 2050, in harmony with reference scenarios of (EC, 2011a).

### 5.3.4 FINAL ENERGY CONSUMPTION AND EFFICIENCY

The Portuguese total final energy consumption (TFEC) has decreased in recent years, registering values in 2010 that were close to those values that were observed in 2000. However, relevant changes in the fuel distribution occurred, namely an increase in natural gas and electricity shares over coal and oil products.

In both the Welcome and Cannot_Fail scenarios, a decrease in TFEC through 2020 is observed (Figure 5.7) because of energy efficiency and economic crises. After that period, the TFEC in the Cannot_Fail scenario is expected to increase steadily through the end of the projection period, reaching 15% above the 2010 values, whereas in the Welcome scenario, the rise in the TFEC is not enough to overcome the current values.

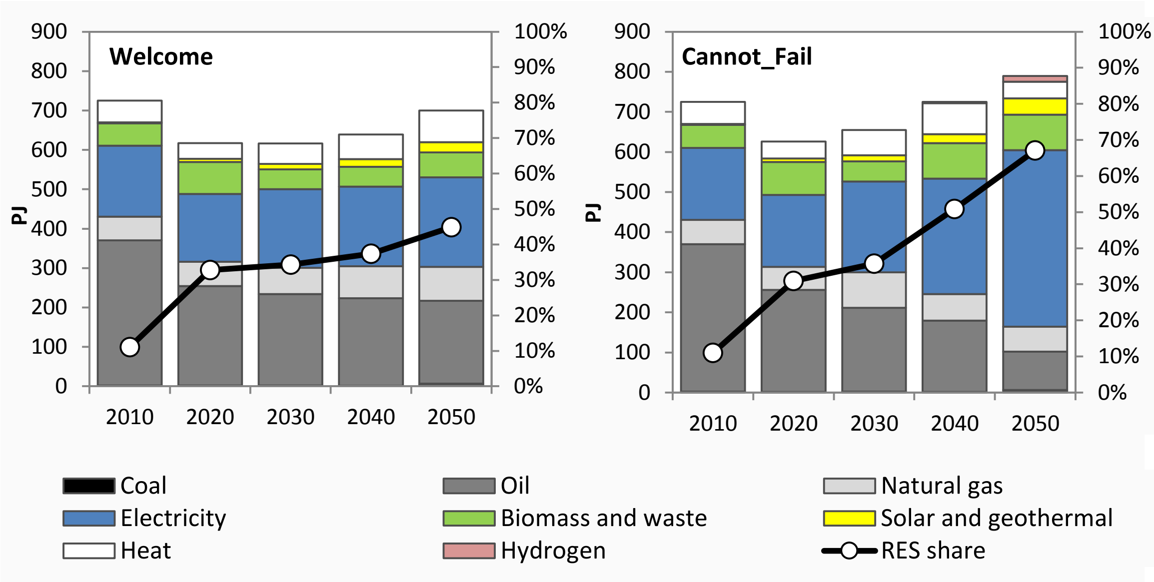


**Figure 5.7** | Final energy consumption (PJ) per energy source and the share of RES consumption (%)

In the Cannot_Fail scenario, significant changes in the composition of the TFEC per fuel type are projected, particularly due to the decline in oil products and to the significant increase in electricity consumption, which more than doubles from 2010 to 2050. Residential and service sectors are almost completely electrified due to technology shifts in most end-use services, such as cooking and space heating, where electricity had a small representation in 2010. Another important aspect in the energy composition is the appearance of energy sources that were non-existent or almost negligible in 2010, such as hydrogen for transports (explained in the previous section) and solar thermal mostly associated with water heating in buildings. In 2050, 83% of water heating needs are fulfilled by solar thermal energy, endorsing the Cannot_Fail storyline that states, "the transformations regarding architectural design of buildings and building techniques and processes to receive the technological innovations in terms of renewable energies, allowed for the diffusion on a large scale of solar thermal energy and of photovoltaic energy in buildings". "Portugal reached a leading position in micro-production through renewable energies being a common practice in 2050". Due to these changes in the final energy profile, the share of renewable energy (including renewable electricity) increases from the obligated 31% in 2020 to 67% in 2050, a growth of 36%, consistent with the increase in renewable energy of decarbonisation scenarios of (EC, 2011a).

In the Welcome scenario, it is also possible to observe an increase in solar and electricity consumption over the decrease in oil products, although the changes in the TFEC profile are not as expressive as in the Cannot_Fail scenario (e.g., electricity and oil product shares of energy consumption migrate from 25% and 51% in 2010 to 33% and 30% in 2050, respectively).

In both the Welcome and Cannot_Fail scenarios, energy efficiency is an important energy option. In Welcome scenario, energy efficiency "is the main pillar of energy policy since the investments associated with the change of the paradigm are [financially] prohibitive", whereas in the Cannot_Fail scenario, "Portugal is one of the European countries that presented better results in terms of energy solutions in the residential, service, and transport sectors". Using the final energy intensity (measured as the final energy input per unit of GDP) as a proxy indicator of the economy energy efficiency, notably, a more efficient use of energy over time occurs in both quantitative scenarios (Figure 5.8).

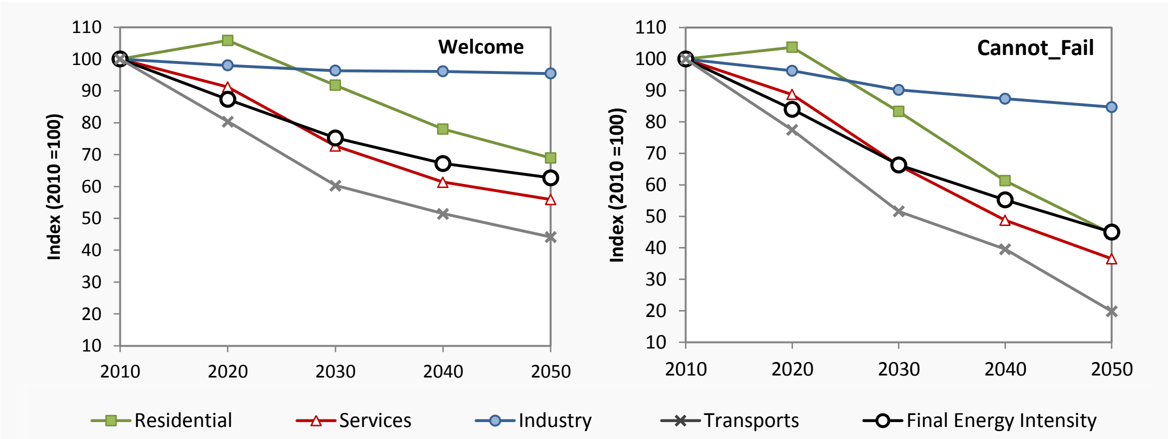


**Figure 5.8** | Final energy intensity and sector energy intensity evolution (2010 = 100)*
*The following indicators were considered: final energy intensity = final energy/GDP, residential = energy consumption/private consumption, services = energy consumption/GVA services, industry = energy consumption/GVA industry, transports = energy consumption/GDP)

In 2050, the energy intensity of the Welcome scenario is 37% below the 2010 values, whereas the energy intensity in the Cannot_Fail scenario is less 55%, representing an annual improvement of approximately 1.2% and 2.0%, respectively. All sectors in the long-term show a decline in their energy intensity values. Transports and services present above average contributions to reduce the economy energy intensity, whereas industry shows the lowest efficiency improvement gains. The comparison between energy intensities from the Cannot_Fail and the decarbonisation scenarios of (EC, 2011a) demonstrates that Portugal only presents higher reduction rates for the transport sector, indicating that the expected idea that Portugal can be one of the EU countries with better results in terms of energy efficiency is optimistic. However, this comparison is not straightforward because the inclusion of non-energy factors (e.g., structural changes in the economy or in lifestyles) in the energy intensity yields a highly limited indicator of efficiency gains.

### 5.3.5 GHG EMISSIONS

The configuration of the energy system from both scenarios results in different energy-related GHG emission trajectories, as shown in Figure 5.9. In 2020, the GHG emissions are greatly below (approximately -27%) the national cap. This difference can be explained by the following three factors: i) current economic crises have significantly decreased the energy consumption; ii) the increase in low carbon energy due to the RES target commitment, and iii) the 2020 EU-ETS and non EU-ETS caps were set from 2005, which, together with 2002 (both dry years), register the highest GHG emissions in Portugal since 1990, representing an outlier benchmark year. In fact, in the Cannot_Fail scenario, where more restrictive climate policies are implemented, the Portuguese GHG emissions are below the national cap (Table 5.2) through 2035. After this period, the national emissions follow an annual reduction that is equal to the EU level, leading to a global mitigation of approximately 70% in 2050 compared with the 1990 values. Power and heat production is the sector with higher emission reduction, whereas transport has a lower decline in its GHG emissions. In 2050, half of the industry emission reduction is a result of carbon technologies that meet the expectations of the Cannot_Fail storyline ("Portugal also managed to position itself in carbon capture, becoming part of international projects").

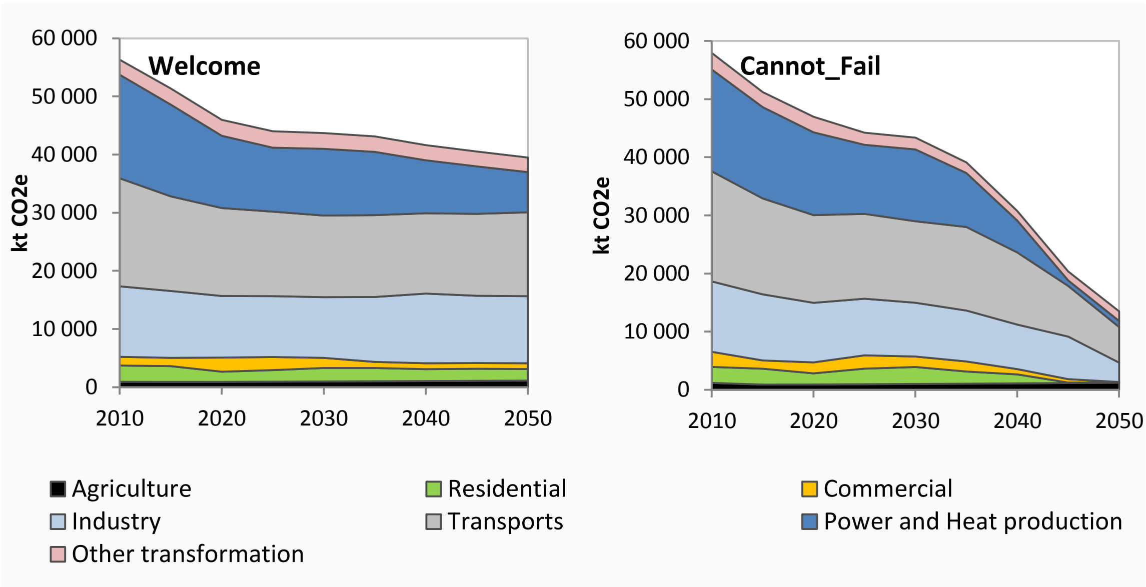


**Figure 5.9** | Greenhouse gas emissions evolution (kt $CO_2e$) per sector

In the Welcome scenario, the total GHG emissions remain almost constant after 2020, with an average annual reduction of -0.5% through 2050. This situation is translated to a global mitigation of -12% in 2050 compared with the 1990 values, with power and heat production and industry as the only activities that reduced their emissions.

## 5.4 DISCUSSION

The comparative analysis between quantitative and qualitative energy scenarios revealed that for most of the issues (Table 5.3), the two methods present the following similar visions for the Portuguese energy system: i) efficiency plays an important role, although associated with an energy system that is dependent of fossil fuels due to transport and a power sector where emergent renewable sources do not thrive for the Welcome scenario; ii) the power sector is primarily sustained by emergent renewable energy sources, with electric vehicles as a key technology in transport sector, and the prevalence of solar in buildings for the Cannot_fail scenario.

**Table 5.3** | Comparison of Portuguese energy system development from qualitative and quantitative scenarios

| | Storylines visions | Model achievements | Similar |
|---|---|---|---|
| **Welcome scenario** | "Portugal is still strongly dependent on fossil fuels". | The fossil fuels consumption in primary energy does not decrease below 62% in the period 2010-2050. | ✓ |
| | "The large investment in (…) wind power and photovoltaic (…) did not achieve a considerable reduction in dependence on external energy (…) nor allow for a substantial (…) growth of an industrial cluster around these energies". | Although wind offshore and CSP investments are not continued, wind onshore and solar PV increase significantly, achieving more than 7 GW of installed capacity each in 2050. | ✓/× |
| | "Was not possible to move, in a significant and fast way, to the adoption of the electric vehicle (…) Electric vehicle did not make it, at least until 2030". | Electric mobility is negligible for the modelling period. | ✓/× |
| | "Energy efficiency is the main pillar of energy policy". | The Portuguese energy intensity is reduced by 37% in 2050 compared with 2010 values. | ✓ |
| | "The expansion of the national electricity production system suffered major delays at the beginning of the period". | Stagnation of the electricity supply through 2020, increasing by only approximately 0.9%/year afterwards. | ✓ |
| | "Investment in natural gas exploration, contributed to a decrease in energy dependence". | Energy dependence reduced from 75% in 2010 to 53% in 2030. Nevertheless, the endogenous potential of natural gas only satisfies the national needs for approximately 15 years (2025 to 2035) and in 2040 energy dependence is above 70%. | ✓/× |
| **Cannot_Fail scenario** | "The national energy bill was drastically reduced and Portugal tends to be self-sufficient in energy terms". | Energy dependence reduced from 75% in 2010 to 47% in 2050, signifying a relevant decrease; however, the idea that Portugal can be self-sufficient is too optimistic. | ✓/× |
| | "Transformation of Portugal into an exporter of green energy". | In 2050, Portugal imports electricity and biomass, no green energy is exported. | × |
| | "Portugal positioned itself as a country of clean energies, acquiring strong competences in the production of renewable energies, namely wave, photovoltaic energy and off-shore wind energy". | In 2050, RES-E presents 86% of the total electricity supply, with wave, solar PV and offshore wind representing 36%. | ✓ |
| | "Expansion not only of the cogeneration of electricity / heat but also of the ability for decentralized electricity production using renewable energies". | Electricity from CHP almost triples from 2011 to 2050. Although micro generation increases over time, its importance in the total electricity generation does not exceed 4%; therefore, the role of decentralized electricity may not be as expressive as mentioned in the storyline. | ✓/× |
| | "Portugal also managed to position itself in carbon capture, as part of international projects". | In 2050, CCS represent 5% of the total electricity supply and half of GHG emissions in industry are reduced through capture technologies. | ✓ |

| Storylines visions | Model achievements | Similar |
|---|---|---|
| "Diffusion on a large scale of solar thermal energy and of photovoltaic energy in buildings. (…) In fact, Portugal reached a leading position in micro-production through renewable energies being a common practice in 2050". | In 2050, 83% of water heating needs (in households and services) are fulfilled by solar thermal, representing a large diffusion of this technology. However, roof panel solar PV technology does not have a significant expression. | ✓/× |
| "The diffusion and implementation of networks for the supply of electric or hydrogen vehicles (…) contributed very significantly to the sustainable change in the profile of energy consumption in transports". | By 2050, electricity and hydrogen mobility account for 61% and 19% of light duty vehicles and heavy truck fleets, respectively. In 2050, 60% of the energy consumed in the transport sector is renewable (RES-E, hydrogen from renewable sources and biofuels). | ✓ |
| "Portugal is one of the European countries that presented better results in terms of energy solutions in the residential, service, and transport sectors". | Compared with average EU roadmap results, Portugal only presents better results in terms of the sector energy intensity reduction for transports. | ✓/× |

Legend: ✓ similar; × divergent; ✓/× Although with points in common, the entire vision of the qualitative scenario and the modelling results is not completely similar

The divergent points from the two approaches are primarily associated with the role of specific technologies, where the cost-effective criteria of the modelling results do not match the expectations of national stakeholders. Some technologies that stakeholders thought would not have representation become competitive after 2040 according to the modelling results (e.g., centralize solar PV in the Welcome scenario), whereas other technologies that stakeholders thought could be promising in the future are not cost-effective (e.g., micro-production in the Cannot_Fail scenario), which may influence different energy planning decisions.

One of the reasons for this mismatch may be related to the fact that the stakeholders' reasoning emphasizes that the narratives are not able to deal with complex variables in long-term periods. Qualitative scenarios more easily accommodate interdisciplinary perspectives and the interrelations in a country's development, including the connection between the energy system and the rest of the society structure (social and economic). In fact, workshops with stakeholders from many areas facilitate the broadening of future perspectives (Börjeson et al., 2006). However, due to its heterogeneity, the global knowledge of the participant group regarding energy and energy technologies is not supported by any technical or scientific literature. This limitation resulted in visions that might not be cost-effective or even consistent with the expected technological developments and with existent resources. The idea that Portugal can be self-sufficient in energy resources, which may not be feasible through 2050 considering the known endogenous resources, is only one example. Whenever a quantitative target is considered (e.g., the RES consumption share or GHG emissions cap), qualitative scenarios are not able to assess their compliance. Moreover, the focal issue of the participatory process was the design of socio-economic scenarios for Portugal; energy only appeared as one of the areas of reasoning. Therefore, the stakeholders' creative effort was not particularly concentrated on how the Portuguese energy system might evolve.

In contrast, energy models such as TIMES_PT model are only focused on the energy system, and all the model's decisions are purely rational to optimize the system. The model's outcomes are not postponed by either an uncertain long-term policy, a resistance to change due to imperfect information, or subjective preferences (Fortes et al., 2013) such as the stakeholders' choices. Although technological models can test the viability of storylines and design a path to achieve a quantitative target, these models also present some weaknesses. Even if some technologies may appear cost-effective in the time horizon of the analysis, in the short-term, these technologies can represent a tremendous investment that is not compatible with the social and economic reality of the scenarios. Conversely, some technologies may seem more expensive but have a positive impact in other areas, i.e., on energy security or employment with a creation of business clusters, which is not captured by technological models.

Despite all these aspects, energy modelling is essential to confirm whether the qualitative visions are technically feasible and cost-effective, whereas the socio-economic storylines provide context and support many of the assumptions of the modelling exercise, as seen in Section 5.2.3. The lack of a socio-economic vision can hamper the robustness of modelling outcomes and the acceptance of decision makers to use those scenarios to support policy choices, for example. Storylines that are derived from participatory processes, such as workshops, can be better accepted due to the presence of stakeholders and/decision makers in the process (Börjeson et al., 2006). These advantages compensate for the clear handicap of this linking process, which is time-consuming and organizationally demanding.

One of the limitations of the present work refers to the absence of an iterative process between the model outcomes and the visions of workshop attendees. In fact, the national stakeholders should be confronted with the comparison between their views and the modelling results (and input assumptions), and a discussion around those results should occur. This final step is the goal of a further work because this paper aimed to evaluate to what extent both approaches presented similar outlooks and how this level of similarity could affect energy planning, illustrating the strength and weaknesses of each approach.

## 5.5 CONCLUSIONS

This paper demonstrates how qualitative socio-economic storylines and quantitative energy modelling can be linked in a comprehensive framework and emphasizes the importance of an integrated social, economic and technological context for the development of long-term energy scenarios. Moreover, this paper assesses the extent of the differences/similarities between the energy visions that were drawn from a participatory process and the quantitative energy system configuration that was generated from modelling, identifying the strengths and weakness of each approach.

The evolution of the Portuguese economy and its society is subject to a high degree of uncertainty, particularly today when the country is facing the greatest economic crisis since the early 1980s. From these crossroads of the Portugal socio-economic pathway, two contrasting qualitative long-term scenarios were designed through a participatory process with different stakeholders in a co-creative framework. A detailed analysis of the two qualitative scenarios was performed to gain insights into the governing of the quantification of energy system aspects, i.e., on resource availability, energy demand, policy constraints and technology. These aspects were assumed by the optimization technological model TIMES_PT to generate two quantitative energy scenarios through 2050.

Generally, the energy pathways behind the modelling results were consistent with the visions that were designed by the stakeholders and that were contained in the storylines. In the scenario that considered a world GHG emissions mitigation objective (Cannot_Fail), the vision that "Portugal positioned itself as a country of clean energies" was translated by the model through a high share of RES-E (86% of the electricity supply in 2050). In contrast, under a no global environment consensus (Welcome), the vision of the country continuing "strongly dependent on fossil fuels", was quantified by TIMES_PT by more than 62% of fossil fuels in the total primary energy consumption through 2050. However, some divergences were also identified, primarily associated with the importance of specific technologies. For instance, according to the Cannot_Fail storyline, "Portugal reached a leading position in micro-production through renewable", whereas the modelling results showed that micro-production represented less than 4% of power production. The Welcome storyline mentioned, "electric vehicle did not make it, at least until 2030"; however, model outcomes were less optimistic once electric mobility was negligible throughout the modelling period.

Qualitative scenarios from participatory processes embrace multiple perspectives and more easily accommodate the relation between the energy system and the social and economic path. However, these visions might not be cost-effective or even technical feasible, and whenever a quantitative target is being considered, qualitative scenarios are not suitable. Therefore, corroborating or contradicting stakeholders' expectations with the support of a modelling tool in a virtuous and coherent framework highlights the aspects that are deserving of policy support or of additional care, respectively.

Regarding energy futures, decision makers tend to favour quantified elements that offer an objective and comparable interpretation, simultaneously respecting stakeholders' perspectives. Generally, studies rely almost exclusively on modelling tools, although in some cases, the results are subject to the stakeholders' scrutiny (i.e., consultation process). This paper shows that by linking both approaches, the robustness of model outcomes for energy planning is increased.

Building long-term scenarios is, unavoidably, an unfinished process. This process establishes the capacity of collectively "thinking the future", which is a necessary ability for acting on that future. This process is an unfinished cycle that is in constant evolution due to the appearance of new issues and new challenges, suggesting new starting points for shared research. Combining different methods, as this paper proposes, is a way to advance scenario building by integrating different collective thinking.

## 5.6 APPENDIX

Table 5.A presents TIMES_PT demand categories and the respective socioeconomic indicators that are associated with equation 5.1.

**Table 5.A** | TIMES_PT end-use sectors and the respective socio-economic indicators

| End-use sector | Energy (materials, mobility) services demand category | Demand unit | Socio-economic driver |
|---|---|---|---|
| Residential | Space heating, Space cooling and Water heating (for existing rural, urban and multi-apartment and new rural, urban and multi-apartment categories) | PJ | Private consumption per household[1] |
| | Refrigeration, Cooking, Dish washing, Cloth washing, Cloth drying, Lighting, Other electric and energy demand | PJ | Private consumption |
| Services | Space heating, Space cooling and Water heating (for small and large services categories),<br>Cooking, Refrigeration, Electric appliances, Lighting, Public lighting, Other energy demand | PJ | GVA: Services |
| Transport | Long distance private car, Motorcycles | Pkm | Private consumption |
| | Short distance private car, BUS, Intercity coach, Passengers train, Light passengers train | | Population |
| | Road freight, Train freight | Tkm | GDP |
| | Domestic aviation, Domestic navigation | PJ | |
| Industry | Iron and Steel | Mt | GVA: Iron&steel and nonferrous metals |
| | Non-ferrous metals | PJ | |
| | Ammonia, Chlorine, Nitric Acid | Mt | GVA: Chemical |
| | Other chemicals | PJ | |
| | Cement, Lime, Hollow glass, Flat glass, High quality paper, Low quality paper | Mt | GVA: Energy intensity industries |
| | Other non-metallic minerals | PJ | |
| | Other industry | PJ | GVA: Other industry |
| Agriculture | | PJ | GVA: Agriculture |

[1]The number of dwellings is the ratio between population and family dimension (see (Gouveia et al., 2012) for more details)

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# CHAPTER 6

## INTEGRATED TECHNOLOGICAL-ECONOMIC MODELLING PLATFORM FOR ENERGY AND CLIMATE POLICY ANALYSIS *

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## ABSTRACT

Computable general equilibrium (CGE) and bottom-up models each have unique strengths and weakness in evaluating energy and climate policies. This paper describes the development of an integrated technological, economic modelling platform (HYBTEP), built through the soft-link between the bottom-up TIMES and the CGE GEM-E3 models. HYBTEP combines cost minimizing energy technology choices with macroeconomic responses, which is essential for energy-climate policy assessment. HYBTEP advances on other hybrid tools by assuming 'full-form' models, integrating detailed and extensive technology data with disaggregated economic structure, and 'full-link', i.e., covering all economic sectors. Using Portugal as a case study, we examine three scenarios: i) the current energy-climate policy, ii) a $CO_2$ tax, and iii) renewable energy subsidy, with the objective of assessing the advantages of HYBTEP vis-à-vis bottom-up approach. Results show that the economic framework in HYBTEP partially offsets the increase or decrease in energy costs from the policy scenarios, while TIMES is very sensitive to energy services-price elasticities, setting a wide range of results. HYBTEP allows the computation of the economic impacts of policies in a technological detailed environment. The hybrid platform increases transparency of policy analysis by making explicit the mechanisms through which energy demand evolves, resulting in high confidence for decision-making.

## 6.1 INTRODUCTION

Energy-economy-environment models have been widely applied to support energy and climate policies, helping to explore and plan alternative energy futures and carbon mitigation strategies. Energy bottom-up (BU) and economic top-down (TD) models, are the two main modelling approaches used, differing essentially in the technological detail and endogenous market adjustments (Böhringer and Rutherford, 2008). The terms “bottom-up” and “top-down” are shorthand for disaggregated technological and energy systems models and aggregate economic models, respectively (Metz et al., 2001).

BU models focus on the energy system, characterizing it with great technological detail, including technical and economic information (e.g. efficiency, lifetime, investment and operation and maintenance costs). They are typically cast as optimization problems (Böhringer and Rutherford, 2008), defining the cost minimizing set of technologies needed to meet a given level of demand for energy services. Because BU models ignore that emergent technologies have greater financial risk, or may not be perfect substitutes to consumers, they do not provide a realistic microeconomic framework (Bataille et al., 2006). Moreover, they neglect interactions among the energy system and the rest of the economy. To accommodate responses to prices change, these models allow for energy service demand adjustments through energy service price-elasticities. Some authors (e.g., (Bataille and Columbia, 2005; Labriet et al., 2012)) argue that this response captures part of the feedback effects between the energy system and the economy. Good estimates of energy services price-elasticities are rare, however, as the econometric literature focuses mostly on energy demand (Duerinck and Van Regemorter, 2011).

Conventional TD models focus on the economy as a whole, disaggregating it in production sectors and consumption categories. The TD approach has been dominated by computable general equilibrium (CGE) models (Hourcade et al., 2006) which compute the levels of supply, demand and price that support the equilibrium across all the markets (e.g. capital, labour, materials/services). CGE models have an explicit representation of the micro-economic behaviour of the economic agents (e.g., households, firms and government), however, the energy sector is represented by aggregated production functions, capturing substitution possibilities between input factors and energy forms through substitution elasticities (Böhringer and Rutherford, 2008). These are usually estimated from historical data, with no guarantee that they will remain valid in the future (Grubb et al., 2002). CGE models enjoy widespread use in evaluating market based energy and environmental policy instruments, such as, energy or carbon taxes. Yet, due to the lack of detailed technology information, they have proven ineffective in assessing technology policies, while violations of energy and matter conservation principles may occur (Böhringer and Rutherford, 2009).

Decision makers need clear and consistent information concerning the impact of energy and climate policies in the economy, as well as the cost-effective technology portfolio to achieve their goals. Historical use of CGE and BU models has not adequately address these various policy dimensions. Hybrid models, that combine the two approaches, have been developed, with the objective of providing an integrated modelling framework: technologically explicit, with strong microeconomic foundations and macroeconomic closure (Hourcade et al., 2006).

Hybrid models can be classified according to their different approaches to integration. One method is a "soft-link" between two independent TD and BU models, exchanging data and solving them iteratively until the two models converge (e.g., (Hoffman and Jorgenson, 1976; Labriet et al., 2010)). This approach has the advantage of being a transparent process and allows the use of complete models, as its computational complexity and running times are generally manageable (Martinsen, 2011). However, due to the heterogeneity of the models, it may be difficult to achieve consistency and convergence (Böhringer and Rutherford, 2009). Although some soft-linking processes have been implemented, they are mostly done through a single sector alone, e.g., transport (Schäfer and Jacoby, 2005), residential (Drouet et al., 2005), electricity (Martinsen, 2011), thereby lacking in a full macroeconomic feedback over the range of technological choices of the entire energy system.

Another approach is linking one model to a reduced form of the other. The most common development is to couple a simple macroeconomic sector, producing a single non-energy good, to a BU model (e.g., (Manne and Wene, 1992; Manne et al., 1995; Messner and Schrattenholzer, 2000; Bosetti et al., 2006; Strachan and Kannan, 2008)). Although this method includes energy-economy interactions, its high aggregation limits its usefulness in assessing sector specific effects.

A third approach combines BU and TD models in a Mixed Complementarity Problem (MCP) format (e.g., (Bohringer, 1998; Frei et al., 2003; Böhringer and Rutherford, 2008; Wing, 2008; Proença and St. Aubyn, 2013)), introducing BU technological detail (commonly discrete electricity generation technologies) into a CGE framework. Its complexity and dimensionality, however, restricts the introduction of an extensive set of technologies, limiting the analysis of technology-oriented policies. (Böhringer and Rutherford, 2009) have further outlined a method to decompose and solve iteratively MCP model, overcoming dimensionality issues ((Tuladhar et al., 2009; Lanz and Rausch, 2011) applied this method using just electricity generation BU models).

Despite the extensive literature on hybrid models, there are few quantitative examples employing a "full-link" (i.e., not focusing on only one sector) and 'full-form' BU and TD approaches (i.e., extensive technology data and disaggregated economic structure). This paper proposes a "full-link" and a "full-form" hybrid model, supported by an integrated methodology to soft-link the extensively applied BU TIMES model, developed by Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency[27] (IEA), with the CGE GEM-E3 model, used by several Directorates General of the European Commission[28].

The hybrid platform, hereafter named HYBTEP (Hybrid Technological Economic Platform) overcomes the main limitation of CGE models – failure in represent technology choices – by considering the energy profile and prices computed by TIMES, which are sustained by a detailed technology database. It contains (current and emergent) technologies per sector, considering its characteristics and specificities. To minimize the drawback of bottom-up modelling – failure to represent adequately the link between energy and the economy – the changes in the sectors economic behaviour are set by GEM-E3. According to the energy consumption profile and costs defined by TIMES, the CGE model defines the changes in the sectors' production functions, including the input of labour and materials.

HYBTEP allows each sector to respond differently to the energy-climate policies according to the cost-effective technology portfolio available and its sector specific economic environment (e.g. interdependency in terms of intermediate consumption and distinct substitution and demand elasticities).

HYBTEP is applied to the Portuguese case, defined by the single country versions of the two models: TIMES_PT and GEM-E3_PT. Currently concerns about economic growth and high levels of public indebtedness are at the forefront of the Portuguese political discussion. At the same time, as a member of the European Union, Portugal is subject to demanding energy and climate policy goals, which cannot be dismissed. In the last decades significant changes in the national energy system have taken place, namely the increase of electricity generation from renewable sources. Still Portugal is highly dependent on imported fossil fuels, which corresponds to two-thirds of its primary energy consumption (DGEG, 2013). This is reflected in its energy and carbon intensity (measured per unit of GDP), which are above the EU28 average, revealing lower productivity and indicating that there is potential to improve energy efficiency and decarbonize the economy (OECD,

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[27] See http://www.iea-etsap.org/web/Applications.asp for a list of TIMES applications and respective publications

[28] See http://ipts.jrc.ec.europa.eu/activities/energy-and-transport/gem-e3/publications.cfm for a list of GEM-E3 applications and respective publications

2011; APA, 2014). This highlights how important it is for Portugal to integrate energy and economic concerns in comprehensive framework, assessing the impacts of energy-climate policies on both the energy system and the economy, making the country a relevant case study.

This paper presents a detailed description of the HYBTEP modelling framework and its application in three policy scenarios. The objective is to provide insights on the advantages of HYBTEP in assessing the impact of climate and energy policies on the energy system and the economy, and in defining mitigation strategies, when compared with conventional BU models. Thus, HYBTEP results are compared with TIMES outcomes considering different values for energy service-price elasticities, evaluating the performance of the modelling tools under each policy scenario.

The remainder of the paper is organized as follows: Section 6.2 describes TIMES and GEM-E3, and the linking methodology to build HYBTEP. Section 6.3 presents the calibration procedure between the models and outlines the assumptions under each policy scenario. Section 6.4 investigates the impact of the policy scenarios on the energy system, greenhouse gas (GHG) emissions and the economy, allowing for a comparison between HYBTEP and TIMES outcomes. Section 6.5 concludes and evaluates the strengths and weakness of the hybrid approach in the assessment of energy and climate mitigation policies.

## 6.2 METHODOLOGY

This section presents a characterization of the two models connected in HYBTEP modelling framework, as well as a description of the soft-link methodology.

### 6.2.1 TIMES MODEL

TIMES (The Integrated MARKAL-EFOM system) is an inter-temporal linear optimization energy model generator. In its partial equilibrium formulation, the objective of TIMES is to minimize total energy system cost to satisfy energy services demand, i.e., maximization of the total net surplus, subject to technological, physical and policy constraints. The model computes the energy demand/supply equilibrium, by making simultaneous decisions about technology investment and operating costs, primary energy supply and energy trade (Loulou et al., 2005), in an environment in which all agents have perfect foresight.

TIMES_PT characterizes the entire chain of the Portuguese energy system from 2005 to 2050 (in 5-year steps), including energy imports and production (e.g., oil and bio refineries), transformation, (e.g., power and heat production), distribution, exports and end-use consumption, in industry, residential, services, agriculture and transport sectors and their respective sub-sectors. Each year is divided in 12 time slices corresponding to average day, night and peak demand for each season: fall, winter, spring and summer.

The model contains three energy economy entities, which define the Reference Energy System (Loulou et al., 2005): i) Technologies, corresponding to processes that transform energy commodities into other energy commodities (e.g., electricity generation technologies) or fulfil energy services demand. The TIMES_PT technological database has more than two thousands existing and future, supply and demand, energy technologies, with detailed information such as efficiency, capacity factor, availability, technical lifetime, investment, operation and maintenance costs and emission factors. ii) Commodities, comprising energy carriers, energy services, materials and emissions. A commodity is generally produced by some technologies (output) and consumed by others (input). iii) Commodities flows, which link processes and commodities.

TIMES_PT is driven by energy service demands, which are external to the model or are dependent of its endogenous energy costs through energy service-price elasticities. In its elastic demand version (hereafter called TIMES-ED), the model can increase or reduce energy service demand as a function of their market price in an alternative scenario (e.g., a policy scenario) as in Eq. (6.1).

$$D_{j,t} = D0_{j,t} \cdot \left(P_{j,t}/P0_{j,t}\right)^{elas_j} \tag{6.1}$$

Where,

$\mathrm{D_{j,t}}$ is the demand for energy service *j*, at time period *t*, in a counterfactual scenario;

$\mathrm{D0_{j,t}}$ is the demand for energy service *j*, at time period *t*, in the base scenario;

$\mathrm{P_{j,t}}$ is the marginal price of energy service demand *j*, determined by TIMES, at time period *t*, in a counterfactual scenario,;

$\mathrm{P0_{j,t}}$ is the marginal price of energy service demand *j*, determined by TIMES, at time period *t*, in the base scenario,;

$\mathrm{elas_j}$ is the (negative) price elasticity of the energy service demand *j*.

### 6.2.2 GEM-E3 MODEL

GEM-E3 (General Equilibrium Model for Economy, Energy, Environment) is a multi-regional, multi-sector, recursive dynamic CGE model, describing the interactions between economy, energy and environment (E3M - Lab, 2010). The model computes the equilibrium price of goods, services, labour and capital that simultaneously clear all markets and optimize the behaviour of economic agents.

GEM-E3_PT corresponds to a single country version of the model, covering the Portuguese economy. It is based on data for the benchmark year 2005, combining the Portuguese economic Social Accounting Matrix (SAM), from national account statistics (INE, 2013) and input-output tables (EC, 2011a), with price and physical energy data and GHG emissions ($CO_2$, $CH_4$ and $N_2O$), from national energy balance (DGEG (Directorate-General of Energy and Geology), 2007) and emissions inventories (APA, 2014), respectively.

In GEM-E3_PT, firms maximize profits producing output according to a four-level nested constant substitution elasticity (CES) production function, which combines primary factors (capital and labour) with intermediate consumption of materials, services and energy (coal, oil, natural gas and electricity) (Figure 6.1). The model includes eighteen production sectors ranging from agriculture, energy industries (including oil refinery and power and heat production), iron & steel industry, land transport, services of credit and insurances, among other.

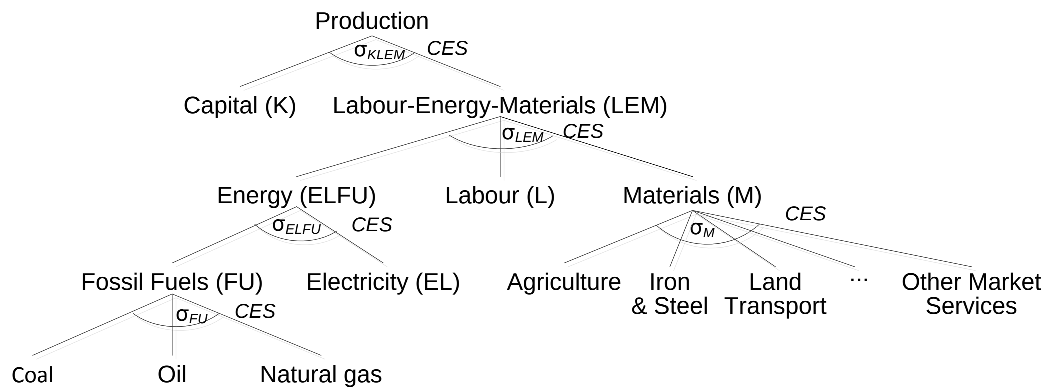


**Figure 6.1** | Nesting constant substitution elasticity production structure of standard GEM-E3_PT (σ represents the substitution elasticities).

Households maximize their inter-temporal utility, in an extended linear expenditure system (LES), choosing between present and future consumption of goods/services, leisure and savings, subject to a budget constraint. Their consumption is thereafter allocated between eleven non-durable consumption categories, such as, food, clothing, health services, culture, fuels and power and two durable goods: residential heating systems/electric appliances and private transport equipment, which are associated with productive sectors through fixed coefficients.

Bilateral trade between Portugal and the rest of the World follows an Armington specification, thus total demand is allocated between produced and imported goods, under the hypothesis that these are imperfect substitutes. GEM-E3_PT Armington elasticities are derived from the European GEM-E3 model (E3M - Lab, 2010).

Government behaviour is set exogenously based on economic projections. Its income is generated through the collection of taxes, as, social security, import duties, value added and environment taxes, which are spend in public consumption, investment and transfer to other economic agents. In the current analysis we impose a revenue-neutrality, in the sense that government's deficit/surplus is fixed as percentage of gross domestic product (GDP), and additional revenues are recycled to economy to reduce endogenously employers' social security tax.

### 6.2.3 HYBTEP SOFT-LINK METHODOLOGY

HYBTEP corresponds to a modelling platform built through an iterative process to link the two abovementioned models. Inspired by the work of (Labriet et al., 2010), we set an approach whereby, TIMES_PT provides the configuration and the evolution of energy costs for the Portuguese energy system, which is assumed by GEM-E3_PT. The CGE model in its turn, defines the configuration of the national economic structure, driving the energy services demand that feeds TIMES_PT. The two models are solved independently and in succession, reconciling the equilibrium of energy sector profile and energy system costs.

#### DEFINING COHERENCE BETWEEN THE TWO MODELS

The integration of the two modelling frameworks requires the establishment of a coherent data structure across the modelling tools. This primarily manifested itself through the correspondence between the different activity sectors and energy commodities disaggregation across the two models (Table 6.1). The corresponding sectors and commodities (i.e., HYBTEP disaggregation) were further used as interaction indexes in the soft-linking methodology.

A crucial step to achieve consistency among the models is associated with the definition of common scenario assumptions, namely fossil fuel import prices, interest rates, energy constraints and policy assumptions. In the present analysis, we defined the following equal conditions for both models and across scenarios: i) an interest rate of 4%; ii) fossil fuel import prices according to 4D scenario of the World Energy Technology Perspectives (IEA, 2012a) with prices in 2050 reaching US$$_{2010}$118/barrel for crude oil, US$$_{2010}$12/MBTU for natural gas, and US$$_{2010}$109/ton for coal; iii) restrictions on Iberian electricity trade, which is set to zero after 2015, preventing GHG leakage and inconsistence between the models results.

**Table 6.1** | Correspondence between GEM-E3_PT and TIMES_PT activity sectors and energy commodities in HYBTEP.

| | GEM-E3_PT | | TIMES_PT | | HybTEP |
|---|---|---|---|---|---|
| | | | ***Activity sectors*** | | |
| *Private consumption categories* | Households fuels and power associated with heating and cooking appliances and electric systems | *Demand Categories (energy services, materials and mobility)* | Residential space heating and cooling, water heating, lighting, cooking, and electricity demand for electric appliances | *Economic Sectors* | Residential |
| | Households operation of transport associated with operation of transport | | Road car long distance and short distance, road moto | | Private road transport |
| *Production Sectors* | Agriculture | | Agriculture | | Agriculture |
| | Ferrous and nonferrous metals | | Iron and steel, nonferrous metals | | Iron and steel and nonferrous metals |
| | Chemical | | Ammonia, chlorine, acid nitric and other chemicals | | Chemical |
| | Energy intensive industry | | Cement, lime, glass, other non-metallic minerals, paper | | Energy intensive industry |
| | Electric and other equipment goods,<br>Transport equipment,<br>Other Industries,<br>Consumer goods, food and textile industries<br>Construction | | Other industries | | Other industry |
| | Land transport | | Road heavy and light freight, rail freight; road urban bus; road intercity coach, rail passengers heavy, rail passengers light | | Land transport except private transport |
| | Other transport | | Aviation, navigation | | Other transport |
| | Services of credit and insurances,<br>Other markets services,<br>Non-market services | | Commercial space heating and cooling, water heating, cooking, refrigeration, electric appliances, lighting and public lighting | | Services |
| | Electricity | *Supply sectors* | Power sector | | Power sector |
| | Oil | | Oil refinery | | Oil refinery |
| | Coal<br>Natural gas | | Other supply sectors[a] | | Other supply sectors[a] |
| | | | ***Energy commodities*** | | |
| | Biomass[b] | | Biomass, biofuels, biogas | | Biomass |
| | Coal | | Hard Coal, Lignite, Brown Coal | | Coal |
| | Oil products | | Crude oil, gasoline, diesel, LPG, heavy fuel oil, light fuel oil, other petroleum products | | Oil products |
| | Natural gas | | Natural Gas | | Natural Gas |
| | Electricity | | Electricity | | Electricity |
| | -----[c] | | Non biomass renewables (wind, hydro, solar, geothermal, wave, etc) | | ---- |

[a] Without significance in Portugal due to the absence of coal mining and natural gas extraction.

[b] Although the standard version of GEM-E3_PT does no assume biomass as an energy commodity, in HYBTEP we added biomass produced by Agriculture sector as a new energy commodity, allocating its overall demand to the intermediate consumption of different sectors.

[c] It should be underline that due to its nature (a standard CGE model sustained by national accounts), GEM-E3_PT does not represent explicitly renewable energy sources.

### DEVELOPING A NEW ENERGY MODULE IN GEM-E3_PT

To allow GEM-E3_PT to replicate the energy system profile defined by TIMES_PT outputs, the model's CES production technology for the top level energy aggregate (ELFU), was replaced by a Leontieff function, setting the CES elasticities to zero and defining exogenously total energy consumption and the shares for energy consumption by carrier and sector. The model structure above this nest was preserved, as depicted in Figure 6.2. As a result of these changes, the demand functions for the electricity, fuel aggregate and fuel consumption (Eq. (6.2)-(6.5)) of standard GEM-E3_PT were replaced by Eq. (6.6) and Eq. (6.7) associated with a new linking energy module.

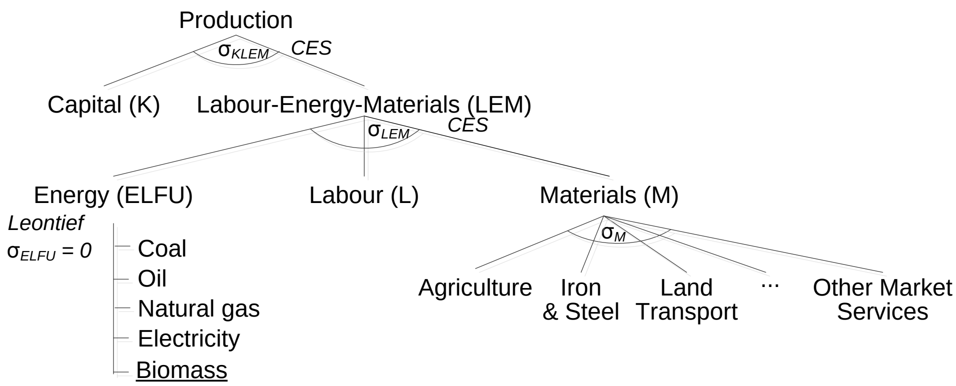


**Figure 6.2** | Nesting constant substitution elasticity production structure of modified GEM-E3_PT in HYBTEP version (σ represents the substitution elasticities).

*Standard GEM-E3_PT:*

$$ELFU_{S,t} = LEM_{S,t} \cdot \delta_{ELFU_S} \cdot \left(PLEM_{S,t}/PELFU_{S,t}\right)^{\sigma_{LEM_{S,t}}} \tag{6.2}$$

$$EL_{S,t} = ELFU_{S,t} \cdot \delta_{EL_S} \cdot \left(PELFU_{S,t}/PEL_{S,t}\right)^{\sigma_{ELFU_{S,t}}} \cdot e^{tge_{el,S,t} \cdot \left(\sigma_{ELFU_{S,t}}-1\right)} \tag{6.3}$$

$$FU_{S,t} = ELFU_{S,t} \cdot \delta_{FU_S} \cdot \left(PELFU_{S,t}/PFU_{S,t}\right)^{\sigma_{ELFU_{S,t}}} \tag{6.4}$$

$$FF_{f,S,t} = FU_{f,S,t} \cdot \delta_{FF_{,S}} \cdot \left(PFU_{S,t}/PE_{f,S,t}\right)^{\sigma_{FU_{S,t}}} \cdot e^{tge_{f,S,t} \cdot \left(\sigma_{FU_{S,t}}-1\right)} \; \forall f = coal, oil, gas \tag{6.5}$$

Where,

$ELFU_{S,t}$ is the energy aggregated consumption per productive sector *S* and time period *t*;

$EL_{S,t}$ is the electricity consumption per productive sector *S* and time period *t*;

$FU_{S,t}$ is the fuel aggregate consumption per productive sector *S* and time period *t*;

$FF_{f,S,t}$ is the fuel consumption per fuel carrier *f*, productive sector *S* and time period *t*;

$LEM_{S,t}$ denotes the labour-energy-materials aggregate per productive sector *S* and time period *t*;

$\delta_{ELFU_S}$, $\delta_{EL_S}$, $\delta_{FU_S}$ and $\delta_{FF_S}$ represent the scale factors for *ELFU*, *EL*, *FU* and *FF*, respectively, derived from the base year 2005;

$PLEM_{S,t}$, $PELFU_{S,t}$, $PEL_{S,t}$ and $PE_{f,S,t}$ represent the price of *LEM*, *ELFU*, *EL* and energy (per fuel type *f),* respectively, per sector *S* and time period *t*;

$\sigma_{LEM_{S,t}}$, $\sigma_{ELFU_{S,t}}$, $\sigma_{FU_{S,t}}$ are the substitutions elasticities between Labour, Energy, Materials productive factors, between Electricity and Fuels and between Fuel carriers, respectively;

$tge_{el,S,t}$ and $tge_{f,S,t}$ are the technical progress of electricity (*el*) and technical progress for each fuel type (*f*), respectively, per sector *S* and time period *t*.

*HYBTEP:*

$$ELFU_{S,t} = \sum_{e} \frac{EC_{e,S,t}}{CONVERS_e \cdot (1 - NEU_{e,S})} \tag{6.6}$$

$$ES_{e,S,t} = \alpha_{e,S,t} \cdot ELFU_{S,t} \tag{6.7}$$

Where,

$EC_{e,S,t}$ is the physical energy consumption from TIMES_PT results per energy commodity *e (electricity, biomass, coal, oil and natural gas)*, sector *S* and time period *t*;

$CONVERS_e$ represents a conversion parameter that “transform” the physical units of energy consumption from TIMES_PT in monetary units for GEM-E3_PT. $CONVERS_e$ is calibrated in the base year (2005) trough IEA energy prices and taxes statistics (IEA,2011), energy balance (DGEG (Directorate-General of Energy and Geology), 2007) and national accounts (INE, 2013);

$NEU_{e,S}$ represents the share of non-energy uses in energy commodity *e* and sector *S*. The parameter refers for example to the energy products consumed as raw materials in the chemical, industry. $NEU_{e,S}$ is calibrated in base year through national energy balance and national accounts and kept constant;

$ES_{e,S,t}$ is the energy consumption in monetary units per energy commodity *e*, sector *S* and time period *t*. $ES_{e,S,t}$ symbolizes $EL_{S,t}$, $FU_{S,t}$ and $FF_{S,t}$ when *e* is referred to electricity, the sum of fossil fuels and each fossil fuel, respectively;

$\alpha_{e,S,t}$ is the share of each energy commodity *e* in total energy consumption, per sector *S* and time *t* (i.e., is the amount of each energy commodity in monetary units per $ELFU_{S,t}$). It must be the case that (Eq. (6.8)):

$$\sum_{e} \alpha_{e,S,t} = 1 \tag{6.8}$$

These changes further implied alterations to the definition of the price of the energy aggregate, as following (Eq. (6.9) and Eq. (6.10)):

*Standard GEM-E3_PT:*

$$PELFU_{S,t} = \left[\delta_{EL_S} \cdot \left(PEL_{S,t} \cdot e^{(-tge_{ELC,S,t})}\right)^{(1-\sigma_{ELFU_{S,t}})} + \delta_{FU_S} \cdot PFU_{S,t}{}^{(1-\sigma_{ELFU_{S,t}})}\right]^{\frac{1}{1-\sigma_{ELFU_{S,t}}}} \tag{6.9}$$

*HybTEP:*

$$PELFU_{S,t}=PELFU_{S,t-1} \cdot (1 + \Delta \frac{ECOST_{S,t}}{ELFU_{S,t}}) \tag{6.10}$$

Where,

$\Delta \frac{ECOST_{S,t}}{ELFU_{S,t}}$ represents the growth rate of the energy system costs from TIMES_PT outcomes for each energy aggregate $ELFU_{S,t}$ per sector S, from time period t-1 to t. $ELFU_{S,t}$ includes technology investment, operation and maintenance costs, energy (fuels, biomass, electricity) price, plus energy and/or environmental taxes, minus subsidies. The energy price computed by TIMES represents the marginal cost as the BU model follows a competitive market assumption, where the market price of a commodity is equal to its marginal cost in the economy. The energy system structure determined by TIMES_PT is computed taking into account the satisfaction of its energy service demand in each time-slice including in the peaks and thus its energy price responds to the peak demand. $ELFU_{S,t}$represents an annual weight average of the energy price to be accommodated by GEM-E3_PT.

Regarding households, the GEM-E3_PT specification for private consumption activities was preserved with the exception of expenditures on *Fuels and Power* and *Operation of Transport* which were defined exogenously according to TIMES_PT model outcomes. The physical units for energy demand were converted in monetary units as in Eq. (6.6) and Eq. *(*6.7). Moreover, the fixed shares of energy consumption in the total expenditure categories were altered to reflect substitution among energy carriers in the demand for *Fuels and Power* and *Operation of Transport*. The energy price structure in households was not changed as it is determined as a weighted average of the price of output from each energy productive sector (e.g. electricity price from power generation sector) contributing to the production of a particular household commodity demand group.

In the standard GEM-E3_PT, energy efficiency improvements are considered through an exogenous energy productivity variable i.e. technical progress. Usually this value is based on historical data or future political goals (e.g. energy efficiency standards). Within HYBTEP integrated modelling platform, technical progress for energy is calculated based on TIMES_PT results according to what is defined in Eq. (6.11) and Eq. (6.12). Technical progress for energy is determined uniquely for each sector:

$$eff_{S,t} = PROD_{S,t} \Big/ \sum_{e} EC_{e,S,t} \qquad (6.11)$$

$$TPe_{S,t} = eff_{S,t} / eff_{S,2005} \qquad (6.12)$$

Where,

$eff_{S,t}$ denotes the energy efficiency per energy commodity $e$, sector $S$ and period $t$;

$PROD_{S,t}$ represents TIMES_PT production values for the case of electricity and some industrial processes (cement, paper, glass, iron & steel, lime), mobility for transports and energy services demand for residential, services, agriculture and other industrial sectors (e.g. chemical, non-metallic mineral products, other industry);

$TPe_{S,t}$ = represents the evolution of the technical progress for energy per sector S and period t.

### DEFINING THE ITERATION PROCEDURE AND CONVERGENCE BETWEEN THE TWO MODELS

Figure 6.3 presents the schematic view of HYBTEP platform, which comprises the following iteration steps:

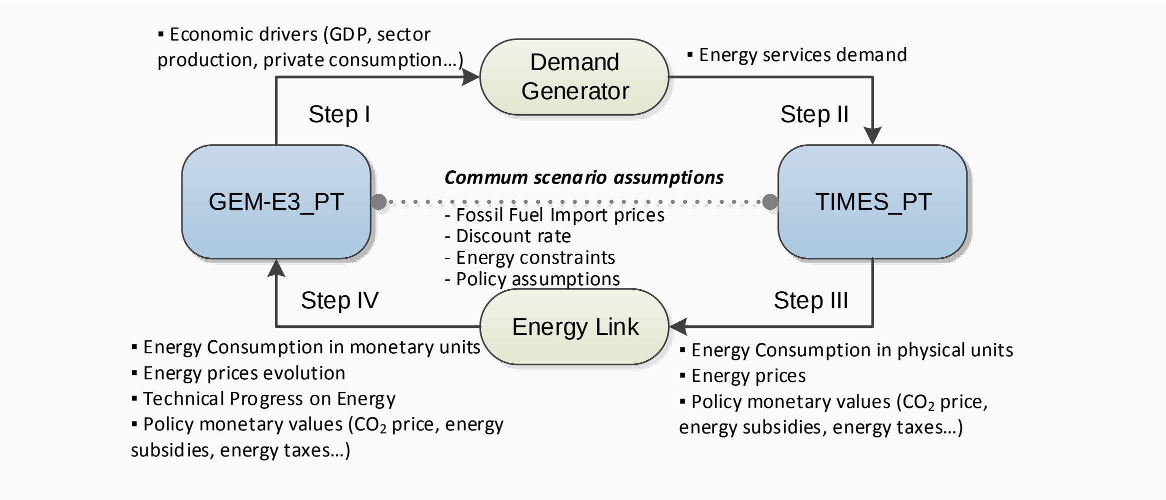


**Figure 6.3** | Schematic view of HYBTEP soft-link framework.

**Step I:** GEM-E3_PT is run assuming some exogenous input variables, namely, world energy import prices, energy constraints (e.g. no electricity trade), active population growth, technical progress[29] (capital, labour and materials) and expectations on future sector-specific growth. The two latter exogenous variables are calibrated so the model could produce a reference scenario consistent with a predefined economic projection. The model outputs, including GDP, sector production and

[29] In the first iteration, the technical progress of energy was set to zero. In the subsequent iterations and as explained before this parameter was determined based on TIMES_PT results.

private consumption are used to produce energy services, materials and mobility demand according to Eq. (6.13) and Eq. (6.14) of demand generator module:

$$D_{j,t} = D_{j,t-1} \cdot \left(1 + DRGR_{j,t} \times ELASI_j\right) \cdot (1 - AEEI_j) \tag{6.13}$$

$$D_{j,t} = KM_{j,t-1} * (\left(1 + RSH_t \times ELASI_j\right) \cdot Pop_t \quad \forall\, j \tag{6.14}$$ = p.km for cars short distance, long distance and motorcycles

Where,

$D_{j,t}$ is the demand for each energy service, material or mobility *j* (see Table 6.1 for an overview of TIMES_PT demand categories), in time period *t*. For the base year (2005), $D_{j,2005}$ was developed considering the historic national materials and energy consumption and the corresponded technological profile and its characteristics, namely installed capacity, efficiency, availability, among other factors;

$DRGR_{j,t}$ is the annual growth of population and the economic drivers from GEM-E3_PT (i.e., GDP, private consumption, sector production) associated with each energy service, material and mobility demand *j*;

*ELASj* is the income elasticity per energy service, material and mobility demand *j*;

*AEEIj* is autonomous energy efficiency improvement factor in industrial sectors;

$KM_{j,t-1}$ is the average km travelled by habitant for the demand categories cars short distance, cars long distance and motorcycles for period *t-1*;

$\mathrm{RSH}_t$ is the annual growth of private consumption per household in period *t;*

$\mathrm{Pop}_t$ is the resident population in period *t.*

For the residential sector, demand is generated through a more complex formula, which depends on the age and characteristics of dwellings (new or existing, single house situated in rural or urban area or multi apartment), the number of persons per house, among other parameters as explain in (Simões et al., 2008).

**Step II:** The energy service and materials demand projected by the Demand Generator module are entered into TIMES_PT, which defines the energy system configuration, determining, among other important quantities, the energy consumption (quantities per sector per energy source), the corresponding GHG emissions and system costs which includes investment, operation and maintenance, fuel costs, subsidies and/or taxes. TIMES_PT is run assuming the same interest rate, world energy prices and energy constraints considered in GEM-E3_PT. Energy taxation in the Portuguese economy, which includes excise duties on energy, is also included in TIMES_PT, and is assumed to remain constant through 2050.

**Step III**: TIMES_PT physical energy consumption and system costs are "translated" in GEM-E3_PT monetary units, technical progress on energy and energy prices through an Energy Link Module, comprising Eq. (6.6)-*(*6.7), and Eq. (6.10)-(6.12). When a market policy instrument is being considered in TIMES_PT, e.g., an energy tax or a feed-in tariff, the respective economic value is also included in GEM-E3_PT associated with the respective payer and payee sectors. This way the CGE model assumes the transfers between the economic agents and computes the impact of those on economy. GEM-E3_PT emission factors per energy carrier and sector are also adjusted to reflect TIMES_PT emissions. This change is of special relevance when the BU model selects carbon capture and storage technologies.

**Step IV:** GEM-E3_PT is run, sustain by its new algebraic formulation and STEP III outputs.

Modifications in the energy profile and prices can have impact on the economic projections structure described by GEM-E3_PT and, consequently, on TIMES_PT demand categories. Thus, to reflect the macroeconomic feedback of the changes in the energy system, the four steps described above are repeated until the two models converge to a satisfactory level, which is defined with respect to the following metric (Eq. (6.15)), close to (Labriet et al., 2010) convergence criteria:

$$Max\ C_j = \frac{\sqrt{\sum_{t=2005}^{2050}\left(D_{j,t,i} - D_{j,t,i-1}\right)^2}}{\sqrt{\sum_{t=2005}^{2050} D_{j,t,i}^2}} < \beta \tag{6.15}$$

Where,

$C_j$ is the convergence function per demand category *j*;

$D_{j,t,i}$ indicates the energy services demand of category *j*, at time period $t$, in iteration $i$.

$\beta$ represents the iteration stopping threshold, reflecting the fact that with minimal energy service demand differences, the energy sector profile and energy system costs of iteration *i* and *i-1* are defined to be very small and consequently the economic drivers from GEM-E3_PT, achieving convergence across the two models results.

As observed by (Turton, 2008), in some cases, due to the stepped supply curves stemming from discrete choices consistent with linear programming models like TIMES_PT, small changes in energy services demand can induce considerable changes in the energy prices, prompting, in turn, fluctuations in energy services demand between iterations. Competing technologies have different costs, and deployment limits, associated with maximum capacity or primary energy potentials. Thus, when a technology achieves its maximum availability, a new technology is installed, which may have significant higher costs. When energy service demand is not convergent we considered an approach close to (Turton, 2008; Labriet et al., 2010), assuming that the optimal demand level lies between the previous iteration values[30].

## 6.3 Scenarios simulation

The main goal of this paper is to evaluate whether HYBTEP represents a more suitable tool than a conventional bottom-up model, to assess the impact of energy and climate policies on the energy system and GHG emissions. We design three policy scenarios, reflecting current climate and energy regulation and additional policy assumptions, to evaluate the performance of both tools. The GEM-E3_PT and TIMES_PT were harmonized and calibrated within a Calibration scenario, used as starting point for the subsequent counterfactual policy simulations. This section outlines the assumptions for each scenario.

### 6.3.1 Calibration scenario

To harmonize the two modelling tools and test the iteration and convergence procedure, we developed a Calibration scenario (CALIB), reflecting the evolution of the Portuguese economy and energy system in the absence of any energy and climate policy constraints. It should be noted that this scenario does not represent a business-as-usual scenario, as TIMES_PT was left 'free' to optimize the energy system.

The evolution of the energy system is driven by a large number of factors, including economic activity and demography. The socio-economic scenario considered for CALIB was generated within the national project HybCO$_2$[31] (Alvarenga et al., 2011). It comprises a decline in population (-0.3% p.a. from 2015 to 2050), and a moderate evolution of the economy after the current economic crises (GDP annual growth of 0.1% from 2010 to 2020 and 1.5% from 2020 to 2050), consistent with the 2012 European (EU) Ageing Report projections (EC, 2012c).

After calibrating GEM-E3_PT exogenous variables in line with the above mentioned economic assumptions, the two models were run in HYBTEP iterative process, achieving consistency after 3 iterations (Figure 6.4). The demand for energy services resulting from the calibration process was used for the policy scenario simulations because it represents equilibrium between TIMES_PT energy system and GEM-E3_PT economic structure.

[30] In the present paper this situation only happen with the RES policy scenario (section 6.3.2) regarding chemical energy services demand, representing currently just 1% of the Portuguese GDP (INE, 2013) and less than 3.5% of the national final energy consumption (DGEG, 2007).
[31] HybCO$_2$ Project: "Hybrid approaches to assess the economic, environmental and technological impact of long term carbon reduction scenarios – the Portuguese case-study" (http://hybco2.cense.fct.unl.pt/)

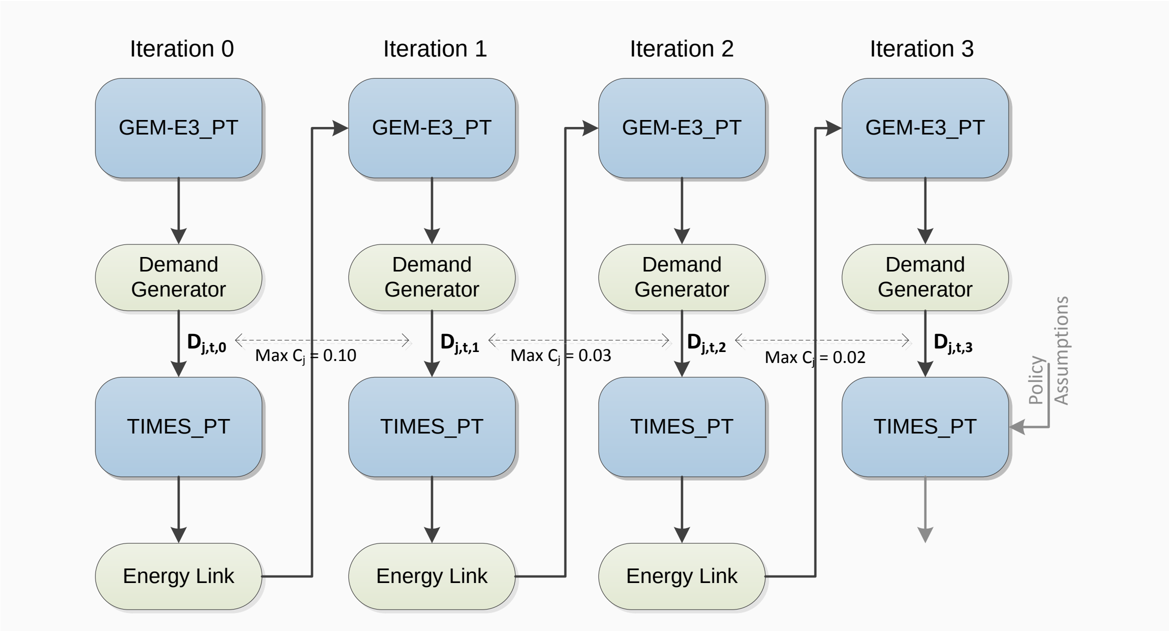


**Figure 6.4** | Schematic view of HYBTEP iteration process for the CALIB scenario (grey lines in iteration 3 represent the initial step of the policy scenarios).

Table 6.2 indicates that in general, without a soft-link, energy services demand may be underestimated, especially for residential and passengers' mobility and for energy intensive sectors such cement, paper and ceramic in the long term. The differences between energy services demand before and after the calibration are related to the consumption and effective cost of energy in each sector and its impact on the macroeconomic drivers. The technological choices of TIMES_PT minimize energy system costs, inducing generally a reduction in energy costs (exception for iron and steel and other industry), which were assumed in GEM-E3_PT with positive impacts on the demand for energy services.

**Table 6.2** | Demand for energy services, materials and mobility in selected sectors, in iteration 0 and 3 of CALIB scenario for 2030 and 2050.

| Demand | 2030 | | | 2050 | | |
|---|---|---|---|---|---|---|
| | It. 0 | It.3 | Difference (%) | It.0 | It.3 | Difference (%) |
| Residential (PJ) | 104.5 | 110.3 | 6% | 122.7 | 130.3 | 6% |
| Services (PJ) | 172.6 | 177.8 | 3% | 196.8 | 203.6 | 3% |
| Passenger.km | 94 894.8 | 100 259.4 | 6% | 113 404.7 | 120 675.1 | 6% |
| Tonne.km | 32 857.9 | 33 506.9 | 2% | 41 626.8 | 42 784.4 | 3% |
| Chemical industry (PJ) | 24.4 | 24.9 | 2% | 30.8 | 30.6 | -1% |
| Iron and Steel (Mt) | 2.0 | 2.0 | -4% | 2.5 | 2.4 | -3% |
| Cement (Mt) | 10.2 | 10.3 | 1% | 11.6 | 12.1 | 5% |
| Paper (Mt) | 2.7 | 2.7 | 1% | 3.3 | 3.5 | 8% |
| Ceramic (Mt) | 29.7 | 30.1 | 1% | 37.3 | 40.6 | 9% |
| Other industries (PJ) | 85.1 | 84.2 | -1% | 103.9 | 103.1 | -1% |

### 6.3.2 ENERGY-CLIMATE POLICY SCENARIOS

In this section, we describe the key elements of the three policy scenarios aiming to decarbonise the energy system.

**Current Policy Regulation** (CPR): The current Portuguese energy-climate policy within the EU climate-energy package extended beyond 2020. This includes a reduction in GHG emissions, an increase in renewable energy consumption and an improvement in energy efficiency.

i. Extension up to 2050 of the EU Effort Sharing Decision, i.e., Portugal can increase (from 2005 values) the emissions from sectors not included in the EU Emissions Trading System (EU-ETS) by 1%.
ii. Decline of the EU-ETS emissions ceiling after 2020 at a linear rate of 1.5% p.a., i.e., lower than the current rate of decline, as defined in the Reference Scenario of EU Energy Roadmap (EC, 2011b). The goal of the ETS scheme is to reduce EU ETS emissions, with national allocations units based on benchmarks. For simplicity and due to the absence of national information beyond 2020, we assumed that the EU wide ETS annual emission ceiling also applies to Portugal. No trade in emissions permits, exogenous $CO_2$ price or other policy instrument was assumed for ETS emissions besides the cap.
iii. The national renewable targets stated by National Renewable Energy Action Plan (NREAP) (RCM 20/2013) are maintained through 2050: 31% of renewable energy sources (RES) consumption in final energy demand; 49.6% of renewable electricity (RES-E); 11.1% of RES in transport energy consumption (RES-T); and 33.6% of RES consumption on Heating and Cooling (RES-H&C).

Extension up to 2050 of the national primary energy savings target defined by the National Energy Efficiency Action Plan (NEEAP) for 2020: 26% (RCM 20/2013, 2013). CPR scenario does not include directly the measures presented in NEEAP, meaning that the deployment of efficient equipment is determined by TIMES_PT, based on costs. However, NEEAP primary energy consumption limit (925.3 PJ) was considered as an upper bound, ensuring compliance with the national goal.

No new ‘conventional’ coal power plants could be installed after 2015 following the EU Parliament's Environment Committee vote to limit the $CO_2$ emissions for new large combustion plants (capacity over 0.3 GW) to a maximum of 500g $CO_2$/kwh (138.9 kt/PJ) .

**$CO_2$ price scenario** (TAX): It comprises, in addition to the CPR assumptions, a domestic carbon tax on GHG emissions from energy consumption (Table 6.3) instead of the ETS and Non-ETS emissions caps. The $CO_2$ tax is set at the highest carbon price scenario indicated in the EU roadmap for moving to a competitive low carbon economy (EC, 2011c) and is applied after 2020 uniformly to all sectors of the economy. In HYBTEP (through GEM-E3_PT), tax revenue was used to reduce endogenously the social security contributions of employees assuming government's revenue-neutrality.

**Table 6.3** | $CO_2$ price ((€$_{08}$/t $CO_2$e) (EC, 2011c)) considered in TAX policy scenario.

| | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| **$CO_2$ price (€$_{08}$/t $CO_2$e)** | 25 | 39 | 62 | 69 | 100 | 218 | 370 |

**RES support scenario** (RES): It involves, in addition to the CPR assumptions, a monetary incentive to renewable energy, including renewable electricity, biofuels, and solar and biomass consumption in buildings and industries. The incentive goes from 50 €$_{08}$/MWh in 2020 to 191 €$_{08}$/MWh in 2050 (half of the RES-value of High RES scenario of EU Energy Roadmap (EC, 2011b)). In HYBTEP, this feed-in tariff was modelled as a subsidy paid by the Government to the respective sector according to their renewable energy consumption. Considering the revenue-neutrality this subsidy is financed through increased social security contributions.

In addition to the HYBTEP runs, the policy scenarios were run by the standard TIMES_PT (without energy service-energy service-price elasticities) and by TIMES_ED (with elasticities). Following previous TIMES studies for Portugal (Simões et al., 2008; Fortes et al., 2013), the price elasticity was set at -0.3, for all categories except, commercial cooking and public lighting, whose values were -0.2, and residential cooking with -0.1. Due to uncertainty in the estimated price elasticities, a sensitivity analysis considering higher (-0.5) and lower (-0.1) values was conducted as in (Chen et al., 2007). The TIMES_PT endogenous energy prices defined in the CALIB scenario (last iteration), were taken as the base prices for TIMES_ED policy simulations.

## 6.4 Results and Discussion

This section discusses the impacts of the policy scenarios on the energy system, GHG emissions and the economy, by comparing the results from the HYBTEP with those from TIMES_ED and the standard TIMES_PT. This comparison allows us to evaluate the value added of incorporating the interactions among technological choices and the economic drivers. Results are present from 2030 onwards due to their small differences trough 2020 (inclusive), e.g., maximum difference in final energy consumption between the modelling tools (HYBTEP, TIMES_PT, TIMES_ED(-0.1), TIMES_ED(-0.3), TIMES_ED(-0.5)), in 2020, in each scenario, is less than 1.1%.

### 6.4.1 Impact on energy consumption

Under CALIB scenario, and after the decline of energy demand due to the short term economic crises, final energy consumption presents a smooth increase of approximately 0.7% p.a. between 2030 and 2050 (Figure 6.5), achieving in the latter year, values close to 2010 level. The final demand for energy differs across the modelling platforms for the policy scenarios considered. The extent of this variation varies across the scenarios modelled, as illustrated in Figure 6.5, and is mostly due to the mechanisms that each modelling tool is designed to examine. Under CRP policy scenario, HYBTEP and TIMES_ED(-0.3) assume also an annual growth in energy consumption of approximately 0.7%. The maximum difference (1.4%) between HYBTEP and TIMES_ED(-0.3) energy consumption suggests that the approaches are consistent. In fact, comparisons between HYBTEP and TIMES_PT, without elastic demand, and TIMES_ED(-0.5), with relatively elastic demand, shows differences below 2.0%. These outcomes underscore the fact that, when compared with calibration scenario (CALIB), CPR does not induce major changes in the energy system structure and costs and on the economy, and thus all the modelling tools present close outcomes.

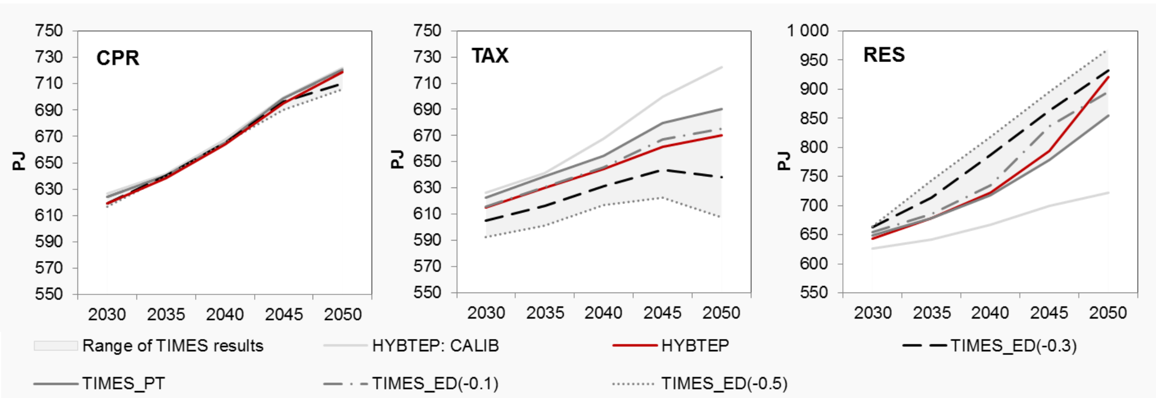


**Figure 6.5** | Final energy consumption pathway per scenario and modelling tool (results from CALIB scenario are represented in each chart by HYBTEP:CALIB).

Under the TAX and RES policy scenarios, however, important differences arise. The introduction of a $CO_2$ tax represents an additional expense, both directly and indirectly, through the increase in costs from a shift to alternative energy carriers and the deployment of more expensive technologies. The increase in energy costs results, in both HYBTEP and TIMES_ED(-0.3), in a decrease of energy consumption, when compared with a non-elastic run (TIMES_PT outcomes), which in its turn, shows a lower energy consumption than CALIB scenario due to the presence of more efficient equipment (e.g. heat pumps in buildings). HYBTEP and TIMES_ED(-0.3) present a maximum difference of 5.0% in total final energy consumption, with the hybrid tool depicting the larger demand over the modelling horizon. In HYBTEP, the carbon price induces an increase in production costs, leading to a decrease in quantity. However, the $CO_2$ tax also represents a source of additional revenue to government. The income is recycled to the economy through a reduction in labour costs, which can partially offset the increase in energy costs in production. This economic framework justifies the fact that HYBTEP shows a lower impact on energy consumption than TIMES_ED(-0.3).

The differences across modelling tools, with respect to total final energy consumption, differ across energy carriers due to dissimilarities among economic sectors. Under the TAX scenario, the largest divergence between the HYBTEP and TIMES_ED(-0.3) results is associated with fossil energy demand, especial after 2040, with the hybrid platform defining consumption levels 12.9% above the BU model in 2050 (Figure 6.6). This is mostly associated with transports and other industry, for which HYBTEP defines greater levels of energy consumption, namely for oil products in transportation (+20.3% in 2050) and natural gas (+13.7% in 2050) in other industry.

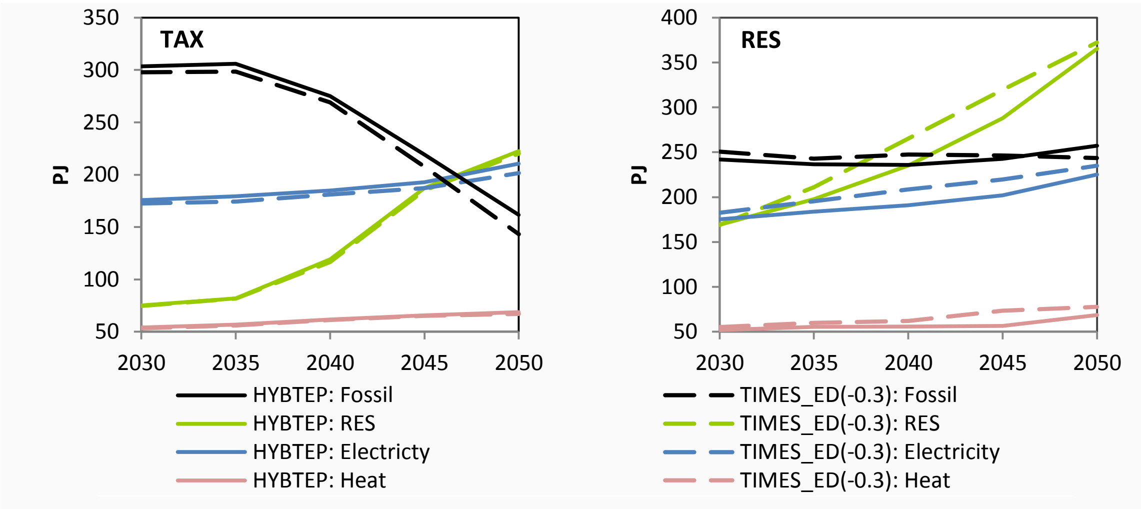


**Figure 6.6** | Final energy consumption pathway per energy carrier under TAX and RES scenarios, modeled by HYBTEP and TIMES_ED(-0.3)

In contrast to a $CO_2$ tax, in HYBTEP, the additional RES financial support from the government is financed through an increase in social security taxes (i.e., increase of labour costs). The fiscal dimensions of the subsidy are not considered by TIMES_ED(-0.3), in which the subsidy represents a simple reduction in energy price with positive effects in energy consumption as illustrated in Figure 6.5. For this reason, although both models assume an increase in total final energy consumption above 1.7% p.a. between 2030 and 2050 in RES scenario, the BU model presents greater values (up to 8.3%) over the modelling horizon. In fact, up to 2040, HYBTEP results are very close to the inelastic TIMES_PT, suggesting that the reduction in energy prices, financed by an increase in labour costs, leads in general to a relatively small impact on production and on the demand for energy services.

As shown in Figure 6.6, for the RES scenario, the most substantial differences between the models in terms of energy carriers are related to renewable, through 2045, and to power and heat energy consumption, with TIMES_ED(-0.3) presenting consumption levels greater than HYBTEP. The higher renewable energy consumption is related with biomass consumption in industry (e.g., +13.5% of biomass consumption in 2040 and 2045), while for electricity demand, the higher values are due to greater levels of consumption for residential consumers, services, and other industry sectors (e.g., +9.7 in 2040).

The economic framework of HYBTEP explained above, justifies the fact that for most sectors, HYBTEP presents higher values of energy consumption than TIMES_ED(-0.3) under TAX scenario and lower for RES scenario (Figure 6.7), leading to a similar relation in terms of energy carriers. The exception is the demand for oil products in 2050, under RES scenario due to transports behaviour.

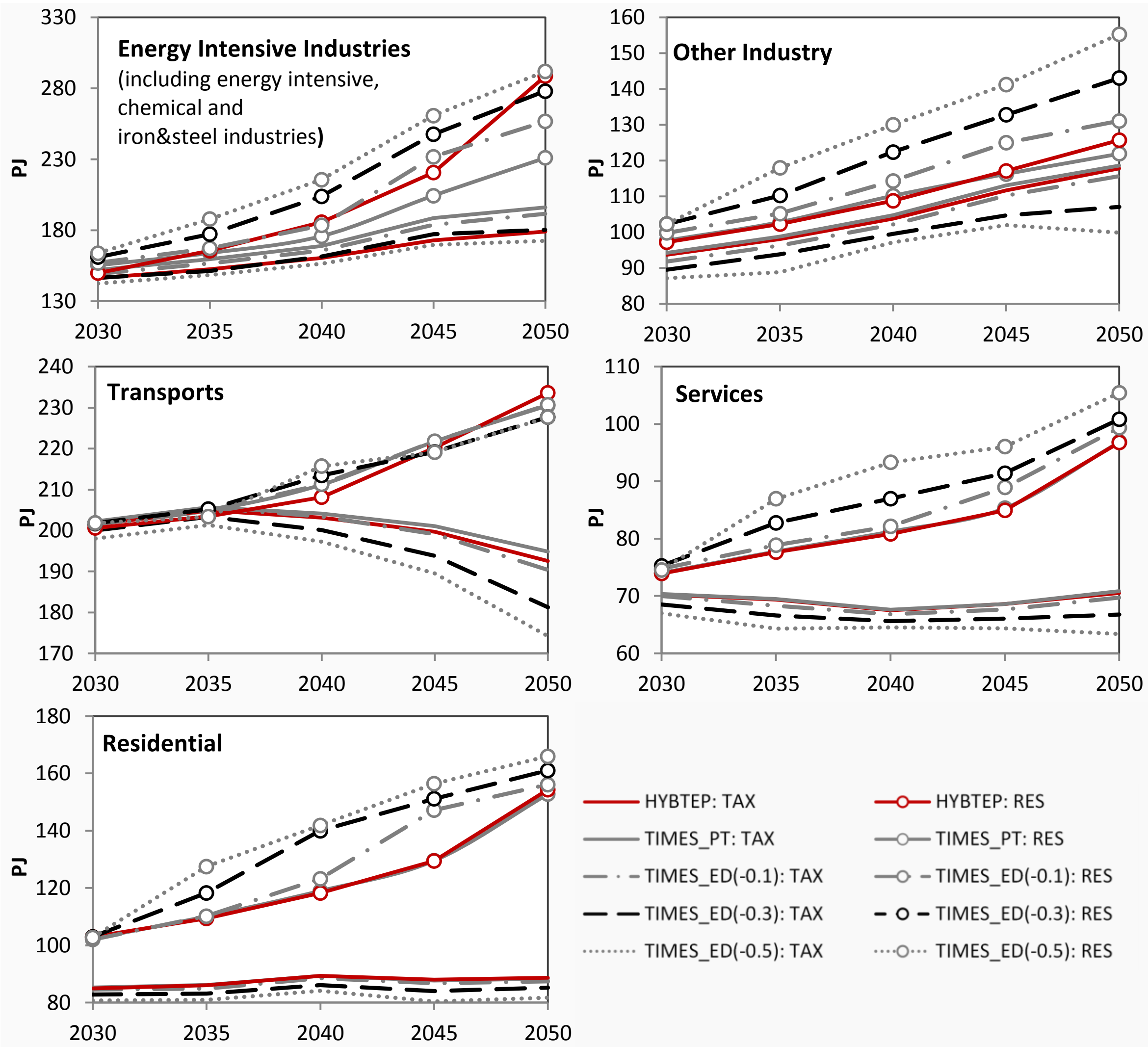


**Figure 6.7** | Final energy consumption pathway per sector and modelling tool under TAX and RES scenarios.

The sensitivity analysis with respect to the energy service-price elasticities highlights the impact of this parameter on energy consumption, as the BU model outcomes can present differences (TIMES_PT vis-à-vis TIMES_ED(-0.5)) from 5.1% to 13.6% and from -2.2% to -11.8% in the total final energy consumption in the TAX and RES scenario, respectively, for the period 2030 to 2050 (Figure 6.5). As shown in Eq. (6.1, the effect of TIMES_ED energy services elasticities on energy demand stem from the endogenously defined energy costs dictated by the technology mix. This means that the effect of the elasticities will implicitly vary across scenarios and years, as the model generate different energy prices according to its technology choices. With exception of 2050, under the TAX scenario, HYBTEP total final energy consumption is close to TIMES_ED(-0.1) values, while under the RES scenario the hybrid model show a lower degree of responsiveness to price changes, closer to the TIMES_PT results. This general outcome is associated with end-use behavior, which varies significantly across sectors depending on the elasticity considered (Figure 6.7). For energy intensive and other industry, for example, the results from TIMES_PT and TIMES_ED(-0.5) can vary by more than 20% under RES scenario. This demonstrates the high degree of uncertainty associated with the use of energy service-price elasticities and its impact on sectors energy consumption. Since TIMES elasticities are mostly homogenous across sectors, the model does not capture its specificities. Thus, in general, the greater the energy services elasticity, the lower is energy consumption under the TAX scenario and the higher it is for the RES scenario, although some technology choices may alter this relationship, as is the case for transportation, which lead to an inflexion in the relation between oil products consumption from TIMES_ED(-0.3) and HYBTEP in 2050.

There is no linear relation between HYBTEP results and TIMES elasticities, as price responsiveness varies across sectors and scenarios. In general, HYBTEP depicts less elastic behaviour than TIMES_ED(-0.3), being almost inelastic in some sectors, such as residential, services and other industry for both TAX and RES policy scenarios. For energy intensive industries and transports sectors, under TAX scenario, the hybrid platform results are more close to TIMES_ED(-0.3) and TIMES_ED(-0.1), respectively. While, in RES scenario, in the long term, HYBTEP shows higher levels of energy consumption for these two sectors, illustrating a greater degree of responsiveness, near the end of the modelling period with large subsidies to RES.

Besides the impact of the revenues recycling scheme explained above, in HYBTEP, the sectors are connected through intermediate consumption, and thus, variations in the production price of one sector, also affect domestic demand and other sectors production. In TIMES, with exception of the energy sector (e.g. power or refinery), theses linkages are completed ignored, justifying the different behaviour of the two modelling tools.

### 6.4.2 IMPACT ON GHG EMISSIONS

The changes to energy consumption described above yield congruent effects in GHG emissions as depicted in Figure 6.8. Under the cost-effective CALIB scenario, GHG emissions increase at 0.5% p.a., reaching, in 2050, 2% above 1990 values. For the CPR scenario, both HYBTEP and TIMES define a smooth evolution of GHG emissions, achieving in 2050 a decrease of 11% to 12% of the 1990 emissions, including the outcomes from TIMES_PT and TIMES_ED(-0.5). This reduction of GHG emissions compared to the CALIB scenario is due to the decline of the EU-ETS emissions ceiling and is mostly associated with power production, as RES-E increases in 2050 from 68% under the CALIB scenario to 78% under the CPR for all the modelling tools.

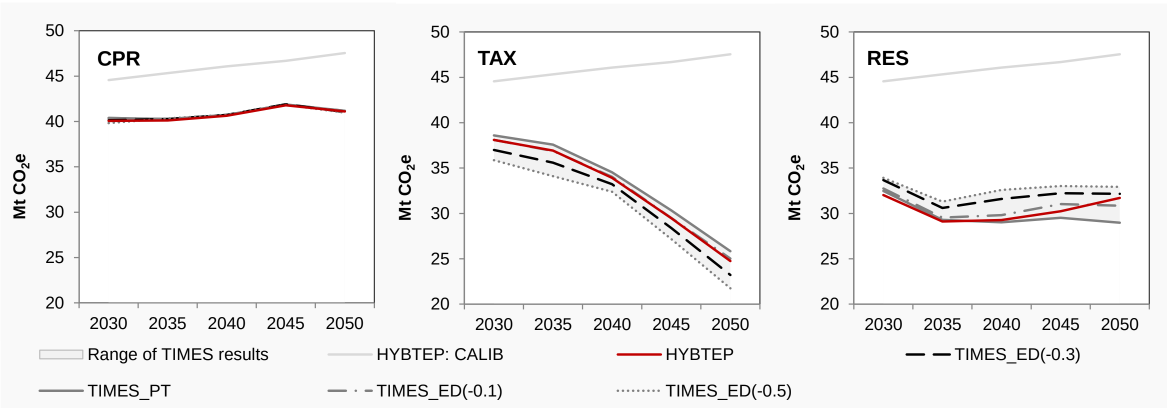


**Figure 6.8** | Total GHG emissions pathway per scenario and modelling tool.

Under the TAX scenario, GHG emissions reduction follows the shift from fossil to renewable energy, with HYBTEP showing, over the entire modelling horizon, higher emissions than TIMES_ED(-0.3). By 2050, the hybrid tool suggests a decrease of 47% in GHG emissions (from 1990 level), while the BU model suggests a 50% reduction, both insufficient to meet the 80% reduction defined by the EU objective. Power production and transports are the principal sectors responsible for this reduction. In 2050, RES-E, mostly supported by hydro, onshore wind and solar PV, represent 88% of total electricity generated for both HYBTEP and TIMES_ED(-0.3), while RES-T (associated with biofuels and electric vehicles) achieves 61% and 65% of the energy demand in transports for HYBTEP and TIMES_ED(-0.3), respectively.

For the RES scenario, the models display a sharp decrease in GHG emissions from 2030 to 2035, due to the decline in natural gas consumption in power and heat production, increasing thereafter. Although the differences between HYBTEP and TIMES_ED(-0.3) emissions are always greater than 5%, by 2050, the two models produce similar reductions in GHG emissions, around -31%/-32% relative to 1990 levels. Again, this reduction in GHG emissions is mostly due an increase in renewable energy in power sector, with renewable energy sources accounting for 97% of electricity generation in 2050 across all modelling tools. Besides the renewable technologies mentioned for the TAX scenario, in the RES, this requires the deployment of offshore wind, wave and concentrated solar power.

The sensitivity analysis for TIMES energy services-price elasticities illustrates that under the TAX scenario, larger elasticities produce larger reductions in GHG emissions, while the opposite occurs for the RES scenario. In the TAX scenario, total emissions in the TIMES model (i.e. TIMES_PT versus TIMES_ED(-0.5)) differ by more than 6% across the entire modelling horizon achieving a maximum difference of 16% in 2050. In this year, and compare to 1990 values, the BU model defines an emissions reduction of 44% and 53%, according to TIMES_PT and TIMES_ED(-0.5), respectively. Besides demand reduction, transports play an important role in carbon mitigation differences as renewable energy represent 61% and 68% of transportation consumption for the TIMES_PT and TIMES_ED(-0.5), respectively.

For the RES scenario, TIMES_ED(-0.5) sets GHG emissions 12% above those of TIMES_PT outcomes after 2040. In 2050, this corresponds to a reduction relative to 1990 levels of 38% by TIMES_PT to 29% according to TIMES_ED(-0.5). These differences are mostly related to demand fluctuations, as no significant differences in terms of renewable energy are observed.

As with total final energy consumption, emissions in the TAX scenario under the HYBTEP modelling platform are very close to those derived from TIMES_ED(-0.1), while for the RES, the hybrid tool exhibits GHG emissions close to the inelastic TIMES_PT, rising after 2040, in the direction of TIMES_ED(-0.3) values due to demand behaviour and technological choices in energy intensive industries and transportation (see Figure 6.7).

### 6.4.3 ECONOMIC IMPACTS

A substantial added value of HYBTEP, relative to the TIMES model, is the ability to compute the economic impacts of the scenarios modelled. Table 6.4 illustrates the economic impacts of the three policy scenarios, reported as a percent change from the CALIB scenario.

Over the medium term (2030), GDP falls by 0.4%, 1.0% and 0.9%, for CPR, TAX and RES scenarios, respectively. Over the long term (2050), and due to the moderate CPR assumptions, GDP losses remain at 0.4%, while the increase in energy costs in the TAX scenario, induces a decrease of 2.4% in GDP. Unlike CPR and TAX scenarios, RES produces an increase in gross value added (GVA), especially for industry (7.7%) and GDP gains of 2.8%.

The mechanisms underlying these results are due to the balance between the financial instrument modelled and the revenue recycling scheme assumed, translated roughly in a balance between energy and labour costs. The introduction of a $CO_2$ tax increases production costs, leading to higher prices and the subsequent reductions to private demand, as observed for the medium term. Nevertheless, because tax revenues are used to reduce employers' social security contributions (reductions of 4.9% in 2050 comparing with CALIB) and thus labour costs, the negative effect of the carbon price on production is offset in 2050, leading to an increase in private consumption (1.1%). The decline in exports by 6.8%, leads to a reduction of production in 2.4%, and thus, the increase of private consumption is satisfied by an increase in imports (1.6%). The results here suggest that the double dividend – a reduction in emissions and an improvement in economic performance – does not materialize.

**Table 6.4**|Economic impacts for 2030 and 2050 modelled by HYBTEP. CALIB values in index (2005=1), remainder scenarios as percentage change from CALIB results.

| | | **2030** | | | | **2050** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Index (2005=1)** | **% change from CALIB** | | | **Index (2005=1)** | **% change from CALIB** | | |
| | | CALIB[a] | CPR | TAX | RES | CALIB[a] | CPR | TAX | RES |
| GDP | | 1.3 | -0.4 | -1.0 | -0.9 | 1.7 | -0.4 | -2.4 | 2.8 |
| GVA | Industry | 1.5 | -0.7 | -0.9 | 0.9 | 2.1 | -0.4 | -1.9 | 7.7 |
| | Services | 1.4 | -0.8 | -0.8 | 0.9 | 2.0 | -0.4 | -2.3 | 4.5 |
| Private Consumption | | 1.3 | -0.4 | -0.6 | -0.4 | 1.9 | -0.2 | 1.1 | 1.3 |
| Production | | 1.2 | -0.3 | -1.0 | -1.1 | 1.4 | -0.3 | -2.4 | 2.9 |
| Domestic demand | | 1.2 | -0.2 | -0.3 | 0.0 | 1.7 | -0.2 | -0.5 | 2.7 |
| Exports | | 1.2 | -0.5 | -2.3 | -2.9 | 3.6 | -0.8 | -6.8 | 7.7 |
| Imports | | 1.2 | -0.2 | -0.4 | -0.7 | 1.5 | -0.2 | 1.6 | 2.5 |
| Agriculture | Production | 1.3 | -0.2 | -0.5 | -0.2 | 1.7 | 0.0 | -0.4 | 4.5 |
| | Domestic demand | 1.2 | 0.4 | -0.5 | 3.8 | 1.7 | 0.0 | 1.3 | 9.9 |
| | Exports | 2.7 | 0.3 | -0.8 | -0.3 | 3.6 | 0.1 | -3.3 | -0.3 |
| | Imports | 1.1 | 0.3 | -0.3 | 3.4 | 1.5 | 0.0 | 1.5 | 8.9 |
| | Production | 1.2 | -0.2 | -0.4 | -0.3 | 1.6 | -0.2 | -0.9 | 0.4 |
| Service | Domestic demand | 1.2 | -0.3 | -0.5 | -0.3 | 1.6 | -0.2 | -1.0 | 0.6 |
| | Exports | 1.4 | 0.6 | 0.4 | -1.0 | 1.7 | 0.3 | 1.1 | -3.0 |
| | Imports | 1.4 | -0.6 | -0.7 | 0.1 | 2.0 | -0.4 | -1.4 | 2.0 |
| Industry | Production | 1.3 | -0.6 | -1.4 | -1.7 | 1.7 | -0.5 | -2.4 | 7.2 |
| | Domestic demand | 1.3 | -0.3 | -0.4 | -0.2 | 1.8 | -0.2 | 1.2 | 4.3 |
| | Exports | 1.2 | -1.0 | -3.0 | -4.1 | 1.6 | -1.1 | -7.5 | 13.3 |
| | Imports | 1.3 | -0.2 | 0.0 | 0.2 | 1.8 | -0.1 | 4.6 | 4.0 |
| Transports | Production | 1.2 | -0.2 | -0.8 | -1.0 | 1.6 | -0.4 | -5.6 | -5.0 |
| | Domestic demand | 1.2 | -0.5 | -0.9 | -0.7 | 1.7 | -0.6 | -5.8 | -2.6 |
| | Exports | 1.3 | 0.4 | -0.5 | -1.9 | 1.6 | 0.0 | -5.4 | -10.6 |
| | Imports | 1.4 | -1.0 | -1.2 | -0.3 | 2.0 | -1.1 | -6.6 | -0.3 |

[a]The economic drivers of CALIB scenario are the resultant from iteration 3, described on section 6.3.1., which originated TIMES_PT demand.

Government support for renewable energy (RES scenario) contributes, on one hand, to a reduction in production costs as a result of lower energy costs. On the other hand, the increase in the social security tax rate by 8.5% in 2050, needed to finance the renewable energy subsidy, leads to an increase in production costs. The net effect is a negative impact in both GDP and private consumption in the medium term, but a positive effect in 2050. The results indicate that in the long term the RES support will induce an increase in domestic production (2.7%) and exports (7.7%). Thus, the absence of a double dividend under the TAX scenario suggests that distortions in energy markets in Portugal are more severe than in labour markets. The corollary then is that a reduction in energy costs financed by an increase in social security contributions can have a positive impact on GDP over the long run.

HYTEP allows for the study of the mechanism behind the sector impacts of policies. Under a TAX scenario, over the long term, domestic demand for transportation and services drives the reduction in output. Although, domestic demand in both industry and agriculture increase, the decrease in exports offsets the possible rise of the sectors production. Under RES in 2050, almost all the sectors see an increase in production, with the exception of transports, for which the energy structure is more costly than CALIB even with a RES subsidy[32]. For industry, the production increase is mainly a result of exports growth (13%), while for services and agriculture is the domestic demand that gives rise to the increase in output.

The impact of the policy scenarios on the economy can also influence energy system indicators which are commonly used by policy makers to assess, for example, energy efficiency in each sector of economic activity. In some cases, the behaviour of the HYBTEP platform versus TIMES in terms of energy consumption is not reflected in energy intensity (Figure 6.9), due to differences in economic development. Under TAX scenario, for example, HYBTEP defines an energy consumption for transports above TIMES_ED(-0.3) values, i.e., between TIMES_ED(-0.1) and TIMES_PT outcomes. However, the reduction of GDP computed by HYBTEP makes the sector's energy intensity higher than the ones resulting from the BU model, which assumes no changes in the macroeconomic drivers. In RES scenario, the energy consumption in services computed by HYBTEP is similar to the inelastic TIMES_PT. Yet, due to the increase in GVA of services reported by HYBTEP, the hybrid tool defines an energy intensity lower than the one calculated trough TIMES results.

[32] It should be underline that TIMES optimizes the energy system as a whole, this means that even in the presence of a subsidy, and although globally the total energy system costs are lower, some sectors can experience higher costs due to different technology choices in others, which can originate cheap resources depletion. In the case of transports this is associated with the increase of biomass price, which is used to produce second generation of liquid biofuels.

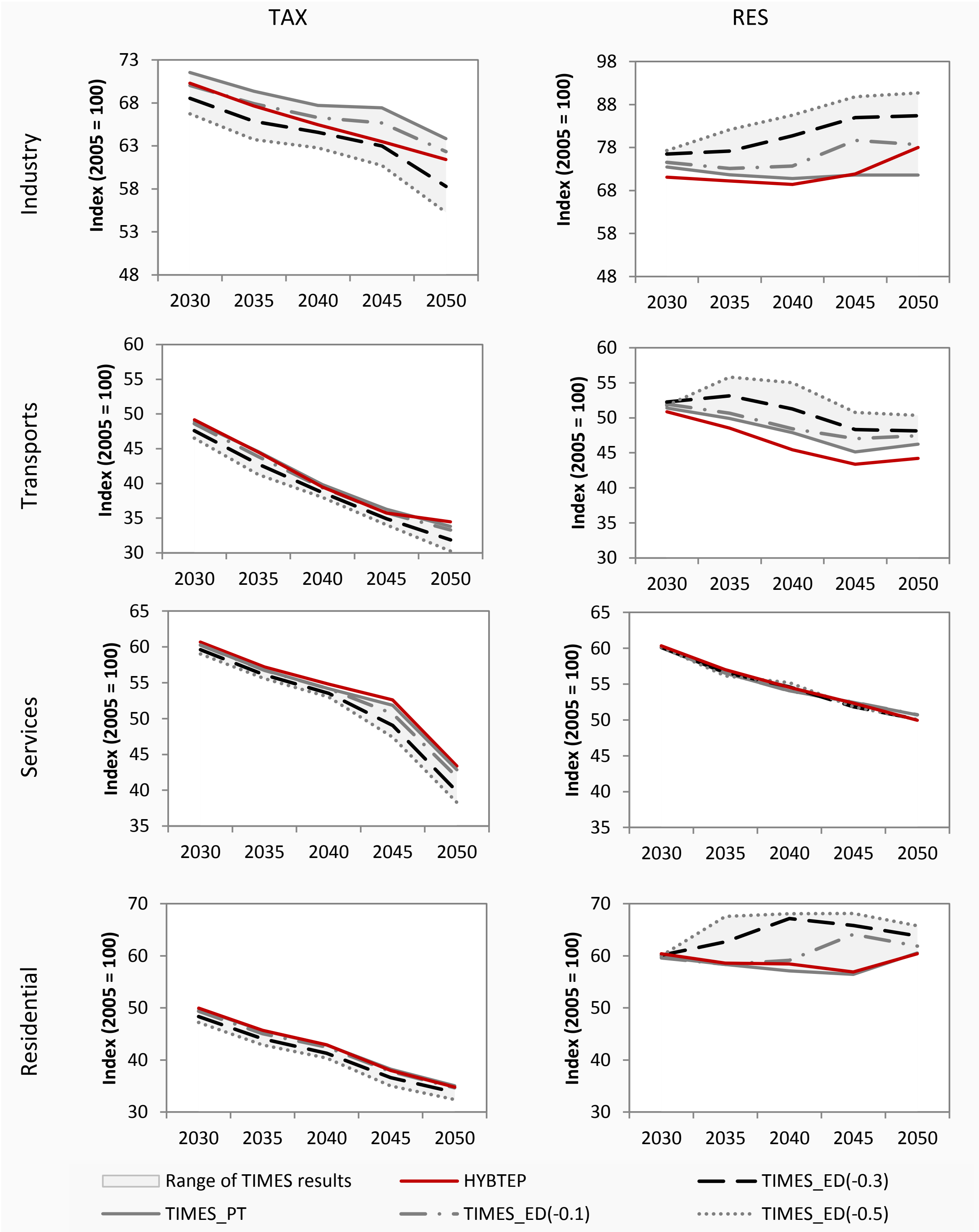


**Figure 6.9** | Sector energy intensity pathway per modelling tool under TAX and RES scenarios, measured as: Industry (energy consumption/GVA), services: (energy consumption/GVA) Transports (energy consumption/GDP), residential (energy consumption/private consumption).

The most significant difference between HYBTEP and TIMES sector's energy intensity pathway is associated with industry. For the hybrid platform, under TAX scenario, industry energy intensity follows a linear decrease path; whereas, TIMES defines a more pronounced decline after 2045. Under RES scenario and according to TIMES, in the long term industry's energy intensity stabilizes or experiences a smooth decrease, while HYBTEP sets after 2040, an increases of the sector energy intensity. These differences are mostly justified by the divergences on the sector production/energy service demand, which in its turn induce changes in the energy choices.

The sensitivity analysis with respect to TIMES energy service-price elasticities shows uncertainty in the energy intensity of some sectors. For instance, in the residential sector under the RES scenario, TIMES_ED(-0.5) sets an increase in energy intensity through 2035 declining thereafter. For TIMES_ED(-0.3), this decline occurs only after 2040 and for TIMES_ED(-0.1) after 2045. The energy intensity specified by TIMES_PT falls from 2030 through 2045, rising thereafter, describing a path equal to HYBTEP. The RES scenario similarly produces varied industry energy intensities. TIMES_ED(-0.5) and TIMES_ED(-0.3) exhibits an increase of energy intensity in the beginning of the time horizon, while for TIMES_ED(-0.1) and TIMES_PT this occurs only after 2040.

## 6.5 CONCLUDING REMARKS

Traditionally, CGE and BU models have not allowed for an integrated assessment of climate and energy policy instruments with a detailed technology profile for the energy sector and macroeconomic feedbacks and impacts, both of which are essential metrics for policy makers. This paper describes a method of soft-linking 'full-form', multi-sector BU and CGE models, resulting in an integrated modelling platform - HYBTEP. Since the main structure of each model is maintained, HYBTEP accommodates an extensive group of technologies and economic responses, allowing for the analysis of the economic, technological and environmental impact of energy and climate policies.

In HYBTEP, energy prices and consumption are included in a comprehensive economic context, and accordingly changes in the energy sector affect factor demand, intermediate demand, output and private consumption, as well as the trade balance and government revenues. This economic framework allows us to examine the mechanisms driving changes in demand, namely those associated with the changes in domestic production, making the analysis more transparent. The detail of HYBTEP allows us to evaluate the impact of energy and climate policy on specific sectors, instead of aggregate macroeconomic variables.

To assess the advantages of HYBTEP relative to the traditional BU approach (including the response to prices change through energy service price-elasticities), we compared the outcomes of three policy scenarios representing the current Portuguese energy and climate policy and additional policy instruments for GHG mitigation and an increase in renewable energy.

The application for Portugal indicates some important differences between the modelling tools, mostly related to the impact of the policy scenarios on energy system costs and thus on demand for energy services, which in turn affects energy consumption, GHG emissions and economic output. As the deployment of technologies may differ across policy scenarios, sectors and years, the implied price and energy system structures are not constant. As a result, it is not possible to specify a general relationship between HYTBEP and TIMES energy service-price elasticities. TIMES energy demand reductions are only affected by its elasticities and endogenously determined energy prices. Energy consumption and GHG emissions can change substantially according to the energy service elasticity considered. The uncertainty surrounding the elasticity parameters, due to the lack of national studies, can thus lead to uncertainty in the model results.

Naturally, the HYBTEP results presented here have some limitations, mainly inherited from each of the two models being linked. The hybrid platform assumes perfect competitive markets, except labour and considers the optimism of TIMES model over future technologies and its deployment, which can result in a lower bound of the macroeconomic impacts of energy and climate policy scenarios. In HYBTEP although the differences between the technologies (in terms of technical and cost data) are considered through an extensive and detailed technological database strengthen the energy system, the required labour and intermediate material input are represented in an abstract way sustain by historical substitution elasticities. Thus, further work will be developed to allocate the non-energy inputs (materials) per sector and the wages and salaries paid to employees (labour) to the cost of power sector technologies.

Despite these limitations, and this is the main point of this paper, our results illustrate that the HYBTEP platform has advantages compared to independent use of conventional BU and TD models, in the development and analysis of energy and climate policy scenarios. These advantages stem from the integration of the strengths of a detailed technology model, namely the identification of mitigation technologies, with those from an economic tool, namely the impact of these policies on macroeconomic drivers. A major conclusion concerns the increase of transparency of modelling outcomes achieved with the HYBTEP platform, since the economic framework allows us to understand the mechanisms driving the evolution of energy demand while taking into account the cost-effective energy profile from a technological model, which results in a higher confidence for decision making. Although the present methodology and results are directly relevant for policy making in Portugal, the concerns about energy-environment policies and economic growth are in the forefront of the policy discussion in several countries, for which HYBTEP soft-link methodology can be replicated to support policy decisions.

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# CHAPTER 7

## CONCLUSIONS AND FURTHER DEVELOPMENTS

*The purpose of computing is insight, not numbers*

*Richard Wesley Hamming (1962)*

The research conducted under this dissertation aimed to advance on energy-environment-economy modelling and energy and greenhouse gas (GHG) emissions scenarios development, to better support energy and climate policy decisions. Using Portugal as a case study, alternative mitigation futures were explored. Thus, the contributions of this research comprised both methodological advancements in scenarios development, as well as an empirical understanding of how to enable a low carbon transition for the Portuguese energy system, as follows:

I. Provide one approach to link socio-economic storylines developed by stakeholders from different knowledge fields with energy modelling, which can be applied in further scenario exercises to tackle the uncertainty associated with modelling assumptions and increase the coherence and robustness of modelling exercises;

II. Present a comprehensive economic and technological hybrid model for Portugal (HYBTEP), which involves the full macroeconomic feedback assessed by the computable general equilibrium (CGE) GEM-E3_PT over the range of energy choices of the entire energy system from the bottom-up (BU) TIMES_PT. The HYBTEP building methodology was clearly formulated, allowing its replication to other CGE and BU models and regions;

III. Provide major findings for the Portuguese energy-climate policy decisions for the long-term, namely regarding the role of technology and the impact of different policy instruments in economy, which can contribute to national decision-making process.

This section presents the major findings for each of research questions addressed in this thesis, in addition to a general discussion of the results for Portugal and a proposal for a future research agenda.

## 7.1 ANSWERS TO THE METHODOLOGICAL RESEARCH QUESTIONS

*A. WHAT IS THE ROLE OF EXOGENOUS MODELLING ASSUMPTIONS (E.G. ENERGY PRICES, TECHNOLOGICAL DEVELOPMENT, SOCIO-ECONOMIC GROWTH, ENERGY RESOURCE AVAILABILITY) ON POLICY RELATED OUTCOMES? WHICH ARE THE MOST SIGNIFICANT ONES THAT SHOULD BE ASSESSED IN GREATER DETAIL?*

Energy-economic-environment models are frequently used to generate GHG emissions and energy scenarios and support policy-makers' decisions. These models require a set of exogenous assumptions, which affect the overall degree of uncertainty of each scenario. It is common practice to model sets of alternative scenarios, representing different sets of assumptions combined as interesting pathways (Riahi et al., 2007). Each pathway combines two or more sets of exogenous assumptions, resulting in a set of outcomes. Usually, only a very limited number of assumptions are analysed in terms of its impact on the results (e.g. trough sensitivity analysis) due to limited time and resources. Chapter 2 addresses this issue by assessing the contribution of a large set of exogenous parameters, used in policy support process, namely: penetration of end-use energy efficient equipment; socio-economic growth rates; rate of implementation of policy incentives & investments for promotion of renewable electricity; availability of water resources for hydropower; and primary fossil energy import prices. Through the use of TIMES_PT model, it is concluded that the most relevant assumptions for overall GHG variations were those related to socio-economic growth and technology, represented by the penetration of end-use energy efficient equipment. These assumptions have a greater impact (variations of more than 7% of a Baseline) on GHG emissions, than fossil fuel prices and the availability of renewable energy resources, which did no present relevant impact on the final results through 2020 (less than 2% of a Baseline). These outcomes are contrary to what is commonly perceived by policy makers, judging by the large number of scenarios that include a more detailed analysis of oil and natural gas prices parameter (see (van Ruijven and van Vuuren, 2009) for an overview of these studies). The assessment shows that a higher GDP growth (0.7% in the annual growth rate between 2005 and 2020) induces GHG emissions rise of around 7% (compared to Baseline); while a severe increase of fossil import prices (72% for oil and gas and 40% for coal in 2020) only reduce GHG emissions in 0.3%.

Following the conclusions of Chapter 2, regarding the importance of technological changes on GHG emissions scenarios, in Chapter 3 an exploratory analysis was developed to better understand the role of technology for Portugal to achieve a reduction of 80% of its energy related GHG emissions by 2050, compared with 1990 levels. Thus, two alternative scenarios of technological development were considered: a conservative scenario, assuming that the prospects on technical and economic data will remain constant from 2015-2020 onwards and an optimistic scenario assuming a technology evolution, in terms of increasing efficiency and decreasing costs, in line to what is set in the literature. Results showed that it is feasible to decarbonise the Portuguese energy system satisfying at the same time the national energy services/materials and mobility demand. The only exception refers to clinker, which could not be produced nationally by 2050, in a scenario that does not incorporate technological advances, in particular the availability of carbon capture and storage (CCS). This result corroborates the fact that CCS is essential to reduce $CO_2$ emissions in cement sector. In fact, by 2050, CCS accounts for more than 50% of GHG emissions reduction in cement sector at global level to achieve a global warming below the 4 °C (IEA, 2012a). Other conditionally relevant emerging technologies are electricity generated from waves and hydrogen trucks, which are only deployed in 2050 in the technology evolution scenario. Especially for the case of waves, this conclusion is significant as national stakeholders consider it as a driver to decarbonise the energy system and to foster the Portuguese economic growth (seen in Chapter 5) – "the wave pilot experience in S. Pedro de Moel was a lever for the promotion of an industrial cluster related to sea activities in Portugal and the acquisition of strong competences in the production of energy from the sea waves was translated into international acknowledgement of the country as one of the world ocean energy center of excellence, namely in wave".

Chapter 3 also highlighted that electric mobility is highly associated with the evolution of technology. Even in a Baseline scenario, with GHG emission in 2050 38% higher than in 1990, electric and plug-in vehicles may represent a relevant technology if an optimistic development is assumed, namely the decline of costs over time (-19% in 2030/2010; -31%2050/2010). In general, Portugal is a price taker of energy technologies. Therefore, scenario analysis considering a wide set of technical and costs assumptions are crucial to decide if and whether to subsidize non-mature technologies, to speed up its cost-effectiveness. It should be noted that Portugal has made large investment in promoting electric vehicles throughout the implementation of a charging network with more than 1 300 stations all around the country (MOBI.E, 2012), in addition to a consumer incentive for electric vehicles acquisition (e.g. exempt from vehicle tax).

Thus, the role of non-mature technologies, for which there are large uncertainties in the future concerning costs and technical development, such as wave based power, electric vehicles or carbon capture technologies should be analysed in greater detail, not only through a cost-effectiveness analysis, as developed in this dissertation, but also through a cost-benefit evaluation. The results presented in Chapter 2 and 3 should also be understood under the framework of a technological optimization model as TIMES_PT, which is only driven by cost-effectiveness criteria, neglecting for example the historical microeconomic behaviour of the economic agents.

*B. To what extent different model structures and characteristics (e.g. technological bottom-up versus economic top-down), lead to different GHG reduction strategies and climate policy recommendations, even when calibrated to a common baseline scenario?*

The relevance of the modelling tool used to support the design of national energy-climate policies was assessed, in Chapter 4, by evaluating the mitigation options generated by the bottom-up TIMES_PT and the computable general equilibrium model GEM-E3_PT, under the same climate policy regime. To guarantee that possible model differences were associated with their features and not just a consequence of divergent baselines, the two models were benchmarked within a common baseline scenario in the absence of energy and climate policies. The models harmonization included assumptions about energy consumption and emissions, plus other exogenous factors (e.g. GDP, population, and energy import prices).

Results showed that, for moderate GHG emissions mitigation (e.g. linear reduction from 2015 of GHG emissions up to -20% in 2050/1990), the models yielded close results regarding sector abatement, suggesting that energy supply has the largest national mitigation potential (e.g. -76% of GHG emissions in 2050 comparing with a baseline scenario according to GEM-E3_PT and -82% set by TIMES_PT). However, as the stringency of the cap was increased, the abatement effort and the strategy required to reduce emissions increasingly diverged. Under a -60% emissions reduction scenario (in 2050/1990), TIMES_PT had set a very significant reduction in transports emissions (-87% compared to a baseline) due to a shift to biofuels and electricity based technologies, while GEM-E3_PT did not went below the -67% due to its substitution elasticities based on historical values. Thus, to achieve the global cap this model had set a higher reduction effort in industry compared with the BU model (-79% in 2050 vis-à-vis -56%). By allocating significant emissions reductions in one sector rather than another, the models indicate where the cost-effective mitigation policy opportunities are, which might influence policy decision, e.g. the potential for emissions trading, and in this exercise, we show that different models may produce different insights.

The main drivers responsible for GHG emissions and for their abatement, computed by each modelling tool, were analysed through a modified Kaya identity. The analysis revealed that the main strategy in TIMES_PT to reduce GHG emissions was to decarbonise the power sector through renewable-based technologies, and to shift the energy consumption of end-use sectors to electricity. For GEM-E3_PT, the strategy to reduce end-use sector emissions relied mainly on energy savings, which was also reflected in the decline of electricity production.

The different outcomes of each model suggested different mitigation strategies, which may have crucial impact on the climate policy design. In fact, TIMES_PT model revealed that the most cost-effective solution was the adoption of low carbon technologies, which are typically promoted by carbon taxes, financial incentives, or regulations, whereas GEM-E3_PT showed that demand side energy efficiency policies are more relevant, for example through efficiency standards and incentives. These results indicate that policy makers should take carefully the insights from different modelling tools to support their policies, once their specific structures make them more appropriate to address certain policy questions than others. Thus, using both modelling approaches in an integrated framework has advantages and robustness to energy-climate policy design. This feature was accomplished in Chapter 6.

*C. HOW CAN QUALITATIVE VISIONS OF STAKEHOLDERS FROM DIFFERENT FIELDS BE INTEGRATED IN A MODELLING FRAMEWORK TO OBTAIN A HYBRID COMBINATION OF SOCIO-ECONOMIC STORYLINES AND ENERGY MODELLING OUTCOMES?*

Qualitative scenarios embody the visions and beliefs of different stakeholders/experts and generally focus on describing expected social, political and cultural developments (Söderholm et al., 2011), which, ultimately, have influence on energy and GHG emissions. However, most of the energy and GHG emissions scenarios exercises (Clarke et al., 2009; EC, 2011b; IEA, 2012) present great technical details, but neglect the entire interaction between social, economic and technological factors, which represent a major limitation for its understanding. For example, the GDP growth is associated with a specific structure of the economy and society, such as the economic profile (e.g., energy intensive industries versus energy extensive services) or the social behaviour (e.g., higher or lower demand for energy services and tendency to choose more advance cost-effective technologies or mature equipment). Both have significant impact on the entire energy system, but generally only the first aspect is considered. Following the conclusions of Chapter 2, indicating socio-economic development as one of the main uncertainties in scenarios assumptions, Chapter 5 presented a participatory process, to build storylines regarding the Portuguese socio-economic evolution up to 2050 and demonstrated how these qualitative visions might be linked within a comprehensive framework with energy modelling.

This process was divided in three distinct phases that differ with respect to their objectives. The first phase was dedicated to the development of qualitative socio-economic scenarios for Portugal, holding several workshops with national stakeholders including business managers, university professors, policy makers and national experts in the fields of economics, energy, design, science, environment, and foresight, among others. From this process emerged two national divergent storylines, one describing Portugal incapable of making significant structural changes and inserted into a World of international instability, and other considering that Portugal develops in a world in expansion, investing in major structural changes and managing to participate in the new technological and innovation waves, which is reflected in this dynamic economy.

A second phase comprised the transformation of the storylines into input parameters usable in energy modelling. Selected aspects of the storylines were quantified in socio-economic indicators, based on national studies and supported by experts' best guess. Also, aspects of the storylines were translated into additional assumptions, namely energy-climate policy constraints, technology improvements, and energy resources prices and availability. Although the two storylines have highlighted aspects of national energy system, such as energy sources, the increase of energy efficiency or the decrease of energy dependence, those were not transformed into quantitative indicators, in order to leave the TIMES_PT model "free" to define the most cost-effective technologies and energy carriers per scenario. This "translation process" indicated clearly the coherent context for modelling assumptions allowing better reasoning, which is most valued for the decision-making process. This aspect can represent a meaningful advance to other modelling exercises (Usher and Strachan, 2013)

A third phase involved a comparative analysis between qualitative visions of national stakeholders and the quantitative energy and GHG emissions scenarios generated by TIMES_PT, regarding the national energy system profile, aiming to assess the strengths and weakness of both approaches. Major findings revealed that the two methods presented similarities: i) a scenario where efficiency plays an important role, although associated with an energy system that is still dependent of fossil fuels due to transport and a power sector where emergent renewable sources do not succeed, and; ii) a scenario were power sector is mainly sustained by emergent renewable energy sources, with electric vehicles as a key technology in transport sector, and the prevalence of solar in buildings. The main divergent aspects relates with the role of specific technologies (e.g. micro-production), where the cost-effective criteria from the modelling tool did not match the expectations of national stakeholders. These contradicting expectations should thus be analysed with additional care for policy decision.

By joining different communities within a common framework this approach increased the scenarios coherence and its adequacy to support decision making as the common visions corroborated aspects that justified higher policy support

D. *HOW CAN TECHNOLOGY BOTTOM-UP AND ECONOMIC TOP-DOWN APPROACHES BE INTEGRATED IN A HYBRID MODELLING PLATFORM COMBINING EXTENSIVE TECHNOLOGY DETAIL WITH ECONOMIC SECTOR DISAGGREGATION? WHAT ARE THE ADVANTAGES OF SUCH MODELLING TOOL FOR POLICY ANALYSIS?*

The integration of bottom-up and top-down approaches was described in Chapter 6, where HYBTEP – hybrid technological economic platform – was fully presented. HYBTEP is a modelling tool built through the soft-link between the bottom-up model TIMES_PT and the computable general equilibrium (CGE) GEM-E3_PT. HYBTEP assumes that the configuration of the energy system and the evolution of energy costs is computed by TIMES_PT and exogenously assumed by GEM-E3_PT. In its turn the CGE model reflects the macroeconomic feedback of the changes in the energy system, defining the configuration of the national economic structure, which drives the energy services demand that feeds TIMES_PT. The two models are solved independently and in sequence, reconciling the equilibrium of energy sector profile and energy system costs. Thus, in HYBTEP, the energy prices and consumption are included in a comprehensive economic context, and accordingly, changes in the energy sector affect factor demand, intermediate demand, output and private consumption, as well as the trade balance and government revenues.

Despite the existence of other hybrid models, there are few examples employing: i) a 'full-link' (i.e., not restraining the analysis to one sector only) and thereby lacking to get a full macroeconomic feedback of different energy systems profiles and ii) 'full-form' BU and TD approaches, i.e., combine extensive technology data (and not just few power sector technologies) with disaggregated economic structure. This last capability enables HYBTEP to evaluate the impact of energy and climate policy on specific sectors, instead of aggregate macroeconomic variables, as is usually analysed with hybrid macro-bottom-up models. To evaluate the value added of HYBTEP compared with standard bottom-up models[33], the outcomes from the hybrid platform for three policy scenarios (current policy regulation, increasing $CO_2$ tax and increasing renewable energy subsidy) were compared with TIMES_PT results. To reflect adjustments in demand in function of the energy prices in counterfactual scenarios, TIMES_PT was run assuming a range of exogenous energy services demand elasticities. Results showed that a $CO_2$ tax, in line to what is set in by the EU energy Roadmap (around 350€$_{2008}$/t$CO_2$ in 2050) induced, according to HYBTEP, a GHG emissions reduction of 47% by 2050 (from 1990 level). According to TIMES_PT, the same tax may represent a reduction of GHG emissions ranging from -44% to -53%, without price elasticities and with a high price elasticity of -0.5, respectively. According to HYBTEP, an increasing monetary renewable incentive

[33] We considered that the use of energy and GHG emissions scenarios to support of climate and energy policy decisions should present insights about the technological transitions. Standard computable general equilibrium models do not fulfill this requirement and thus they were not considered in this comparative analysis.

(i.e., 191 €$_{2008}$/MWh in 2050 – half of the RES-value of High RES scenario of EU Energy Roadmap) leads to a reduction of GHG emissions in -37%, while TIMES_PT defined a range of results from -38% to -29%. This analysis illustrated two important aspects:

i. The uncertainty surrounding the elasticity parameters of TIMES_PT and its impact on the modelling outcomes. Note that good estimates of energy services price-elasticities are rare, as the econometric literature focuses mostly on energy demand (Duerinck and Van Regemorter, 2011). In fact, to the best of our knowledge there are no national studies regarding energy services-prices elasticities, which increases the uncertainty of the model results.

ii. More important, the economic framework of HYBTEP allows us to examine the mechanisms driving changes in demand, namely those associated with the changes in domestic production. The reduction of GHG emissions under the $CO_2$ tax for example, is due to the balance between this policy instrument and the revenue recycling scheme assumed, translated roughly in a balance between energy and labour costs. The introduction of a $CO_2$ tax increases energy costs, leading to higher purchase prices. However, because tax revenues are used to reduce employers' social security contributions and thus labour costs, the negative effect of the carbon price on production is offset, leading to an increase of private consumption (1.1%). In the long term, domestic demand for transportation and services drives the reduction in output and although, domestic demand in both industry and agriculture increase, the decrease in exports offsets the possible rise of the sectors production.

The results from HYBTEP make the of climate and energy analysis more clear and consistent than simpler exogenous energy services-prices elasticities. Naturally, HYBTEP presents some limitations associated with GEM-E3_PT and TIMES_PT and that should be underlined, namely, it assumes perfect competitive markets, except for labour and it considers the technological adoption of TIMES model over future, which may result in a lower bound of the macroeconomic impacts of energy and climate policy scenarios.

## 7.2 INSIGHTS FOR PORTUGAL

The EU has already endorsed climate and energy policy goals to comply with a global objective to keep Earth's temperature below 2 °C rise (EC, 2011a). Some EU member states as UK and Germany have defined national climate change mitigation goals setting similar mitigations targets for 2050 of 80% reduction, compared with 1990 (HMG (Her Majesty's Government), 2008; Federal Government, 2010). In Portugal, although some national studies have been developed namely the national Low Carbon Roadmap (Seixas et al., 2012) which assessed a total GHG emission reduction of around 50% and 60% (equivalent to 60% and 70% for the energy system), no official position has already been set regarding long-term climate mitigation. During the first months of 2014, national policy and decision makers have been discussing the Portuguese goals up to 2030 within the Portuguese National Climate Change Programme.

A long set of scenarios covering different options for energy and climate policies, technology deployment and economic development have been described and quantified in the previous chapters. Even though, the particular characteristics of each scenario lead to different configurations of the energy system, overall insights on energy technology and climate mitigation options can be outlined, contributing to the ongoing national debate. This section and the Tables 7.A and 7.B in Appendix 7.5 summarize the major findings, addressing the questions raised in Section 1.4.

*TO WHAT EXTENT CAN PORTUGAL REDUCE ITS ENERGY RELATED GHG EMISSIONS AND WHAT ARE THE ASSOCIATED ECONOMIC IMPACTS?*

Results show that it is technological feasible to reduce the national GHG emissions of the energy system up to 80% below the 1990 baseline in 2050 (CAP_TE scenario). Even under a pessimistic technological progress pathway (CAP_TF) this target can be achieved. Under an optimistic technological development in line to what is projected in the literature (e.g. lower costs and higher efficiencies for non-mature technologies like electric vehicles or solar CSP) the transition of the energy system from a reference scenario (corresponding to +38% of GHG emissions relative to 1990) to a low carbon path represents a maximum increase of the total energy system costs of 2%, equivalent to 0.3% of GDP during the period 2010-2050.

However, a $CO_2$ tax to achieve the 80% EU-wide 2050 GHG emissions reduction target (EC, 2011b), represents for Portugal a decline of its emissions only around -47% in 2050 (TAX) (-40% when compared with a scenario assuming the extension of the current regulation (CPR)). The government may use the tax revenues to reduce pre-existing tax distortions in the labour market and thus reduce the labour cost which can partially offset the increase of energy costs in production. Compared to the extension of the current regulation that Portugal is subject (CPR), this $CO_2$ tax (TAX) represents a GDP loss of about 2% (-2.4% with regard to a non-policy scenario (CALIB)), associated mostly with a severe decrease of exports.

National policy makers need however to choose wisely the policy instrument to decarbonise the energy system. A subsidy to promote the consumption of renewable energy (RES) might have a long-term positive impact at both environmental and economic level. A renewable support scheme of half what is defined by the EU Energy Roadmap (EC, 2011b) in 2050 lead to a reduction of the national emissions of -32% in 2050 and at the same time an increase of the national GDP and households consumption of 2.8% and 1.3%, respectively, when comparing with a non-policy scenario (CALIB). However, in the medium-term the same type of instrument, although with a different monetary value (around 78 $€_{08}$/MWh), resulted in a reduction of GDP in 2030 of 0.9%. The mechanisms underlying these results are due to the balance between the policy instrument and the revenue recycling scheme assumed, translated roughly in a balance between energy and labour costs (in this dissertation). Other revenue recycling schemes, namely lump-sum income transfers to households, should also be analysed in order to explore its implications in the Portuguese economy and energy system. In fact, although some studies, such as from EPA (2010) found that recycling revenues through labour tax cuts, rather than lump sum payments to increase household welfare can reduce longer-term negative impacts on economic growth, a national study assessing the impact of Portuguese 2020 energy-climate policy targets revealed the opposite (Proença. 2013).

*WHAT ARE MOST COST-EFFECTIVE TECHNOLOGIES THAT PORTUGAL SHOULD PROMOTE AND UP WHAT POINT CAN PORTUGAL ENHANCE ITS ENERGY EFFICIENCY AND RENEWABLE ENERGY CONSUMPTION?*

Whatever the mitigation goal, renewable energy (RES) resources have an important role in the Portuguese power production, with minimum of 57% and 68% in 2030 and 2050, respectively (BASE_TF), vis-à-vis 48% as today (DGEG, 2013b). A transition to a low carbon economy implies a conversion to a renewable-based electricity, which can achieve values beyond 85% electricity generated from RES by 2050 under a GHG emission reduction of at least -70% from 1990 levels (NF, CAP_TF, CAP_TE) or a $CO_2$ tax of around 370$€_{2008}$/t (TAX). This means that important intermittency issues may arise which will need to be analysed by Portuguese policy-makers and utilities. Hydro, wind onshore and solar photovoltaic (PV) are the most cost-effective technologies, while wind offshore, wave and concentrated solar power (CSP) are complementary to achieve aggressive mitigation targets. Within this dissertation CCS is not a relevant cost-effective alternative for the

Portuguese power sector (see Chapters 3 and 5), although it might be considered a necessary option for industry, namely for the cement sector.

Under a stringent GHG emission cap or tax, renewable electricity and bioenergy are decisive for transport sector, reaching values of 60% or more (CAP_TF, CAP_CAP_TE, NF and TAX). Electric mobility via electric or electric plug-in vehicles are cost-effective options capable of satisfying for example more than half of light-duty road mobility (Chapter 3), while biofuels consumption can be five times higher than today in 2050.

Due to the limited potential of the national bioenergy resources (see Chapter 3.6) the increasing consumption of this energy resource may signify a shift of paradigm from oil import to bioenergy import. This underlines the relevance of accurately assessing the national renewable potentials, which are generally associated with a large uncertainty, particularly biomass due to the "competition" between energy and food.

The decarbonisation of the Portuguese economy is also associated with an electrification of buildings and the deployment of solar thermal and more efficient measures and equipment as insulation and heat pumps. Energy efficiency roughly measured as the reduction of final energy intensity can vary from -1.3%pa to -3.0% p.a., trough 2050 continuing the trend of the past years (i.e. 2.6% p.a. in average from 2005 to 2012 (DGEG, 2013a)).

*ARE THE NATIONAL POLICY GOALS SUPPORTED THROUGH EU MODELS AND ASSUMPTIONS IN LINE WITH THE NATIONAL POTENTIAL?*

Looking to the Reference Scenario provided by the PRIMES model under the study (EC, 2013b), there is some optimism about the national Portuguese potential to reduce its GHG emissions and to generate renewable electricity, which in its turn affects the gross final consumption of renewable energy. According to the study, Portugal can reduce its GHG emissions around -17% by 2050 compared to 1990 values, assuming a moderate economic growth (1.2%p.a. between 2010 and 2030, and 1.4%p.a. onwards). This reduction is mainly sustained by the power sector, with 97% of renewable production in 2050. Considering all the scenarios studied along this dissertation, this level of renewable electricity is only achieved when a strict GHG emission cap (i.e. -80%) or a high RES subsidy (RES scenario) is considered. Obviously the cost curves of the power generation technologies are a decisive driver for these outcomes, and during the thesis period significant updates of the TIMES_PT technology database occurred following updated literature (e.g. solar PV). Nonetheless, even considering that PRIMES technology data is probably different from the ones used in this dissertation, it still seems quite optimistic for example that solar reaches 1 051 MW in

2015, when currently (2013) only 278 MW are installed (DGEG, 2013b) and when the Renewable Energy Action Plan (NREAP) (RCM 20/2013) defines 417 MW and 720 MW for 2015 and 2020, respectively. These divergences between EU and national projections should be taken into account in the pos-2020 negotiations. Although policy makers require specific answers, the analytical outputs from the models are just designed to produce insights (Huntington et al., 1982). Modelling per se do not drive climate or energy policy, nor decide the political feasibility of achieve specific targets. Instead it offers structured insights into key uncertainties (Strachan et al., 2009).

Concerning the role of renewable energy on transports and energy efficiency measure stated as a reduction energy intensity, EU perspectives are in line or even more conservative to what is achieved by the scenarios generated along our research, namely by assuming 13% consumption of renewable energy consumption in transport sector, and a reduction of final energy intensity of around 1.2%p.a. during the period 2010-2050 (EC, 2013b).

## 7.3 FURTHER DEVELOPMENTS

The research work in this dissertation focused in the development of a technological-economic hybrid platform and in a process to link qualitative storylines with quantitative modelling, to deal with the uncertainties inherent to energy modelling, contributing also with mitigation scenarios for Portugal. Nevertheless, the findings and limitations the current analysis indicates areas for further developments.

All the technology choices presented throughout this dissertation were determined by the technological TIMES model and sustained by its database. Technology development represents a key uncertainty as our current understanding about its evolution is limited. This uncertainty can under or overestimate the national potential do reduce GHG emissions or achieve a certain RES target, as technology can change (e.g. costs and efficiencies) slower or faster than the historical trends and new technologies more efficient can emerge. Moreover, the technological options identified result from the cost-effectiveness character of TIMES_PT, which represent a simplified reality without fully including aspects of consumers' behavior, as the resistance to change due to imperfect information, or subjective preferences. Thus, a comparison of these results with similar scenarios from other models is highly desirable in order to improve the robustness of the outcomes. In order to better assess the impacts of the identified technology pathways via the hybrid modelling it would be relevant to complement these with cost-benefit analysis, beyond the aspect of cost-effectiveness only. Issues as job creation, potential for technological innovations and associated industrial clusters can be assessed as well. New scenarios assuming different policy instruments and revenue recycling schemes should also be explored, as they may have different impacts on the Portuguese energy system and economy.

The research comprised in this dissertation focused primarily on the energy-related GHG emissions. However, non-energy related emissions can also play an important role in the climate change mitigation. In addition, the achievement of a sustainable energy system should consider other environmental externalities, namely, the impact on air pollution, the impact on land use and biodiversity, as well as, the availability of the resources for energy supply and the water-food-energy-nexus. Thus, possible developments would be to: i) integrate acidifying and particulate emissions in order to evaluate the synergies (or antagonisms) of GHG mitigation and air quality improvement; ii) include in the modelling tools water as a commodity needed both for energy technologies (including biofuels production) but also for other uses (from human water consumption, to food production or ecosystem services). This would require including in HYBTEP a link (either soft with other modelling tools or endogenously via enhanced mode features) with land-use, food production and competing common water pools. This integrated energy-water modelling platform would allow to jointly assess mitigation and adaptation options, considering the expected impacts of climate change in Portugal.

On the issue of better studying the effects of intermittency of variable RES electricity a possibility would be to assess extreme climatic conditions, or to include specifically energy storage solutions as part of the energy technologies considered in the modelled tools, ideally combined with a higher time resolution (i.e. higher number of time-slices in TIMES_PT). Another possibility in this regard would be soft-linking the hybrid modelling tools with a power dispatch model.

Finally, it is considered highly relevant to continue to involve stakeholders in scenario development in order to allow for an more "open window" of future possibilities. It is important to improve and reinforce pragmatic approaches to do so, from structured questionnaires to workshops or wide open debates.

## 7.4 APPENDIX

**Table 7.A** | Overview of the scenarios generated in this research – Assumptions

| Scenario | Assumptions[a] GDP growth (%pa) ’10-‘30 | Assumptions[a] GDP growth (%pa) ’30-‘50 | Assumptions[a] Energy-Climate Policy[b] 2030 | Assumptions[a] Energy-Climate Policy[b] 2050 | Assumptions[a] Fossil fuel prices[c] 2030 | Assumptions[a] Fossil fuel prices[c] 2050 | Assumptions[a] Other assumptions[d] | Models used[e] | Purpose |
|---|---|---|---|---|---|---|---|---|---|
| **BASE** | 2.0 | --- | RES-E: 45% RES-T:10% | --- | O:62 NG:8 C: 61 | --- | 26PJ of electricity imports | TIMES_PT | Used as a reference scenario for comparison purposes |
| **DEM** | 3.1 | | | | | | | | Explores the impacts of higher energy demand |
| **EFF** | 2.0 | | + Energy efficiency measures | | | | | | Explores the impacts of additional efficiency measures in buildings |
| **low RES-e** | | | RES_E: 39 RES_T: 6% | | | | | | Explores the impacts of lower renewable energy (power and transports) goals |
| **LowH** | | | RES-E: 45% RES-T:10% | | | | + Lower hydro availability | | Explores the impacts of lower hydro resources availability |
| **HighH** | | | | | | | + Higher hydro availability | | Explores the impacts of higher hydro resources availability |
| **100$** | | | | | O:106 NG:13 C: 91 | | 26PJ of electricity imports | | Explores the impacts of higher fossil fuel import prices |
| **BASE_TE** | 1.3 | 2.9 | EU ETS: -21%/05 Non-ETS: +1/05 RES:31% RES-T:10% | | O:135 NG:13 C: 116 | O:158 NG:14 C: 126 | Techn. Optimistic | TIMES_PT | Used as a reference scenario for comparison purposes assuming optimistic technological development |
| **BASE_TF** | | | | | | | Techn. Pessimistic | | Used as a reference scenario for comparison purposes assuming pessimistic technological development |
| **CAP_TE** | | | GHG:-3%/90 RES:31% RES-T:10% | GHG:-80%/90 RES:31% RES-T:10% | | | Techn. Optimistic | | Explores the impacts of achieving a -80% reduction in 2050/90, assuming optimistic technological development |
| **CAP_TF** | | | | | | | Techn. Pessimistic | | Explores the impacts of achieving a -80% reduction in 2050/90, assuming pessimistic technological development |
| **CAP.ELAS_TE** | | | | | | | Techn. Optimistic | TIMES_ED(-0.3) | Explores the impacts of energy services demand reduction (due to energy price increase) assuming optimistic technological development |
| **CAP.ELAS_TF** | | | | | | | Techn. Pessimistic | | Explores de impacts of energy services demand reduction (due to energy price increase) assuming pessimistic technological development |

| Scenario | Assumptions[a] GDP growth (%pa) ’10-‘30 | ’30-‘50 | Energy-Climate Policy[b] 2030 | 2050 | Fossil fuel prices[c] 2030 | 2050 | Other assumptions[d] | Models used[e] | Purpose |
|---|---|---|---|---|---|---|---|---|---|
| **BS** | 1.9 | 2.4 | No policy | | O:132<br>NG:14<br>C: 114 | O:164<br>NG:18<br>C: 126 | unavailability of CCS technology | GEM-E3_PT<br>TIMES_PT | Used as a calibration scenario between the two models (GEM-E3_PT and TIMES_PT) and as reference scenario for comparison purposes |
| **+27S** | | | GHG: +27%/90 | | | | | GEM-E3_PT<br>TIMES_ED(-0.3) | Explores the impacts of achieving a +27% reduction in 2050/90 |
| **-20S** | | | +4%/90 | -20%/90 | | | | | Explores the impacts of achieving a -20% reduction in 2050/90 |
| **-60S** | | | -23%/90 | -60%/90 | | | | | Explores the impacts of achieving a -60% reduction in 2050/90 |
| **WE** | 0.6 | 1.5 | Non-ETS: +1%/05<br>ETS: -50%/90 in 2050<br>RES:31% RES-T:10% | | O:134<br>NG:13<br>C: 116 | O:149<br>NG:14<br>C: 126 | No electricity trade<br>NG potential | TIMES_PT | Explores the energy system and GHG emissions considering that Portugal is incapable of making significant structural changes and is inserted into a World of international instability |
| **NF** | 1.6 | 2.9 | GHG: -5.1%pa ’20-’50 | | O:97<br>NG:10<br>C: 74 | O:87<br>NG:8<br>C: 60 | Electricity exports max 13% of production | | Explores the energy system and GHG considering that Portugal develops in a world in expansion, investing in major structural changes and managing to participate in the new technological and innovation waves, which is reflected in this dynamic economy |
| **CALIB** | 0.9 | 1.5 | No policy | | O:117<br>NG:12<br>C: 109 | O:118<br>NG:12<br>C: 109 | No electricity trade | HYBTEP<br>TIMES_PT<br>TIMES_ED(-0.1)<br>TIMES_ED(-0.3)<br>TIMES_ED(-0.5) | Used as a calibration scenario |
| **CPR** | | | Non-ETS: +1%/05<br>ETS: -1.5%pa [‘20-‘50]<br>RES:31% RES-T:11%<br>RES-E: 50% RES-H&C: 34% | | | | | | Used as a reference scenario for comparison purposes |
| **TAX** | | | $CO_2$ tax: 62€$_{08}$/t | $CO_2$ tax: 370€$_{08}$/t | | | | | Explores the impact of a $CO_2$ tax in line to what is set by (EC, 2011b) |
| **RES** | | | RES subsidy: 78€$_{08}$/MWh | RES subsidy: 191€$_{08}$/MWh | | | | | Explores the impact of a renewable energy subsidy |

[a] All the assumption associated with the first set of scenarios (BASE, DEM, EFFis, low RES-e, LowH, HighH, 100$) is for 2020 and not 2030.

[b] All the GHG policy goals are set as caps except for TAX and RES scenarios, All the renewable targets are set as minimum shares

[c] Fossil fuel prices units – Oil: O $10/bbl; Naturals Gas: NG $10/MBTU; Coal - C:$10/ton.

[d] Unless mentioned otherwise all the scenarios assume average hydrological conditions.

[e] TIMES_ED corresponds to the elastic version of TIMES_PT. The values in parenthesis corresponds the general energy services-price elasticities (although specific TIMES_PT demand categories can have other values as mentioned in the respective core chapters of this dissertation.

**Table 7.B** | Overview of the major scenarios' results generated in this research

| **Scenario**[a] | **GHG emissions reduction (% compared to 1990)** | | **Renewable electricity (%)** | | **Renewable final energy consumption (and transport T) (%)** | | **Final Energy Intensity evolution per year (2050/210)**[d] | **Economic Impacts**[e] |
|---|---|---|---|---|---|---|---|---|
| | **2030** | **2050** | **2030** | **2050** | **2030** | **2050** | | |
| **BASE** | 51 | --- | --- | --- | 27 | --- | -1.8 | --- |
| **DEM** | 62 | --- | --- | --- | 26 | --- | -2.0 | --- |
| **EFF** | 37 | --- | --- | --- | 31 | --- | -3.0 | --- |
| **low RES-e** | 55 | --- | --- | --- | 24 | --- | -1.9 | --- |
| **LowH** | 54 | --- | --- | --- | 24 | --- | -1.9 | --- |
| **HighH** | 51 | --- | --- | --- | 29 | --- | -3.2 | --- |
| **100$** | 51 | --- | --- | --- | 29 | --- | -3.2 | --- |
| **BASE_TE** | 36 | 38 | 59 | 72 | 31 | 39 | -2.3 | --- |
| **BASE_TF** | 37 | 38 | 57 | 68 | 31 | 33 | -1.9 | --- |
| **CAP_TE** | -3 | -80 | 75 | 96 | 39 | 74 | -2.1 | +2% TSC/BASE_TE |
| **CAP_TF** | -3 | -80 | **75** | 96 | 44 | 82 | -2.0 | +6% TSC/BASE_TF |
| **CAP.ELAS_TE** | -3 | -80 | 71 | 96 | 36 | 68 | -2.2 | -1%TSC/CAP_TE |
| **CAP.ELAS_TF** | -3 | -80 | 74 | 96 | 40 | 84 | -2.4 | -4%TSC/CAP_TF |
| **BS**[b] | 54 / 55 | 68 / 74 | --- | --- | --- | --- | -1.9 / -1.3 | ---- |
| **+27S**[b] | 30 / 27 | 30 / 27 | --- | --- | --- | --- | -2.0 / -1.0 | 54 / 34<br>€2005/t $CO_2$e |
| **-20S**[b] | 7 / 3 | -18 / -20 | --- | --- | --- | --- | -2.7 / -1.3 | 470 / 211<br>€2005/t $CO_2$e |
| **-60S**[b] | -21 / -22 | -59 / -60 | --- | --- | --- | --- | -4.1 / -1.8 | 2 915 / 1 087<br>€2005/t $CO_2$e |
| **WE** | -3 | -12 | 60 | 79 | 34<br>T:12 | 45<br>T:14 | -1.2 | --- |
| **NF** | -4 | -70 | 58 | 86 | 36<br>T:13 | 67<br>T:60 | -2.0 | --- |
| **CALIB**[c] | -4 | 2 | 56 | 68 | 31<br>T:9 | 36<br>T: 9 | -1.2 | --- |
| **CPR**[c] | -14 /<br>[-13/-14] | -12 /<br>[-11/-12] | 58 /<br>[58-59] | 78 / 78 | 33 / 33<br>T: 13 /13 | 38 / 38<br>T: 9 /14 | -1.2 / [-1.2- -<br>1.3] | GDP impact rel.<br>Baseline: -<br>0.4%/'30 \| -<br>0.4%/'50 |
| **TAX**[c] | -18 /<br>[ -17/-23] | -47 /<br>[-44/-53] | 63 /<br>[62/65] | 88 /<br>[88/89] | 35 /<br>[35/36]<br>T: 13 / 13 | 65 /<br>[63/65]<br>T:61 /<br>[61-68] | -1.4 /<br>[-1.4 / -1.7] | GDP impact rel.<br>Baseline: -1%/'30<br>\| -2.4%/'50 |
| **RES**[c] | -31 /<br>[-27/-30] | -32 /<br>[-29/-38] | 75 /<br>[74/75] | 97 /<br>97 | 51 /<br>[49/51]<br>T: 23 / 23 | 63 /<br>[65-66]<br>T:47/<br>[47-48] | -0.7 /<br>[-0.8/-0.5] | GDP impact rel.<br>Baseline: -<br>0.9%/'30 \| -<br>2.8%/'50 |

[a] All the results associated with the first set of scenarios (BASE, DEM, EFFis, low RES-e, LowH, HighH, 100$) is for 2020 and not 2030.

[b] The results of the 3rd set of scenarios (BS, +27S, -20S,-60S) represent the values of GEM-E3_PT/TIMES_PT

[c] The results of the 5th set of scenarios (CALIB,CPR,TAX,RES) represent the values of HYBTEP / [range of TIMES_P'T, TIMES_ED(-0.1,TIMES_ED(-0.2),TIMES_ED(-0.3) results]

[d] Just the results of GEM-E3_PT and HYBTEP reflect the impact of GDP on energy intensity

[e] The economic impacts for the 2nd set of scenarios (BASE_TE,BASE_TF,CAP_TE,CAP_TF,CAP.ELAS_TE,CAP.ELAS_TF) represent the increase/decrease of total energy system cost (TSC) comparing to its corresponding reference scenario. The economic impacts for the 3rd set of scenarios (BS, +27S, -20S,-60S) represent the marginal abatement cost in 2050 in €2005/t $CO_2$e

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