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History and recent state of TIMES optimization energy models and their applications for a transition towards clean energies

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Abstract: Mathematical models of energy-economy-environmental systems (E3) provide a rational framework for exploring the effects of energy and climate policies and support adequate decision-making. Numerous models have been developed over the years with different solution approaches, features, geographical scope and time resolution. There is no complete or ideal models but different models that answer different questions or similar questions with different perspectives. Developed since the early 1980s, the TIMES (The Integrated MARKAL-EFOM System) optimization models have contributed to support decision-making at various geographical scales from global to city levels. In this Chapter, we distinguish a set of national studies that performed TIMES model developments to study the energy transition and address the impacts of integrating high levels of renewable energies on the system. Each study follows a different approach with the sole purpose to optimize the energy used in order to reduce greenhouse gas (GHG) emissions. Examples of applications are provided to illustrate the rich potential of optimization models for assisting decision makers with climate change mitigation. In particular, a special attention is given to the electricity sector as electrification of end-uses and decarbonization of the electricity sector are consistent priorities of actions across studies.

Keywords: Optimization, energy system models, energy transition, climate mitigation, renewable electricity

1 Modeling the energy transition

As part of the Paris Agreement, most countries committed to reduce their greenhouse gas (GHG) emissions with the ultimate goal of keeping the global temperature rise below 2^{o}C. Moreover, it is increasingly argued that the carbon neutrality of the global energy sector should be achieved in 2050 to maintain the temperature below 1.5^{o}C by 2100. Climate change mitigation is a very complex problem with many different combinations of possible solutions, which vary among sectors, among regions, and over time. In all cases, however, achieving these commitments requires important transformation of energy sectors.

The complexity of the links between the different energy sectors, as well as between the energy sector and the rest of the economy suggests the use of a systemic approach. In this context, mathematical models of energy-economy-environmental systems (E3) provide a rational framework for exploring the effects of energy and climate policies and support adequate decision-making. Numerous models have been developed over the years with different solution approaches, structures, intrinsic features, levels of details, geographical scope and time resolution. There is no complete or ideal models but different models that answer different questions and/or similar questions but different perspectives.

Optimization E3 models provide a rigorous analytical basis for defining decarbonization pathways that meet growing demands with progressive reductions in GHG emissions at a minimum cost. Among the optimization category of models is the TIMES (The Integrated MARKAL-EFOM System) model generator developed within a Technology Collaboration Programme of the International Energy Agency and used by a large number of organizations worldwide.

This chapter focuses on recent state of TIMES optimization energy models and their applications for a transition towards clean energies. Section 2 provides a brief overview of the main classes of E3 models with their main characteristics and roles for studying the energy transition. Section 3 takes a closer look at the optimization TIMES approach. Most recent developments in various TIMES models used worldwide are summarized in Section 4. Following these model improvements, examples of applications to a transition toward clean energies are provided in Section 5, before concluding in Section 6.

2 A simplified classification of E3 models

For many years, several models covering energy, economy, and environment (E3 models) have been developed. However, each model may follow a different approach. In order to aid potential users of these models to find out which one is most suited for a certain purpose or situation, several studies have attempted to classify them using different criteria (Bahn et al. 2005; Beeck 1999; Boulanger and Bréchet 2003; Morrison et al. 2015). The most common criteria used to differentiate between these models concerns their analytical approach, namely bottom-up, top-down and hybrid.

Bottom-up models use a techno-economic approach representing the technologies of the energy sector in detail while top-down models use a macro-economic approach based on an entire economic description (Bahn et al. 2005). However, these two approaches become decreasingly relevant to the emergence of hybrid models in which the two approaches have been merged (Vaillancourt 2010). In addition, due to the recent advances in both model categories (bottom-up and top-down), the distinction between these categories tends to be somewhat confused (Loulou et al. 2004).

This review does not include integrated assessment models capturing the feedback between energy and climate systems.

2.1 Techno-economic models

Bottom-up models represent in detail the so-called Reference Energy System (RES) for one or more regions, including energy exchanges between regions. Resources, current and emerging technologies (extraction, production, consumption) and forms of energy are explicitly characterized by their technical and economic attributes (efficiency, emission factors, etc.) (Vaillancourt 2010). Bottom-up models calculate the production of primary and secondary energy and also the consumption of total final energy in order to meet energy demands as well as eventual emission reduction constraints (Bahn 2018). Demands are based on socio-economic (rather than energy) assumptions and are expressed exogenously from actual needs in physical units (number of houses, industrial production, vehicle-kilometers, etc.). We distinguish two main types of techno-economic models namely optimization models and simulation models (Vaillancourt 2010):

- Optimization models minimize the updated total cost of the system in order to meet final demands while respecting environmental constraints. They, therefore, calculate a partial equilibrium between energy supply and demand in a perfectly competitive market and determine the least costly technological combination to satisfy final energy demand, as well as the price of each form of energy. Policies are modeled through constraints on technologies, forms of energy or air pollutants.
- Simulation models focus on the representation of consumer behavior (individuals, industries). They contain information on the competitiveness of rival technologies. The technological choices are determined by investments. Thus, the market shares of different technologies are not always based on optimal choices. Policies are modeled through constraints on market share and technology diffusion processes.

The principal limitation noted in bottom-up models lies in the fact that they do not represent the complete interactions that link the energy sector with the rest of the economy. Indeed, the optimal solution, in this case, corresponds to a partial economic equilibrium (Bahn 2018).

The first optimization models developed were MARKAL (MARKet Allocation) (Loulou et al. 2004), EFOM (The Energy Flow Optimization Model) and MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) (IIASA 2019). They were developed during the 70s and 80s in order to optimize energy systems in the medium term. Improved versions were then combined in more recent models, in particular the TIMES model (Loulou et al. 2016). TIMES are reference analysis tools of the Energy Technology Systems Analysis Program (ESTAP, 2019) of the International Energy Agency.

POLES (Prospective Outlook on Long-term Energy Systems) is a simulation model used by the European Commission (2019a). Similarly, the US Department of Energy uses NEMS (National Energy Modeling System) for annual energy outlook production (EIA, 2019). MAED (Model for Analysis of Energy Demand) is yet another simulation model used to assess future energy demands based on assumptions on medium to long-term scenarios of socio-economic and technological development of a country or region (IAEA 2019).

2.2 Macro-economic models

Top-down models represent the whole economy; however, they describe energy technologies in an aggregated way. These models may represent more interactions that link the energy sector with the rest of the economy. The principal limitation noted in top-down models is that they do not represent precisely energy technologies (Bahn 2018). Two main types of macro-economic models can be distinguished (Vaillancourt 2010):

- General equilibrium models that have a neoclassical view of the economic system describing the global economy through the behavior of economic agents. They consider the feedback between quantities and prices and calculate an equilibrium price in each market assumed to be in perfect competition. They are useful for analyzing major structural effects in terms of supply and demand as well as long-term effects. They are used to analyze impacts of international climate policies on national economies and to proceed to a simulation of international cooperation strategies.

- Macro-econometric models are neo-Keynesian whose economy is demand-driven. They capture the medium-term dynamics of the national economic aggregates and its components. Prices vary with supply and partial market imbalances. They allow analyzing the global impact of climate policy on economic variables such as gross domestic product, employment and balance of trade.

The EPPA (Emissions Prediction and Policy Analysis) model of the Massachusetts Institute of Technology (MIT 2019) and the GEM-E3 (General Equilibrium Model for Energy-Economy -Environment Interactions) model of the European Commission (2019b) are examples of general equilibrium models used to analyze impacts of climate change policies. On the other hand, the Oxford model also called GMM (Global Macro-econometric Model) is an example of a macro-econometric model that has been developed to perform more disaggregated analyses of the energy sector (Oxford Economics 2019). There also exist input-output models based on national data tables that are used to study the intersectoral effects of short-term climate policy at the national level, such as the effects of carbon taxes. The META-Net economic modeling system is applied to find the impacts of carbon taxes on national energy systems (Nakata 2004).

2.3 Hybrid models

Hybrid models have been developed to better integrate macro-economic factors into techno-economic models. For example, TIMES-MACRO (Loulou et al. 2016) is a technological model linked to macro-economic modules. In another example, recent versions of GEM-E3 incorporate in their general equilibrium framework a techno-economic description of electricity supply (Capros et al. 2013). Finally, the Long-Range Energy Alternatives Planning System (LEAP) model combines different modeling approaches: techno-economic, simulation, macro-economic and accounting techniques (Heaps 2008).

2.4 Comparison of approaches

It should be recalled that there is no ideal or complete model, but rather many models whose choice will depend on the type of issues to be analyzed or the type of decisions to be made:

- Bottom-up models are used to identify an optimal configuration of energy systems. These models can assess the impact from a techno-economic point of view on the energy sector of energy and climate policies. They are also called energy system models.
- Top-down models are used to address the impact of energy and climate policies on macro-economic variables such as employment and gross national product.

The main differences in characteristics, as well as the main role and limitations associated with these two categories of models, reside in their traditional forms. These differences are summarized in Table 1. We should note, however, that these distinctions are decreasingly noticeable with the development of hybrid models (Vaillancourt 2010).

In addition, we should note that this is not a comprehensive list of distinct features, as models differ in many dimensions, not only following the bottom-up and top-down classification but within each class of models as well. Bottom-up models for instance are characterized by alternative structures, geographical scopes, time resolution and assumptions about the future. Some models have a specific sector detailed (e.g., the electric sector), while others include a full representation of the whole energy system. They are also characterized by different solution approaches which imply different assumptions about the decision process over time: some assume a perfect foresight context where actors can anticipate future events while making optimal decisions today and some assume they are myopic where decisions are made on the basis of current conditions.

3 A closer look at the optimization TIMES approach

We provide next more detail on the MARKAL/TIMES bottom-up approach, as the reminder of this paper will focus on developments and applications with TIMES models.

Table 1: Characteristics and roles of the two main families of E3 models

Category	Bottom-up models	Top-down models
Database	· Explicit and detailed representation of energy forms and technologies in energy sectors · Energy flows	More general representation of energy supply and demand in the main economic sectors Monetary Flows
Approach	Techno-economic approach where energy balance conditions (supply = demand) are maintained throughout the system in physical units	A macro-economic approach where economic feedback between the energy sector and other economic sectors are taken into account
Balance	Partial balance: energy sector	General balance: entire economy
Demand	Driven by the demand for energy services, exogenously specified by the user	The use of energy is defined as the result of economic equilibrium
Type	· Optimization models · Simulation models	General equilibrium models Macro-econometric models Input-output models
Examples	EFOM, MAED, MARKAL, MESSAGE, NEMS, POLES, TIMES	EPPA, GEM-E3, GMM, META-Net
Hybrid approaches (examples)	· Bottom-up with link to macro-economic: MARKAL-MACRO, CIMS · LEAP: mix of bottom-up and top-down modeling techniques	TB with a bottom-up description of some energy sectors: recent versions of GEM-E3
Role	Identify a configuration of energy systems and measure the technical and economic impacts of implementing policies	Evaluate the impact of policies on the global economy and macro-economic variables such as employment and gross domestic product
Limit (traditional version)	Limited to the energy sector for policy analysis.	Limited to a more general analysis of energy sector policies.

Source: Adapted from Vaillancourt (2010).

3.1 MARKAL model

MARKAL model is one of the first bottom-up energy models that have been developed since the early 1980s after the first oil crisis. It has been widely used subsequently to study energy security issues after the first oil crisis, followed by environmental problems such as acid rain and now climate change mitigation.

It is cast as a dynamic mathematical model with perfect foresight. This implies in particular that investment decisions are made for each time period with perfect knowledge of future events. A period may, for example, be of a 5-year duration; the years of the same period are assumed to be identical.

Including a wide range of energy technologies, the model distinguishes each of them by describing its technical and economic parameters. The model calculates energy balances within the energy system to provide energy services at an overall minimum cost. MARKAL calculates then a (partial) balance of energy markets, meaning that energy producers deliver exactly how much energy consumers are willing to buy.

Contrary to earlier bottom-up energy models, demands for energy services are elastic to their own prices in MARKAL. This enables the model to maximize the total surplus of energy producers and consumers while facing certain constraints, and allows a more accurate computation of the balance between supply and demand (Boulanger and Bréchet 2003). However, assumptions of perfectly competitive markets may be relaxed by introducing specific assumptions, such as penetration limits for new energy technologies.

3.2 TIMES model

The evolution of MARKAL is the TIMES model that combines the two MARKAL and EFOM approaches. TIMES is currently used by more than 80 institutions across 70 countries. It corresponds to a dynamic partial equilibrium model to analyze energy markets.

Similar to MARKAL, TIMES relies on linear programming to maximize the total surplus of energy producers and consumers, while respecting specific constraints. This is operationally done by minimizing the total discounted cost of the energy systems used to meet useful energy demands. The two models also share a multi-period, multi-regional, structure, to analyze a (potentially large) number of regions while capturing energy trade between them. But TIMES provides more flexibility to modelers, for instance through time periods of variable lengths, a flexible number of hierarchical time slices, a more refine approach for representing vintage processes, or a flexible definition of energy processes (Loulou et al. 2016).

Moreover, the timing of investment payments is much more detailed in TIMES and allows distinct (and more realistic) capital flows whether it relates to large infrastructure (e.g., a new hydro dam) or smaller technologies (e.g., a car). TIMES acknowledges as well that global and technology-specific discount rates are time-dependent and not constant over time.

TIMES deals with the entire energy sector but can also apply to a single energy sub-sector (e.g., electricity or transport). To describe energy systems, the model uses inputs that represent inventories of equipment related to existing systems, but also the characteristics of (potential) future technologies. Similarly, TIMES represents current as well as future sources of primary energy supply. In addition to these inputs, the model also supports energy-environment policy analysis (Loulou et al. 2016). Furthermore, in order to explore future energy systems, in the long run, TIMES adopts a scenario approach. A scenario is based on a set of consistent assumptions. The model also recognizes that the demand for energy services is elastic in relation to its own prices. This makes possible the endogenous variation of demands in the policy scenarios relative to the baseline scenario, capturing behavioral changes and their impacts on the energy sector.

4 Recent developments in TIMES models used worldwide

We distinguish a set of studies conducted in different countries that performed TIMES model developments to study the energy transition and address the impacts of integrating renewable energies on the system. Each study follows a different approach and methodology with the sole purpose to optimize the energy used in order to reduce greenhouse gas (GHG) emissions.

Given the popularity of TIMES models for studying the energy transition, it was not possible to review all relevant methodological developments. For instance, the latest review report of the ETSAP (Vaillancourt 2018) includes over 200 references published during the 2014-2016 period only with developments and applications of more than 80 TIMES models.

We have selected few examples of recent papers to illustrate the numerous possibilities of TIMES in terms of analysis of the energy transition and renewable penetration. Moreover, we have restricted the selection of papers with analysis of deep decarbonization scenarios and very high renewable penetration rates. Consequently, other interesting developments of TIMES models are not necessarily covered in this chapter, including better representation of consumer behavior and of other global challenges such as access to water and food.

4.1 Refine the representation of specific sub-systems

Systems analysis is a central concept to the developments and applications of these models. System analysis is a problem-solving method that provides a better understanding of the behavior of complex systems such as energy systems and serves as a basis for improved decision-making with access to better information. The core of the approach is to separate an overall complex system into various components or sub-systems with the most appropriate level of detail for adequately supporting the decision-making process that it is supposed to serve. A sub-system can be considered to be a specific sector in a specific region in a specific time period and its interactions with other sectors and the same sector in other regions and time periods. Policies and targets can apply the entire system, as well as to some or all of the sub-systems.

Given the complexity of energy systems, the large amount of data required to represent them in many details, and the numerous assumptions required to assign values to highly uncertain technical or economic parameters over time, developing specific sub-systems in existing large scale optimization models to study the energy transition is a methodological contribution in itself.

For example, Sgobbi et al. (2016) have developed a comprehensive hydrogen supply chain module in a multi-regional TIMES model for European countries to assess its role in climate mitigation scenarios with reduction targets up to 80% by 2050 compared with 1990 levels. They distinguished four types of hydrogen production technologies from various input fuels in centralized and distributed versions: gasification and pyrolysis, reforming, electrolysis and nuclear reactors. Hydrogen is also a by-product of advanced ammonia and chlorine production technologies. The capture hydrogen transport in liquid or gaseous forms from centralized facilities.

As another example, Vaillancourt et al. (2019) conducted a study to explore the role of bioenergy in Quebec's rapid transition to a low-carbon energy system through a TIMES model for Canada with a detailed representation of multiple bioenergy pathways. Model developments allow a comprehensive representation of supply chains with: i) a large variety of feedstocks (crops, fatty residues, forest residues, agricultural residues, pulp and paper residues, dedicated crops of fast-growing trees, organic municipal waste, manure, sewage sludge, and landfill biogas), ii) many conversion processes (fermentation, transesterification, combustion, gasification, hydrolysis, pyrolysis, anaerobic digestion, etc.), and iii) numerous options for final usages of bioenergies.

4.2 Refine the time resolution

Traditionally, TIMES models are solved for a limited number of time periods over the 2050 or 2100 horizons with a limited number of annual time slice (e.g., 2-4 seasons and 2-4 intraday periods). Given the flexibility of TIMES for defining the time resolution as well as improvements in computing capabilities, few authors have tested the impacts of having a greater disaggregation of the annual time dimension for studying the decarbonization of the electricity sector.

In Krakowski et al. (2016), a TIMES model was used to evaluate the penetration of renewable energy in the French electricity system ranging from 40% to 100%. The purpose of this study was to broaden the debate on whether such high renewable energy penetration rates were feasible. TIMES provides a realistic representation of electrical systems and plausible options for their long-term development. The model was completed with a thermodynamic description of electrical systems to assess their reliability. In addition, the 2012 to 2050 horizon has been divided into 13 annual periods. Each period was further divided into seven seasonal periods (six monthly periods plus one period representing a potential winter week), each seasonal period was divided into two typical days (working days and weekends) and each typical day has been subdivided into six periods including two periods for the night, two for the morning, one for the afternoon period and the sixth period for the maximum demand).

Kannan and Turton (2011) developed the Swiss TIMES electrical system model (STEM-E) to generate insights on long-term development of the electricity sector under a cost-minimization framework. The main objectives were to analyze electricity generation at the hourly level taking into account the availability and operational constraints of the interconnected system elements, and elucidate the problems associated with the integration of intermittent renewable energy technologies. To achieve these objectives, STEM-E was calibrated on historical data from 2000 to 2009. Key inputs included past and future electricity demand, existing technology stocks, national and imported energy resources, technical and economic characteristics of future electricity and heat generation technologies.

Another study done by Drouineau et al. (2015) used a TIMES model to analyze the capacity of the Reunion Island to reach its autonomy in electricity by 2030 with a fine resolution of time periods: each year was divided into two seasons, namely; the summer season and the sugar season and each day has been subdivided into eight time slices. The approach adopted focused on conducting a prospective study, which provides future production mixes under different scenarios. This approach has been associated with a quantitative assessment of the reliability of the power supply using two reliability indicators indicating that intermittent sources can strongly develop and thus worsen their reliability.

4.3 Linking TIMES with other models or tools

Another approach consists to link TIMES models to other models or analytical tools in order to capture additional dimensions of the problem to be solved and provide more complete solutions.

A soft-link approach with a simulation model has been used by few authors as it provides a more realistic picture of technology stocks turnover than optimization models and sometimes include more details and have a finer time resolution (one-year steps). Thellufsen et al. (2019) have analyzed cleaner solutions for district heating in Ireland in a future low-carbon system using the Irish TIMES model. To this end, EnergyPLAN was used to study in addition to the operation of the heating system, the feasibility of district heating compared individual heating solutions. EnergyPLAN allows time simulation of the heating system and therefore, it includes the operation of combined heat and power plants, boilers and storage facilities in relation to the electrical system, on a chronological basis on the year.

Similarly, Vaillancourt et al. (2017) have used a multiregional TIMES model to explore deep decarbonization pathways for Canada in a soft-link framework with a simulation model that is calibrated with historical data from 1978 and enables projections to 2050 and beyond in one-year steps. The soft-link work iteratively in both directions where the simulation model provides projections of key macro-economic drivers and service demands and decision variables from the optimization model are integrated back in the simulation model for further refinements to input variables.

Another area where a soft-link approach with another model has proved to be particularly useful is the analysis of the optimal electricity generation mix with high penetration of renewables over time. Indeed, some electricity sector models provide a more precise representation of electric systems than TIMES namely regarding the optimal dispatch. Tigas et al. (2015) used a TIMES model by linking it to a probabilistic production simulation model (ProPSim) to study the decarbonization of the Greek electricity and transport systems by 2050. The ProPSim model calculates the residual charge duration curves, which are used to calculate the optimal extension of the dispatchable generation plants. This combination makes it possible to better manage the stochastic aspects related to the penetration of renewable energies.

Welsch et al. (2014) have assessed the effects of soft-linking the Irish TIMES model with a well-known unit-commitment and dispatch model: PLEXOS. It allows simulating the electricity market with a more detailed temporal resolution, thus enabling to minimize the expected costs of the electricity dispatch. PLEXOS accounts for additional operational details such as minimum stable generation levels and operating reserve requirements.

Finally, several attempts have been made for linking TIMES models to life-cycle analysis (LCA) tools. McDowall et al. (2018) aimed to flexibly link a LCA-based tool to a European TIMES model in order to determine how the inclusion of indirect emissions can change the optimal technological pathways for the decarbonization of the European energy system. The indirect CO_2 emission factors associated with the construction of power sector technologies have been calculated by means of a hybrid LCA approach. The method consists of a disaggregation of an input-output table and its environmental extension based on data from life-cycle inventories, and the use of Environmentally-extended Input-Output (EEIO) analysis to calculate carbon emissions. It allows overcoming the main limitations of each approach, i.e., the high aggregation of EEIO models and the incomplete system boundaries in LCA.

5 Applications to a transition toward clean energies

Once more, it was not possible to review the numerous publications with applications of TIMES models to study the transition toward clean energies. Examples are provided below to illustrate the rich potential of optimization models for assisting decision makers with such a complex problem that is climate change mitigation.

5.1 Decarbonization of the energy system

Multiple TIMES optimization models are used today to support the analysis of energy and climate policies all over the world. Geographical coverage varies from the global to the city level as does the spatial resolution within each model region (Vaillancourt 2018). Different models with different spatial resolution provides complimentary information for decision makers taking into account both internal regional differences and the global factors.

Due to the large diversity of energy systems within a specific region or even a specific country, detailed national or multiregional approaches are necessary to study the energy transition while capturing the needs for investments in infrastructure for clean energy transport and distribution within the country or between neighboring regions (Vaillancourt et al. 2017). These investments are not captured in global models with continents or multiple countries represented as single aggregated regions. However, limiting assumptions are required in such national models regarding the potential evolution of the international demand for energy resources under different levels of commitments for climate change mitigation in the various countries.

Global models allow making more consistent and comprehensive assumptions regarding the evolution of international trade movements for energy commodities in such a mitigation context. As a global challenge, countries cannot be looked at in isolation when it comes to climate policies. Global models can also be used to study the international cooperation aspects, an important component of the global climate change agenda. This is a significant challenge for emerging countries as significant capital investments are required in order to transform the energy system without jeopardizing socio-economic growth.

As a technology-rich model with a flexible definition of the time dimension, TIMES is also well suited to investigate the techno-economic trade-offs for meeting medium-term targets at the least cost while taking into account the need for meeting even more stringer targets for the long term. Many studies have proved to be especially useful to define optimal pathways for achieving ambitious GHG reductions, while contributing to the growth of the economy and minimizing the risk of technological locked-in (Solano-Rodríguez et al. 2018).

Regardless of the geographical coverage or the time resolution, there are consistent observations across studies regarding priority actions for an optimal transition toward a clean economy: energy efficiency improvements in all sectors, electrification of end-uses (buildings, transports, industries, etc.), and decarbonization of the electricity sector.

Following these transformations, various additional mitigation options are considered to achieve deep decarbonization levels when electrification is not possible. Their role in the energy system depends on the geographical context and the characteristics of regional energy systems. For example, the role for biomass and biofuels is largely depending on the availability of biomass resources. Vaillancourt et al. (2019) conducted a study to explore the role of bioenergy in a Canadian province in rapid transition to a low-carbon economy using a TIMES model for Canada. The model calculates the most optimal energy sector configuration that would reduce GHG emissions to meet the official target by 2030 compared with 1990 levels (37.5%) and beyond (40%). They found out that in order to achieve the desired levels of GHG reduction, the energy transition required should include a larger role for bioenergy in 2030 (from 6% in a reference case to 18% in the most stringent scenario. This requires the access to a large diversity of biomass feedstocks and many improvements in efficiencies and costs of conversion processes.

Although very expensive, hydrogen could also play a role where others are limited and following technological development. For instance, Sgobbi et al. (2016) indicated that low-carbon hydrogen production technologies could become viable options for the transport and industry sectors as early as 2030 in a carbon mitigation context. Electrolysis technologies in particular provide flexibility to the system by absorbing electricity at times of high availability of intermittent sources.

However, it is increasingly argued that the carbon neutrality of the global energy sector should be achieved in 2050 to maintain the temperature below 1.5^{o}C by 2100. Reaching the carbon neutrality goal will require the integration of the most advanced technology innovations for the most energy intensive industrial sectors (aluminum, iron & steel, cement, chemicals, etc.) as well as a closer look to net negative GHG options such as the use of bioenergy with carbon capture and storage (Selosse and Ricci 2014) with all the social perception challenges it raises.

5.2 Integration of renewable electricity and heat

Previous studies exploring deep decarbonization pathways showed that electrification of end-uses and decarbonization of the electricity sector were consistent priorities of actions for many countries. Consequently, any climate change mitigation plan requires a special attention to the electricity sector, in a systemic and dynamic view of the whole energy system given its complexity and regional diversity.

Some studies have proved to be especially useful to describe optimal pathways for decarbonizing the electricity supply mix while taking into account the capacity of the grid to integrate a high share of intermittent renewables.

For example, Amorim et al. (2014) have used a TIMES approach to analyze possibilities to fully decarbonize electricity generation in Portugal by 2050, in order to contribute to a deep decarbonization of the Portuguese energy sector. To this end, two cases were considered: 1) the Portuguese generation sector is optimized as an isolated system, and 2) the latter is part of an integrated Iberian system (Portugal and Spain). The study illustrates the benefits of optimizing the integrated system, which yields reduced energy costs. These cost reductions are achieved through a larger exploitation of renewable energy sources (such as solar and wind energy) in the Portuguese generation sector, together with new interconnections between Portugal and Spain (at the end of the model horizon, 2050) to accommodate higher electricity exports to Spain.

In a soft-link framework with a probabilistic production simulation model, Tigas et al. (2015) have analyzed the possibilities, for Greece, to reduce energy-related GHG emissions by 60% to 70% in 2050, from the 2005 level, in line with the European Union objective to abate its GHG emissions by 85% (in 2050, from the 2005 level). In particular, using the linked TIMES model, they have studied a scenario that envisions an almost 100% electricity generation from renewable energies. Besides, achieving an (almost) complete decarbonization of electricity generation would facilitate an intensive electrification of the transport sector that is currently responsible for a large amount of GHG emissions in Greece. However, this scenario implies higher overall energy costs compared to the situation where the TIMES model is free to choose least costly strategies to achieve the GHG reduction targets. In that case, besides decarbonizing to a large extent electricity generation, the optimal strategy also relies on the implementation of a number of targeted energy efficiency measures, and on a large-scale renewable energy system penetration in all end-use sectors.

A detailed analysis of the electricity sector often requires a finer resolution than for other sectors. In this regard, Krakowski et al. (2016) have analyzed different levels of renewable energy penetration, ranging from 40% to 100% by 2050, in the French electricity generation sector considering seven seasons, a distinction between working days and weekends and six intraday periods. They have relied for their analysis on a TIMES model, together with indicators of the power system reliability. The latter is likely to deteriorate due to the penetration of renewable energy sources, even at moderate levels (40%). However, the use of flexibility options, such as demand-response, shall help reduce the negative impacts of intermittent renewable energy systems. The authors conclude by highlighting the interest for decision-makers of such a study that would help them anticipate the aforementioned negative impacts.

At present, the (French) Reunion Island's electricity generation relies mainly on imported fuels, while it has significant potential for renewable energies. Drouineau et al. (2015) have used a TIMES approach, again together with indicators of the power system reliability, to assess from a techno-economic perspective whether Reunion Island could achieve electricity self-sufficiency by 2030. The authors conclude that self-sufficiency could indeed be achieved, by using in particular biomass (sugar-cane, cane, and wood) but also intermittent energy sources. The latter would negatively impact the reliability of the power system. This effect could, however, be mitigated by imposing some legal limits on intermittent sources for instantaneous electricity production.

By linking a TIMES model with the unit-commitment and dispatch model PLEXOS, Welsch et al. (2014) could also study the evolution of the Irish electricity system in more details. They showed that long-term energy models can clearly underestimate the importance of flexibility in the electrical system if short-term operational requirements are not taken into account. The study highlighted some of the limitations of long-term energy systems models if they do not adequately take into account operational aspects. Energy strategies and policies may, otherwise, underestimate the costs of meeting climate change or energy security targets.

Other aspects not included in traditional analysis using TIMES models can change optional solutions if added to the analytical framework. For instance, McDowall et al. (2018) have conducted a study, using a European TIMES model, to determine the extent to which the inclusion of indirect effects on GHG emissions (from a life-cycle assessment perspective) could change the optimal technological pathway for the decarbonization of the European energy systems (EU28 member states plus Norway, Iceland and Switzerland). Although indirect emissions account for only a small part of the total emissions (less than 10%), their inclusion would lead to changes in the optimal configuration of energy sectors. In particular, some renewable energy technologies (notably solar photovoltaic) become relatively less attractive. But these changes are more pronounced than the reduction in the attractiveness of renewable energy as a whole. Besides, McDowall et al. (2018) also concluded that renewable energy sources remain an essential element of the European decarbonization strategy.

Finally, Thellufsen et al. (2018) have studied the impact of cleaner heating solutions, based on district heating from industrial waste heat and combined heat and power (CHP) plants, on achieving deep decarbonization (up to 80% reduction) in Ireland. They rely on an Irish TIMES model linked to EnergyPLAN, a model that enables to consider hourly operations of both heating and electricity systems. The study indicates that the district heating option is a more fuel-efficient solution than the individual heating one. In the Irish context, this increase in fuel efficiency yields more savings than the higher investment costs incurred by the district heating option. The authors conclude that district heating could play an important role in the transition towards clean energy systems.

6 A need for greater transparency for efficient decision-making

Mathematical E3 models are particularly useful for exploring the transition toward clean energies and by providing decision makers with rigorous insights on deep decarbonization pathway options and long-term mitigation strategies. The TIMES optimization models in particular, developed within the ETSAP program of the International Energy Agency, have contributed to support decision-making all over the world at various geographical scales from global to city levels.

As large-scale energy system models, they describe the energy sector with a complete list of energy forms, as well as different existing, improved and emerging technologies. They allow for detailed accounting of all energy flows within the energy sector from primary and secondary energy production to final energy consumption and useful energy demands. These models are typically projected to 2050 or even 2100, which makes it possible to study the structural changes within the energy sector. In addition, they provide important additional features compared with other types of energy system models, such as simulation models. By following a linear programming formalism, these models make it possible to determine optimal configurations of the energy sector to satisfy the total demand for energy services at lower cost, while respecting GHG emission limits or renewable penetration targets.

However, the use of such models to assist policy-makers with energy and climate policy design and implementation raises issues regarding the robustness of the solutions found by the optimization program, especially given the large number of assumptions required to assign values to highly uncertain technical or economic parameters over time. The main critic addressed to optimization energy system models is indeed the "black box" aspect of the approach which affects the credibility of their outcomes and usefulness to support decision-making.

Different approaches have been used by the TIMES modeler community to address uncertainty issues such as sensitivity analysis, parametric scenario analysis, Monte Carlo simulations, and stochastic programming. These approaches have partially contributed to showing policy-makers and other stakeholders that large-scale optimization energy system models can provide robust insights for policy making despite the large number of assumptions embedded in model databases. Nevertheless, enhancing the credibility further will follow a better understanding of the links between input parameters and output results. The only possible solution to overcome this limitation involves more transparency regarding model inputs, a better dissemination of model roles and possibilities as well as a reinforced communication links between science and policy.

References

Amorim F, Pina A, Gerbelova H, Pereira da Silva P, Vasconcelos J, Martins V (2014). Electricity decarbonization pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modeling. Energy 69: 104–112.

Bahn O (2018) The Contribution of Mathematical Models to Climate Policy Design: a Researcher's Perspective. Environmental modeling & Assessment 23: 691–701.

Bahn O, Haurie A, Zachary SD (2005) Mathematical modeling and simulation methods in energy systems. Encyclopedia of Life Support Systems (EOLSS), p 15.

Beeck Nv (1999) Classification of Energy Models. Tilburg University & Eindhoven University of Technology, p 25.

Boulanger PM, Bréchet T (2003) Une analyse comparative des classes de modèles. Modélisation et aide à la décision pour un développement durable, p 32.

Capros P, Van Regemorter D, Paroussos L, Karkatsoulis P (2013). GEM-E3 Model Documentation. European Commission.

Drouineau M, Assoumou E, Mazauric V, Maïzi N (2015) Increasing shares of intermittent sources in Reunion Island: Impacts on the future reliability of power supply. Renewable and Sustainable Energy Reviews 46: 120–128.

EIA - US Energy Information Administration (2019) NEMS - National Energy Modeling System. [Online] https://www.eia.gov/outlooks/aeo/info_nems_archive.php.

ETSAP- Energy Technology Systems Analysis Program (2019) Official Website. [Online] https://iea-etsap.org.

European Commission (2019a) POLES - Prospective Outlook on Long-term Energy Systems. [Online] https://ec.europa.eu/jrc/en/poles.

European Commission (2019b) GEM-E3 - General Equilibrium Model for Energy-Economy-Environment Interactions. [Online] https://ec.europa.eu/jrc/en/gem-e3/model?search.

Heaps C (2008) Long Range Energy Alternatives Planning System – Anintroduction to LEAP. [Online] http://www.energycommunity.org/documents/LEAPIntro.pdf.

IIASA - International Institute for Applied Systems Analysis (2019) MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental Impact. [Online] http://webarchive.iiasa.ac.at/Research/ECS/docs/models.html#MES-SAGEMERGE.

IAEA - International Atomic Energy Agency (2006) Model for Analysis of Energy Demand (MAED-2). Computer manual series 18, p 189. [Online] https://www-pub.iaea.org/MTCD/publications/PDF/CMS-18_web.pdf.

Jaccard M (2009) Combining top down and bottom up in energy economy models. In: Evans J and Hunt LC (eds) International Handbook on the Economics of Energy: 311–331.

Kannan R, Turton H (2011). Documentation on the Development of the Swiss TIMES Electricity Model (STEM-E). The Energy Departement PSI Bericht Nr. 11.

Krakowski V, Assoumou E, Mazauric V, Maïzi N (2016). Reprint of Feasible path toward 40-100% renewable energy shares for power supply in France by 2050: A prospective analysis. Applied Energy 184: 1529–1550.

Lehtila A, Koljonen T (2019) Pathways to Post-fossil Economy in a Well Below 2 °C World. In G. Giannakidis K. Karlsson M. Labriet B. Ó Gallachóir (eds). Springer Lecture Notes in Energy: Limiting Global Warming to Well Below 2°C: Energy System Modeling and Policy Development: 33–47.

Loulou R, Goldstein G, Noble K (2004) Documentation for the MARKAL Family of Models. Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency. [Online] https://iea-etsap.org/index.php/documentation.

Loulou R, Goldstein G, Kanudia A, Lehtila A, Remme U (2016) Documentation for the TIMES Model. Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency. [Online] https://iea-etsap.org/index.php/documentation.

McDowall W, Solano Rodriguez B, Usubiaga A, Fernandez JA (2018) Is the optimal decarbonization pathway influenced by indirect emissions? Incorporating indirect life-cycle carbon dioxide emissions into a European TIMES model. Journal of Cleaner Production 170: 260–268.

MIT – Massachusetss Institute of Technology (2019) EPPA - Emissions Prediction and Policy Analysis. Joint program on the Science and Policy of Global Change. [Online] https://globalchange.mit.edu/research/research-tools/eppa.

Morrison GM, Yeh S, Eggert AR, Yang C, et al. (2015) Comparison of low-carbon pathways for California. Climatic Change 131: 545–557.

Nakata T (2004) Energy-economic models and the environment. Progress in Energy and Combustion Science, 30: 417–475, 2004.

Oxford Economics (2019) GMM - Global Macro-Economic Model. [Online] https://www.oxfordeconomics.com.

Selosse S, Ricci O (2014) Achieving negative emissions with BECCS (bioenergy with carbon capture and storage) in the power sector: New insights from the TIAM-FR (TIMES Integrated Assessment Model France) model. Energy 76: 967–975.

Solano-Rodríguez B, Pizarro-Alonso A, Vaillancourt K, Martin-del-Campo C (2018) Mexico's transition to a net-zero emissions energy system: near term implications of long term stringent climate targets. In G. Giannakidis K. Karlsson M. Labriet B. Ó Gallachóir (eds). Springer Lecture Notes in Energy: Limiting Global Warming to Well Below 2°C: Energy System Modeling and Policy Development: 316–333.

Thellufsen, JZ, Nielsen S, Lund H (2019). Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland. Journal of Cleaner Production 214: 377–388.

Tigas K, Giannakidis G, Mantzaris J, Lalas D, Sakellaridis N, Nakos C, Vougiouklakis Y, Theofidili M, Pyrgioti E, Alexandridis A (2015) Wide scale penetration of renewable electricity in the Greek energy system in view of the European decarbonization targets for 2050. Renewable and Sustainable Energy Reviews 42: 158–169.

Vaillancourt K (2010) Modèles énergie-économie-environnement. PRISME.

Vaillancourt K (ed) (2018) Tools for Analysis of a Future Energy Revolution (TAFER): Methodologies, Tools and Data Bases. Final Report for Annex XIII of the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency. [Online] https://iea-etsap.org/index.php/documentation.

Vaillancourt K, Bahn O, Levasseur A (2019). The role of bioenergy in low-carbon energy transition scenarios : A case study for Quebec (Canada). Renewable and Sustainable Energy Reviews 102: 24–34.

Vaillancourt K, Bahn O, Frenette E, Sigvaldason O (2017) Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework. Applied Energy 195: 774–785.

Welsch M, Deane P, Howells M, Ó Gallachóir B, Rogan F (2014) Incorporating flexibility requirements into long-term energy system models - A case study on high levels of renewable electricity penetration in Ireland. Applied Energy 135: 600–615.