Probing the usefulness of technology-rich bottom-up models in energy and climate policies : lessons learned from the Forum project

Reference:
Laes Erik, Couder Johan.- *Probing the usefulness of technology-rich bottom-up models in energy and climate policies : lessons learned from the Forum project*
Futures: the journal of forecasting, planning and policy - ISSN 0016-3287 - 63(2014), p. 123-133
DOI: http://dx.doi.org/doi:10.1016/j.futures.2014.06.001
Handle: http://hdl.handle.net/10067/1190710151162165141

Probing the Usefulness of Technology-Rich Bottom-Up Models in Energy and Climate Policies: Lessons Learned from the Forum project

Erik Laes[a], Johan Couder[b*]
[a]Flemish Institute for Technological Research (VITO), Department Transition Energy & Environment, Boeretang 200, B-2400 Mol, Belgium
[b]University of Antwerp (UA), Department Engineering Management, Prinsstraat 13, B-2000 Antwerpen, Belgium
*corresponding author johan.couder@uantwerpen.be

To be submitted to FUTURES, final draft post-refereeing, June 6th, 2014.

Abstract

The Belgian Science Policy (BELSPO) Forum project aimed to decide what kind of model-based decision support is needed to develop policy making for the transition to a low carbon economy. Starting from decision-support experiences gained in two decision-support methodologies using bottom-up energy models (TIMES-TUMATIM and SEPIA-LEAP), and inspired by Stanford's Energy Modeling Forum (EMF), six intermediaries, who are responsible for communicating the results of models to decision makers, were asked to pass judgment on both models. Firstly, the relevant policy questions the decision makers want answered were revealed in the course of the Forum process. Secondly, the extent to which the existing models can provide meaningful answers to these questions was explored. In the end, it was established that neither of the two existing models is well suited to representing uncertainties or finding robust strategies under deep uncertainty. As models depicting a radical system change over the next 50-100 years must necessarily deal with deep uncertainties, new research methodologies are needed to improve adaptive policy making.

Keywords
Energy system; Bottom-up models; Energy policy; Adaptive policy making; Transition to a low-carbon economy; Deep uncertainty.

1. Introduction

Since the first oil crisis of the 1970s, the need for reliable information about possible energy futures based on energy demand projections, estimates of energy technology development, and related estimates of emissions and costs has been met by the widespread use of technology-rich bottom-up energy system models [1][2]. The growing worldwide scientific consensus that limiting the increase in global average temperature to around 2°C is necessary in order to avoid unacceptable climate change impacts further adds to the need for reliable energy future studies, since global energy production and use is responsible for the lion's share of greenhouse gas (GHG) emissions. In particular, the radical GHG emission cuts implied by this global target require a fundamental societal transition, and energy scenario analysis is used intensively to outline possible paths to future low-carbon energy systems [3]. The successful application and interpretation of energy future studies in terms of expanding alternatives, clarifying policy choices or enabling policy makers to achieve desired outcomes depends on an understanding of the assumptions, structural elements, and theoretical and empirical foundations underlying the models used in these studies [4]. But in spite of efforts to improve the use and usefulness of energy models, with at the forefront the creation of the Energy Modeling Forum (EMF) in 1976 [5], the gap between modelers and potential users of energy future studies remains large.

The persistence of this gap is due to a mix of factors. Firstly, the users of (energy) future studies often maintain unrealistic expectations about the reduction of uncertainty regarding the impacts of policies made possible by these studies. Often, energy scenarios are treated by these users (often policy makers) as predictions or 'future facts' [6]. However, models depicting a radical system change over the next 50-100 years must necessarily deal with deep uncertainties. From this it follows that expecting energy future studies to contribute to the formulation of a fixed set of policies that will perform optimally over the next 50-100 years is actually unrealistic. Secondly, the energy system modelers are themselves to blame for the persistence of this 'gap'. The in-built characteristics of energy models and scenario-building exercises (e.g. assumptions made by energy system modelers) often remain hidden for policy makers, conflict with their suppositions, or offer limited information for targeted policy interventions [7]. In addition, Volkery and Ribeiro [8] find that scenario techniques are most often used in the early phases of the policy cycle – i.e. for indirect forms of policy support such as awareness-raising and issue-framing. However, their role in the 'harder' parts of policy making – i.e. in processes of policy design, choice and implementation – is limited. The expectations of policy makers are often not fulfilled because the model builders are not communicating effectively the insights, structure and understanding available from the model. These observations raise methodological and practical issues regarding the 'interface' between scenario-building practices based on energy system modeling and policy making. Academic literature on the use, impacts and effectiveness of the approaches for long-term future analysis in policymaking in particular is still superficial or absent [9][10]. Our analysis, based on the results of the Forum project, sponsored by the Belgian Science Policy (BELSPO) Office [11], provides an exploratory contribution to this literature in a Belgian energy and climate policy-making context.

Section 2 starts off with a brief account of the Forum project; and continues in Section 3 with a description of the models used by BELSPO. Section 4 zooms in on the relevant policy questions the decision makers want answered as revealed in the course of the Forum process, while Section 5 discusses the extent to which the existing models can provide meaningful answers to these questions. Section 6 lists some of the major recommendations formulated during the Forum project. Section 7 summarizes the findings in terms of improving the quality of the science-policy interface for supporting the Belgian transition to a low-carbon economy and suggests some venues for further research.

2. Brief description of the BELSPO Forum project

The BELSPO Forum methodology was inspired by the Energy Modeling Forum (EMF), located at Stanford University. EMF is an international forum that regularly organizes energy and climate change modeling assessment and comparison exercises among experts. At the heart of each EMF study there is an ad hoc working group, set up to examine a single field of application to which many existing models can be applied [12]. In the BELSPO Forum project, a similar ad hoc “Forum” was established. Six intermediaries, people who are neither modelers nor decision makers but who are responsible for communicating or interpreting analyses performed with models to decision makers, were asked to pass judgment on the usefulness of analyses carried out using two different "bottom up" energy and climate models in the context of the transition to a low-carbon Belgian economy. The limited number of Forum members is justified by the fact that the ideal size of a focus group for non-commercial topics, especially as participants have more expertise of the topic, should not exceed five to six people [13]. The Forum gathered three times during the project.

The two bottom-up energy models under consideration are the techno-economic, partial equilibrium energy model TUMATIM-TIMES [14], as applied by the Flemish Institute for Technological Research (VITO) and the University of Leuven (KU-Leuven); and the energy accounting decision support system tool SEPIA-LEAP [15], as realized by the University of Antwerp (UA). TIMES is an acronym for “The Integrated MARKAL-EFOM System”, a model developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement under the aegis of the International Energy Agency (IEA) [16]. TUMATIM-TIMES is an adaptation of TIMES for the BELSPO-project “Treating Uncertainty and risk in energy systems with MARKAL and TIMES” [TUMATIM]. LEAP is an acronym for “Long range Energy Alternatives Planning System”, an energy policy analysis tool developed and maintained by the Stockholm Environment institute [SEI] [17]. SEPIA-LEAP is an adaptation of LEAP for the BELSPO-project “Sustainable Energy Policy Integrated Assessment” [SEPIA] [18]. Both of these projects embedded the use of the energy models in different scenario-building logics and methodologies (cf. Section 3). For the sake of brevity however, in the remainder of this paper the terms “model” and “tool” will be used as a shorthand for “scenario-building methodologies requiring a software application”.

In line with the recommendations of Grunwald [19], the aim of the Forum project was to engage in a more transparent and deliberative debate about the ‘ingredients’ that should be used in constructing relevant energy future studies, and into the process of their composition. The ultimate purpose of the project was to decide how energy models could be used to support policy making for the transition to a low carbon economy, and more specifically, what are the advantages and drawbacks of the two above-mentioned models in terms of supporting decision making about transition policies. All models simplify reality or they would not be models. The model developers' choices of what to simplify and what to represent reflect not only a paradigm and subjective judgment but also the nature of the questions the model is designed to answer. Therefore, it is useful to start the reflection by clearly formulating the (policy relevant) questions which need to be answered in the decision support process. Based on this insight, the Forum project tried to ascertain the extent to which the two modeling approaches so far have succeeded in providing insights on relevant policy questions as formulated by the intermediaries. In an interactive process, the questions themselves were formulated more sharply as well as the extent to which the modeling approaches used so far succeeded in delivering useful insights.

3. Description of the two bottom-up models and of the assimilated scenarios

Based on the “ATEsT Models Characterization” template [20], the project team prepared detailed technical descriptions of TUMATIM-TIMES and of SEPIA-LEAP. A brief side-by-side summary of the main characteristics of both models was also drawn up and presented to the Forum members during the first meeting. In the TUMATIM and SEPIA projects a number of scenarios had already been explored using the TIMES model respectively the LEAP tool. The TUMATIM scenarios were built on the basis of varying the parameters which determine the outcome of the optimizing runs (e.g. discount rate, availability and penetration rate of technologies, etc.) [14]. The SEPIA project used a combination of backcasting (from desired future states of the Belgian energy system) and trend exploration (i.e. exploring how the future states could be brought about by strategically interacting with the exogenous long-term trends affecting the evolution of the Belgian energy system) [15]. For the benefit of the Forum members it was essential to provide meaningful comparisons between the results one can expect from the TIMES-TUMATIM and SEPIA-LEAP approaches. To achieve this VITO and UA had to re-run the TIMES model and the LEAP tool, but this time based on “similar” scenarios, the so-called “assimilated scenarios”. The original scenarios were converted into two “assimilated scenarios, which were meticulously reviewed during the second Forum meeting.

3.1 Description of TUMATIM-TIMES and SEPIA-LEAP

Both TIMES and LEAP are energy system models or tools, intended to analyze the evolution of detailed energy flows by combining multiple (energy consuming and producing) sectors and energy carriers, with a focus on competition and complementarities between energy technologies. Both are, what ATEsT calls, “hybrid, bottom-up” models. Hybrid refers to models explicitly addressing environmental issues, in the case of TIMES and LEAP all energy related greenhouse gas (GHG) emissions and ambient air pollutants. Bottom-up models are defined as technology-oriented models, using highly disaggregated data to describe energy end-uses and technological options in detail, whereas the macro-economic background remains exogenous. They treat energy demand as either given, or as a function of energy prices and national income [21] [22].

The aim of TUMATIM-TIMES is to generate a long-term roadmap to a sustainable energy system while at the same time maximizing welfare. To solve the TIMES-TUMATIM model, one has to minimize or maximize an objective function (e.g. costs or consumer and producer surplus) under a number of constraints (e.g. a CO_2 emission reduction target). TIMES-TUMATIM selects among technologies and levels of demand for energy services based on their relative (lifecycle) costs. In a typical reference scenario TUMATIM-TIMES uses (exogenous) estimates of end-use energy service demands (e.g. residential space heating, road travel, etc.) and of energy prices. In all other scenarios, where the reference scenario serves as a prerequisite baseline, technology choices, energy prices and energy service demands are computed by the TIMES model.

Whereas TIMES-TUMATIM is more of a stand-alone modeling system mostly used in traditional expert-based policy support, SEPIA-LEAP forms part of a broader (i.e. non-modeling) methodology to assess long-term sustainable energy policy in the Belgian context. SEPIA-LEAP uses built-in, non-controversial physical (energy) accounting relationships to allow for forecasting as well as backcasting analysis. For demand forecasting, LEAP does not optimize or simulate the market shares of technologies based on prices but simply analyses the implications of possible alternative market shares and / or activity levels. On the supply-side it does not – unlike TIMES – aim to find the least cost solutions, but uses accounting approaches to provide answers to “what-if” type of analysis under different scenarios (e.g. what will be the energy savings and emission reductions if one invests in more energy-efficient, renewables-based power plants?) [23]. In SEPIA-LEAP the degree of endogenization is more limited. All scenarios rely on exogenous macro variables such as population and average household size, total floor area of commercial buildings, outputs of different manufacturing sectors (either physical outputs or indices) and number of passenger-km and freight-km. These activity levels, multiplied by energy intensities (i.e. energy consumption per unit of activity level), determine the energy demand in LEAP. In contrast with TUMATIM-TIMES, future activity levels and technology choices (the latter determining the energy intensities) are not necessarily based on costs and energy prices relative to a reference scenario, but can be treated as exogenous variables determined by expert judgment and stakeholder involvement.

3.2 The assimilated scenarios

The project team adopted the “scenario axis approach”, according to which a set of key driving forces is identified and the driving forces regarded to be most important and most uncertain in their future development form the axis or dimensions of a matrix, determining the overall logic of the scenario storylines [24]. Three dimensions were withheld for the Forum assimilated scenarios: 1) behavioral evolution; 2) technological progress (including the role of flow renewables); and 3) the international and economic context.

The assimilated scenarios are summarized as follows:

- A behavior-optimistic / techno-moderate scenario [B++/T+], characterized by 1) a strong and rapid transition to a sustainable (carbon neutral) lifestyle with a high environmental awareness of all actors involved, whereas 2) technological progress (innovation) is gradual and less intensive as compared to the alternative (B0/T++) scenario, with moderate use of domestic flow renewable energy sources (RES) and relatively limited biomass potentials; and 3) geopolitical uncertainties manifesting themselves in the shape of limited imports of 2nd generation biomass and biofuels, combined with a gradual increase to (still) relatively moderate world fossil fuel prices, and high regional carbon taxes;

- A behavior-neutral / techno-optimistic scenario [B0/T++], with 1) a rather slow evolution to a relatively low sustainable way of living, but with 2) a rapid and all-encompassing technological progress (accelerated innovation), with a high potential of domestic flow RES; and 3) high international cooperation with few geopolitical tensions, manifesting itself through large imports of ‘green power’, combined with a gradual increase to high world fossil fuel prices, high carbon value and with a global emission trading system (ETS) in place.

All scenarios use the same population and GDP growth rates. International shipping and aviation were not taken into account, as they were not considered in the original TUMATIM and SEPIA projects.

Table 1: Overview of the assimilated scenarios (*)

Scenario	CO_2	Technology	Behavior
SEPIA-LEAP B++/T+	-80%	Moderate	Optimistic
SEPIA-LEAP B0/T++	-80%	Optimistic	Neutral
TIMES-TUMATIM B0/T++ a	-58%	Endogenous & Optimistic	Like SEPIA, via energy & carbon taxes
TIMES-TUMATIM B0/T++ b	-58%		Like SEPIA, via price elasticity of energy demand

(*) All scenarios exclude nuclear, and include carbon capture and storage (CCS), although the latter is limited in SEPIA-LEAP. The international dimension axis is not shown for readability.

The assimilated scenarios assume a -80% reduction of greenhouse gases (GHG) by 2050 relative to 1990 levels. For SEPIA-LEAP this target in both scenarios applies to the Belgian level, whereas in the TIMES-TUMATIM versions of B0/T++ the -80% by 2050 in the EU is interpreted as a –58% target for Belgium, this being the most cost efficient reduction when using the Pan European TIMES model [25]. In the Pan European model the energy systems of thirty countries are modeled separately, and then synthesized by allowing trade of energy commodities among the countries. In the course of the Forum project, modeling a -80% reduction at the Belgian level was not deemed feasible with TUMATIM-TIMES, as energy prices and / or energy / carbon taxes would have to be set “unrealistically” high. This has since been remedied, and a modified TIMES model was used to model a transition towards a 100% renewable based energy system in Belgium by 2050 [26]. As it turned out, the B++/T+ scenario could only be run with the SEPIA-LEAP tool, basically because radical lifestyle changes are difficult or near impossible to model in TIMES-TUMATIM. It was therefore agreed that VITO should run two versions of the B0/T++ scenario with the TIMES-TUMATIM model, hereby attempting to “emulate” the results of the SEPIA-LEAP B0/T++ scenario, once through changing the energy / carbon tax assumptions in the original TUMATIM scenarios, and once through changing the assumptions concerning the price elasticity of energy demand. In the Forum project, the actual results of the model runs as such were not relevant, so they are not replicated here. The detailed results are available in the BELSPO Forum final report [11]. We limit ourselves in the remainder of this paper to discussing in depth the extent to which both models are able to answer the questions of policymakers as perceived by the Forum members, and based on their understanding of the divergent results as debated during the third and final Forum meeting.

4. Policy relevant questions decision makers would like to see answered

First, a preliminary survey was set up to gain insight in the expectations potential model users might have with regard to long-term energy system analysis practices – i.e. the entire process in which data are gathered, assumptions are formulated, models are run, results are validated and fed into the policy process. The idea was not to identify ‘good’ or ‘bad’ models, but rather to recognize more or less ‘useful’ modeling approaches in the context of energy system analysis in support of appropriate long-term energy strategic planning for Belgium. The survey consisted of five parts: 1) enquiring about energy system analysis in Belgium today and tomorrow; 2) expected outputs; 3) spatial and temporal resolution of analysis results; 4) expertise and role of stakeholders; and 5) modeling methodology. During the first Forum meeting the members were confronted with three challenging statements, extracted from the results of this survey. These statements concerned the relevance of minimizing total social costs, the active participation of stakeholders in energy system analysis, and the use of backcasting and narrative scenario building. From the survey and the discussion during the first Forum meeting in response to the ‘challenging statements’, it became apparent that the intermediaries expected answers to the following questions.

Question 1: Are the **temporal and spatial resolution** of the models sufficient?
Regarding the spatial and temporal resolution of analysis results, the intermediaries expected information on a time horizon beyond 2050. The year 2100 was often mentioned as an adequate horizon to understand the full implications of transition pathways. Furthermore, modeling should always consider Belgium in the European context (e.g. impact of European Union policy making, grid interconnections to other countries, etc.).

Question 2: Is information on **security of supply and reliability of the energy system** provided?
Concerning the outputs of modeling exercises, the intermediaries most of all expected to receive credible information on security of supply and reliability of the energy system in the transition to a low-carbon future, in particular because the electricity systems of the future are generally expected to incorporate a large share of intermittent renewable generation by wind and sun.

Question 3: To what extent do models provide **information on costs and benefits** of energy transition?
Having information on the costs involved in the transition for different sectors was considered to be an absolute requirement in order to have any kind of impact on policy making. Cost information was perceived to be an absolute necessity in order to ‘prove’ that desirable outcomes in the long run are potentially achievable and that large regret can be avoided. For near-term actions information on costs and benefits was equally perceived to be necessary to establish cost-effectiveness and feasibility. The

likelihood that policymakers will adjust their policies grounded on the results of an energy system model without the inclusion of detailed costs figures was considered negligible by the Forum members. But even though minimization of total social costs and detailed cost information incorporating the many uncertainties are vital and valuable pieces of information to provide convincing descriptions of transition pathways, they insisted that costs may never be the only decisive factor.

Question 4: How **comprehensive** are the models?

Models should include effects other than those of price policies (e.g. tax or emission trading schemes); regulatory policies (e.g. norms and standards); and implementation of targets. Other non-price policies may include innovation policies (e.g. Research, Development and Demonstration or RD&D programs) or voluntary approaches (e.g. negotiated agreements with industry), along with accompanying measures (e.g. raising public awareness through information and education campaigns or energy labelling). According to the Forum intermediaries, the organizational, informational and cultural dimensions of decision-making should be given equal weight to the economic aspects.

Question 5: How apt are the models in incorporating **lifestyle changes**?

There is wide agreement among the intermediaries that the transition to a less energy intensive and lower impact society is not only influenced by technical efficiency but also by social-cultural factors and lifestyles. There is less consensus as to the extent of these influences, but energy modelers should none the less consider improved quantitative analysis of energy service demand behavior as a key priority. This analysis should not only encompass non-price determinants (e.g. cultural norms, values and beliefs, fashion, identity, trust, knowledge, social acceptance of innovations, …), but also non-consumptive elements (e.g. social networking, expectations, patterns of time use, mobility, policy acceptance, …) [27].

Question 6: Are the models **internally consistent**?

There is a mutual interdependence between the energy system and the macro-economy. On the one hand, energy is an essential production factor and increasing scarcity of energy may impede economic growth. On the other hand, energy-related investments compete with investments in other capital stocks. The Forum intermediaries expected internal consistency between the evolution in the energy system and the macro-economic evolution in the scenario-building process.

Question 7: Do model results reflect the **views of the stakeholders**?

Active participation of stakeholders is deemed to be absolutely necessary in all stages of scenario-building exercises (from providing inputs to validating outcomes), although the intermediaries recognized that this may difficult to achieve. Indeed, solutions for future energy systems can only be optimal from the perspective of society as a whole if they are formulated by stakeholders, albeit in a complex decision-making process. Recent backcasting experiments for sustainability also strongly emphasize stakeholder involvement [28] [29].

Question 8: How **transparent** are the models?

Given that energy system models are complex, data-intensive, quantitative computer models, the intermediaries insisted that models should be very explicit about assumptions and data used. By showing how the computer models work, e.g. by making the source code accessible as well as by sharing all the data entered into the models, it should be possible for any external observer to replicate the published results and to verify how faithful the models' outputs are to real world outcomes.

Question 9: How do the models deal with **uncertainty**?

The many uncertainties should always be clearly indicated, according to the Forum intermediaries. Individual sources of uncertainty have thus to be identified and, if possible, quantified. These sources include data uncertainty, model uncertainty, uncertainty about policy and ethical choices (e.g. the discount rate used), uncertainty about the future, and idiosyncrasies of the analyst (e.g. interpretation of incomplete information) [30]. This concurs well with the concern shown by Richels, Tol and Yohe that "Until we can keep adjusting the analysis by continually incorporating uncertainty, correction and learning, we shall continue to offer policy-makers an incomplete guide to decision-making" [31: p. 155].

5. Which model is best suited for addressing which policy relevant questions?

In a (partial) response to the questions set out in the previous Section, the Forum members came to the following conclusions.

Question 1: Are the temporal and spatial resolution of the models sufficient?

The time horizon and transition path for TIMES-TUMATIM is medium to long term (20 to 100 years), with variable time intervals. It does multi-year optimization, but does not have to run every year (instead 5 year periods are more commonly used). In LEAP the time horizon can extend for an unlimited number of years, but for SEPIA-LEAP the time horizon was limited to 50 years, with annual time-steps. TIMES and LEAP can be used at the global, multi-regional, national, state/province or community level, although both TIMES-TUMATIM and SEPIA-LEAP were developed to work exclusively at the Belgian (national) level . The separate TIMES Pan European Model does allow TIMES-TUMATIM to trade energy commodities among the member states of the European Union (EU). SEPIA-LEAP has no linkages to other countries, other than constraints on imports and exports of energy commodities.

Question 2: Is information on security of supply & reliability of energy system provided?

Both TIMES-TUMATIM and SEPIA-LEAP are capable of evaluating the impact of technology deployment on the energy system structure and on security of supply in Belgium. They can also evaluate shifting technology options. Reliability of supply, above all in the case of distributed renewable energy such as photovoltaic or wind based systems, can be modeled by means of interconnections between the different energy carriers, as well as by allowing the inclusion of energy storage devices. However, given the seasonal and variable nature of electrical and thermal loads and of renewable energy resources, for a more sophisticated analysis both TIMES and LEAP need to be complemented by more specific models using hourly or even quarter-hourly data.

Question 3: To what extent do models provide information on costs and benefits of energy transition? One of the core strengths of the TUMATIM-TIMES model is that it provides information on the costs of the energy transition for different demand sectors. More in particular, TIMES-TUMATIM is seen as a powerful approach for short-term studies (e.g. what will the costs be of meeting a certain policy target?), especially where many technological options exist. Although the accessibility to fairly detailed cost information was seen as a major advantage of TUMATIM-TIMES, the Forum participants had a number of critical remarks in the way these costs are calculated and presented. Firstly, the modelers have to be very precise and meticulous in their communication on costs. One question to be addressed concerns the type of costs that are being calculated. Possible types include investment costs, overall system costs, shadow costs or macro-economic costs (the latter often being much smaller - see e.g. [32]). Another question is related to what constitutes an adequate base for comparison (e.g. compared to a reference scenario, overall GDP, etc.) Furthermore, modelers have to make sure that all costs are integrated. The Forum members referred to the principle of full social costing, insisting on the inclusion of environmental and health effects [33]. Additionally, TIMES assumes integral comparisons and full liquidity of funds whereas studies show [e.g. 34] that decision making is not always based on the “overall costs”. In some instances – for example in the case of housing – investment costs can and will play a more prominent role in decision making. Finally, the costs for new technologies up to 2050 in TUMATIM-TIMES are very uncertain. This implies that the calculated transition paths are also tentative, since these paths are entirely cost dependent. VITO suggested that TIMES can provide information on the ‘distance’ between the cost-optimal transition path and the technologies that were not chosen in this path. Model users are thus able to identify technologies that were only slightly too costly to be included in the cost-optimal transition path. Given the uncertainty on future costs, this information may indicate possible alternative transition paths. This option was not further explored because it was beyond the scope of the Forum project.

In LEAP the computation of investment costs or social costs and benefits ensuing from the choices made concerning activity levels and technologies is purely optional, and LEAP at the time of the Forum project did not use cost-optimization as a driver[1], which may be relevant for a number of sectors where costs are an important incentive. In the SEPIA project it was decided not to calculate costs, mainly because the project did not allow enough time to build a comprehensive database on technologies including costs data. Using the data of TUMATIM-TIMES was not a valid option either, because at the time these figures were not publicly available. Since policy makers noticeably prefer scenarios in which economic costs are quantified, costs have since been incorporated in the SEPIA-LEAP tool, but not in time to be relevant for the Forum project.

[1] LEAP has since incorporated an optional optimization module, allowing the construction of least cost models of electric system capacity expansion and dispatch.

Question 4: How comprehensive are the models ?
The TIMES-TUMATIM model is an optimization model that attempts to simulate market outcomes. In this respect, a recognized strength of TUMATIM-TIMES, compared to SEPIA-LEAP, is its ability to *explicitly* model the effects of price policies (e.g. subsidies, taxes, tradable green certificates, etc.), in addition to the effects of standards and the implementation of policy targets within the bounds of the rational choice paradigm. However, the role of price elasticities in TIMES was considered a contentious topic. Because price elasticities of energy demand depend on the alternatives available to energy consumers (which in turn depend on the type of public policies in place – e.g. the availability of public transportation determines the price elasticity of the demand for private transportation), historic values of price elasticities might be a bad predictor of future elasticities. In this sense, the TUMATIM-TIMES approach is inherently 'conservative'. This weakness can be mitigated to some extent by allowing for a range of values for price elasticities. Another point of criticism was that TIMES can only model the effects of price policies, standards and the implementation of targets, whereas other types of policy could be just as important. Other policies likely as relevant comprise spatial planning, organization of public transportation, agriculture policy, etc. The incompleteness of TIMES as a decision making tool is further highlighted by the observation of the Forum members that TIMES does not allow policy inferences on social impact and land use.

The SEPIA-LEAP model is essentially a tool for constructing scenarios by means of "what if?" analysis. It does not attempt to simulate market solutions, and so is not constrained by an economic theory of market behavior. SEPIA-LEAP is intended to generate different insights based on deliberation between stakeholders and scenario builders concerning plausible paths to a sustainable energy system by 2050 in Belgium. SEPIA-LEAP offers the possibility to model various scenario 'narratives' taking into account interactions between energy supply and demand going beyond responses to price stimuli. In that respect, it is telling that TUMATIM-TIMES was not able to run the B++/T+ assimilated scenario. Advice on the use of policy instruments is not meant to be a direct output of the SEPIA-LEAP approach. Rather the tool visualizes and rationalizes different and sometimes opposing suggestions to reach a particular vision. As such, SEPIA-LEAP as a tool gives the opportunity to initiate discussions on a wide range of public policy instruments (beyond price instruments) and approaches (e.g. coordination between public policy actors) needed to bring about the transition paths in accordance with the different visions (cf. the Dutch energy transition platforms [35]). This makes LEAP better suited for examining policies that go beyond technology choices or hard to cost policy options.

Question 5: How apt are the models in incorporating lifestyle changes?
A need for a better understanding of lifestyle change mechanisms is apparent from the comparison of both approaches. The relevant question is to what extent such changes can be induced by price changes and/or voluntary acts. A related question is if and how voluntary actions can be steered by policy interventions. Although LEAP gives more leeway to modeling lifestyle changes compared to TIMES, the Forum members noticed that adequately modeling lifestyle changes in both types of

energy model remains very tenuous. Recent advances in political and social sciences can and should clarify these enquiries to some degree [36] [37] [38].

Question 6: Are the models internally consistent?

In both TUMATIM-TIMES and SEPIA-LEAP economic growth is an exogenous variable. As a partial equilibrium model, TUMATIM-TIMES partly reflects possible interactions between the energy system and the rest of the economy through the price mechanism (energy costs). A such, it models energy system development in an internally consistent way. Both energy demand and supply sectors are submitted to the same economic “laws” of rational behavior and hence constantly attune to each other in accordance with these laws. TIMES can be linked to an applied general equilibrium model, more in particular the “General Equilibrium Model for Energy-Economy-Environment interactions” (GEM-E3) [39], which generates the exogenous variables (energy services demand) for the energy model. In LEAP on the other hand, price-consistent solutions between energy demand and supply projections are not automatically generated. LEAP does not include balancing of supply and demand through price or macro-economic feedbacks. While in SEPIA-LEAP stakeholders may propose scenarios with reasonably low activity levels, there is absolutely no guarantee that these will not violate overall macro-economic growth assumptions. One possible solution would be to complement SEPIA-LEAP with a macro-economic accounting model. For both approaches, full integration would imply simplifying both the techno-economic models as well as the macro-economic models. Deciding which (combination of) model to use depends on the type of policy to be evaluated, e.g. detailed bottom-up models to analyze RD&D investments in energy-saving technologies, or macro-economic models to assess the feedback on the rest of the economy [40].

Question 7: Do model results reflect the view of stakeholders?

In both the TIMES-TUMATIM and SEPIA-LEAP approaches the modelers have to consult the stakeholders to ascertain beforehand all the different kinds of costs that the model should take into account in order for the model results to be of any relevance to policy-makers. Furthermore, modelers have to confer in advance with the stakeholders and / or scenario builders about the reliability and degrees of uncertainty of the costs considered in the scenarios. Both approaches depend on a number of (exogenous) key parameters. The selection of these key parameters should always be subjected to stakeholder review. Candidates for key parameters are e.g. potentials for offshore wind turbines, large-scale import of biomass, the electrification level of transportation means, etc. In this, the Forum members referred to the concept of extended peer community, where non-scientific actors can bring in valuable new information or even different perspectives on ill-structured and complex problems [41] [42]. The key advantage of SEPIA-LEAP is that this approach allows model users to quantify alternative visions identified in participatory stakeholder analysis. In principle, one can organize stakeholder workshops to validate the model input data of TIMES-TUMATIM.

Question 8: How transparent are the models?

Providing the intermediaries with all the necessary information includes giving them details on the explicit assumptions in the scenarios concerning activity levels, “way of life”, visions of 2050, etc. The data requirements for TIMES-TUMATIM and SEPIA-LEAP are very similar as far as characteristics and costs of the existing stock of energy related equipment and of promising future technologies are concerned, and also regarding estimates and potentials of present and future sources of primary energy supply. But although data requirements concerning potentials of primary energy sources are almost identical, TIMES-TUMATIM and SEPIA-LEAP originally used substantially different estimates. It was not immediately clear to the intermediaries who or what the sources of those estimates were, let alone how reliable those sources were. The Forum members also expressed the desire to be given more comprehensive results of the modeling exercises. Merely aligning the hypotheses is not enough. For example, concerning the TIMES-TUMATIM output, an overview of the investment intensity in the different scenarios was requested. As a result, both VITO and UA made more detailed results of the assimilated scenario runs available to the Forum members. LEAP as a tool focuses at least as much on decision support (including data and scenario management, reporting, units conversion, etc.) as is does on the actual modeling of the energy system [17]. For this reason, SEPIA-LEAP is considered more a “tool” than a “model”. Whereas in LEAP advanced reporting facilities are wholly integrated into the tool itself, TIMES has to rely on external data handling and analysis software shells to present results in a user-friendly manner. TIMES does not have publicly accessible source code and data.

Question 9: How do the models deal with uncertainty?

The Forum members underlined the importance of elucidating in a simple and understandable way the very large uncertainties that accompany long-term cost estimates and which are often overlooked. One way to deal with uncertainty is to formulate the energy model as a “stochastic optimization problem”, where uncertain quantities are modeled by random variables. In a sequential decision process, a scenario tree is built, probabilities are assigned to future outcomes, and the model optimizes over all possibilities. This is the path taken by TUMATIM-TIMES, of which a stochastic version allows taking into account the uncertainty regarding the cost or availability of future technologies. An alternative is to approximate uncertainty by narrowing down the possibilities until a finite number of different scenarios yield the same solution. This approach, also known as the “coordinating solutions approach” [43], is embraced by SEPIA-LEAP. Although the intermediaries seem to insist on knowing exactly how to get to a 90% reduction in GHG emissions by 2100, what specific policies should be used and what the costs and benefits would be, this is not feasible because models of radical system change 50-100 years in the future must necessarily deal with “deep uncertainty”. Deep uncertainty occurs when analysts do not know 1) the appropriate conceptual models which describe the relationships among the key driving forces that will shape the long-term future, 2) the probability distributions representing uncertainty about key variables and parameters in the mathematical formulations of these models, and / or 3) how to value the desirability of alternative outcomes [44]. Consequently, the probability of selecting a fixed set of policies today that will be optimal over the next 50-100 years is zero. The optimal strategy must therefore be one of beginning in a certain direction and adapting as information is obtained. That direction should be robust in the sense of making progress while keeping promising options open. Or in the words of Swanson et al. [45], there is need for adaptive policies which are “more robust to a range of anticipated conditions and can adapt over time”. As it stands, neither of the two models is well suited to representing uncertainties or finding robust strategies under deep uncertainty. One option is to look for new research methodologies to improve adaptive policy making under deep uncertainty, such as “Exploratory Modeling and Analysis” (EMA). The transition of energy systems using EMA is explored by Pruyt, Kwakkel et al. [46].

6. Explicit recommendations made by the intermediaries

Dreborg [47] identifies four different types of futures studies. Directional studies investigate different measures in the short-term that will probably work in the right direction to a sustainable energy system. Short-term studies take immediate official goals as a starting point and try to find means of achieving them, constituting small steps towards sustainability. Forecasting studies apply a long-term perspective but with restricted presumptions of the possibilities of major changes. Backcasting develops normative scenarios, where the results describe a possible and desirable future.
Long term objectives are important and backcasting is an essential method, but according to the Forum members it should never be the only method The Forum members insisted that all the above mentioned studies have their merits, and that a single method should not be favored to the exclusion of others.

The project brought to light an urgent need to facilitate coordination between competing energy system modelers. The Forum participants proposed that BELSPO should initiate some kind of “platform”, where all energy (and climate change) modelers in Belgium could meet every three months or so, and exchange ideas, assumptions, data, results, etc. One possible good use of such a platform is to achieve unanimity about the terminology used. For example, “energy service demand” in TUMATIM-TIMES may refer to mobility using a particular transportation mode, such as by car, whereby any decrease in car use as a result of increasing energy prices or taxes is recorded as a welfare loss. In SEPIA-LEAP “energy service demand” would normally refer to transportation in general, regardless of the transportation mode, and thus permitting modal shifts without actually compromising overall service demand levels. At the time of writing, there are still no concrete plans for the installation of such a platform. However, as a kind of follow-up study, the federal public service “Health, Food chain safety and Environment” did commission VITO to organize a workshop on the status of long term modeling in Belgium for the transition towards a low carbon society in 2050, in which *all* relevant Belgian energy modelers participated [48].

The Forum members also suggested that both approaches should be made more relevant to energy and climate change policies by combining them in a more “holistic” approach. Such a merger could lead to a win-win situation. One possibility is to use the TIMES-TUMATIM ‘rational actor’ approach to derive the energy demand levels for those sectors (such as energy-intensive industries) where the hypothesis of rational economic behavior is more realistic than for other sectors. SEPIA-LEAP could then explore the behavioral variations or lifestyle changes (driven by other than price policies) in all the other sectors. Alternatively, both approaches could work iteratively. The visions of the Belgian energy system established in SEPIA-LEAP can be used as a starting point for the exogenous demand levels in TIMES-TUMATIM to ascertain the costs of policies leading to those visions. If those costs are considered too high, the initial visions can be adjusted during a second round of the SEPIA-LEAP approach, and run once more in TIMES-TUMATIM, until at some point both approaches converge.

7. Conclusions

In sum, we can conclude that the use of energy system modeling for policy support in the transition towards a low-carbon economy represents a clear trade-off. On the one hand, such models allow for the systematic and consistent inclusion of a variety of dynamic factors such as the demographic composition of the population, macro-economic evolutions, the availability of primary energy supplies, etc. On the other hand, such models may obscure the crucial role of subjective judgments made by the modelers in choosing a particular models structure and parameters. For instance, the typical TIMES model treats the evolution of technologies and demand response to energy prices in a very simple and deterministic way (compared to the 'real world'). Furthermore, the further we look into the future, the less we know with certainty. In the case of policy support for the low-carbon transition models and scenarios should therefore reflect this 'fact of life' and become simpler as they are projected further into the future. The inherent uncertainties presented by a large scale, multi-decadal energy transition imply that modelers cannot present solutions to decision makers that best solve the problem of GHG mitigation from now until 2100 (or 2050, at least). Neither model adequately addresses the uncertainties over a 100 year period nor do they adequately address how to create robust policies that will make progress in the near term while reducing the regret of not meeting the goals to a tolerable level in the long run.

On the timescales typical for this type of exercise (i.e. 2050-2100), formal energy system models are probably best used as inputs to a broader stakeholder process that weighs multiple sources of evidence. This may include sensitivity studies of the values of uncertain parameters as well as using a number of structurally different energy models (as suggested by the Forum intermediaries), but should also include a variety of qualitative considerations that are typically captured inadequately in formal models (e.g. the dynamics of technological innovations, drivers of energy-related behavior, etc.).

Analysts and decision makers should attempt to formulate more meaningful and specific questions that fall within the scope of energy system modelling. There is a clear need to establish a critical dialogue among the concerned parties (decision makers, intermediaries, modelers and analysts) because one cannot simply take the assertions of any of the parties at face value. The research reported in this paper only represents the perspective of the intermediaries; future research could extend the dialogue towards the other parties concerned. There is a huge and growing body of scientific literature discussing science-policy interfaces from a theoretical, empirical and/or normative point of view. Future research on the science–policy interface in the case of energy foresight can of course already draw many lessons from this body of literature. A good example is e.g. the work of Sheila Jasanoff [49, 50], which combines case studies with institutional analysis to consider what counts as “good science”, and gives an outline of the role that science knowledge should be expected to play in public sector decision-making. Having done that, one can evaluate how well different models could provide answers and how those analyses and answers could be communicated.

Perhaps the most important lesson to be learnt from the Forum experience is that different modeling teams are bound to come up with different policy recommendations based on the particularities of their modeling approaches and inevitably subjective assessments. Approaches such as BELSPO Forum precisely aim to more clearly explain and justify the sources of those differences to intermediaries and possibly even policy makers. The outcome of such processes injects a much necessary dose of healthy skepticism with regard to the policy goal of finding ‘the best solution’ to the transition challenge. Because of the political sensitivities involved in such ‘debunking’, it might be difficult to implement such Forum-like exercises as part of official governmental assessment processes. However, when carried out as a carefully thought-out and peer-reviewed independent assessment, the results of such exercises could prove to be very valuable in a more indirect way to the many analysts involved in energy transition policy support activities.

Acknowledgements

The Forum research project was funded by the Belgian Science Policy (BELSPO) Office. The authors first and foremost thank the intermediaries who participated in the Forum project for their many insights and valuable contributions. Also thanks to the project promoters at VITO, Wouter Nijs, and at UA, prof. Aviel Verbruggen. Special thanks to Igor Struyf, at the time program manager at BELSPO, for his much appreciated administrative and logistic support during the project, as well as enriching the discussions with his valuable trans-disciplinary insights. Last but not least, the authors thank two anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper.

References

[1] B. Götz, M. Blesl, U. Fahl and A. Voß, Theoretical background on the modelling of policy instruments in energy system models, Report on Work Package A of the ETSAP Project “Integrating policy instruments into the TIMES Model”, Institut für Energiewirschaft und rationelle Energieanwendung IER, Universität Stuttgart, July 2012. (available at http://www.iea-etsap.org/web/Projects/ETSAP_PI_WPA_IER.pdf)

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

[3] P. Söderholm, R. Hildingsson, B. Johansson, J. Kahn and F. Wilhelmsson, Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050, Futures 43 (2011) 1105-1116.

[4] A.H. Sanstad and L.A. Greening, Economic models for climate policy analysis: A critical discussion, Environmental Modeling and Assessment 3 (1998) 3-18.

[5] J.L. Sweeney and J.P. Weyant, The Energy Modeling Forum: Past, Present and Future, Energy Policy – The Global Challenge, EMF PP6.1, Energy Modeling Forum, Stanford University, Fall 1979. (available at http://emf.stanford.edu/files/pubs/22516/PP0601.pdf)

[6] B. Enserink, J.H. Kwakkel and S. Veenman, Coping with uncertainty in climate policy making: (Mis)understanding scenario studies, Futures 53 (2013) 1-12.

[7] M. Granger Morgan and D.W. Keith, Improving the way we think about projecting future energy use and emissions of carbon dioxide, Climatic Change 90 (2008) 189-215.

[8] A. Volkery and T. Ribeiro, Scenario planning in public policy: Understanding use, impacts and the role of institutional context factors, Technological Forecasting and Social Change 76 (2009) 1198-1207.

[9] EEA, Looking back on looking forward: a review of evaluative scenario literature, EEA Technical report No 3/2009, European Environment Agency, Copenhagen, 2009. (available at http://www.eea.europa.eu/publications/looking-back-on-looking-forward-a-review-of-evaluative-scenario-literature/at_download/file)

[10] EEA, BLOSSOM – Bridging long-term scenario and strategy analysis: organisation and methods, A cross-country analysis, EEA Technical report N° 5/2011, European Environment Agency, Copenhagen, 2011. (available at http://www.eea.europa.eu/publications/blossom/at_download/file)

[11] Couder J., Laes E., Nijs W. and Verbruggen A., Establishment of an ad hoc forum for the comparison of the TIMES-MARKAL and LEAP model as a support for Belgian Long-term energy policy, Final Report, 2014, Belgian Science Policy; Brussels, Available at http://www.belspo.be/belspo/ssd/science/Reports/BELSPO-FORUM_Finalreport_en%20.pdf

[12] All information on Stanford's Energy Modeling Forum EMF is available at http://emf.stanford.edu/

[13] A. Krueger and M.-A. Casey, Focus Groups: A Practical Guide for Applied Research, 3rd Ed., Sage Publications, London, 2000.

[14] D. Van Regemorter, W. Nijs and N. Renders, MARKAL/TIMES, a model to support greenhouse gas reduction policies, CP/22, Final Report, Belgian Science Policy, Brussels, 2007. (available at http://www.belspo.be/belspo/organisation/publ/pub_ostc/CPen/rCP22_en.pdf)

[15] Laes E., Couder J., Verbruggen A., Eggermont G., Hugé J., Maes F., Meskens G., Ruan D., Schröder J., Jacquemain J. and Italiano P., Sustainable energy policy integrated assessment "SEPIA", final report,2011, Belgian Science Policy; Brussels, Available at http://www.belspo.be/belspo/ssd/science/Reports/SEPIA_FinRep_FINAL.ML.pdf

[16] All information on ETSAP TIMES available at www.iea-etsap.org

[17] C.G. Heaps, Long-range Energy Alternatives Planning (LEAP) system [Software version 2012.0049], Stockholm Environment Institute. Somerville, MA, USA, 2012. All further information available at www.energycommunity.org

[18] Couder J. and Verbruggen A., Modelling the Belgian energy system with SEPIA-LEAP, FORUM, Intermediary Report, 2011, University of Antwerp, Available at http://www.ua.ac.be/download.aspx?c=.BELSPO-FORUM&n=103834&ct=103834&e=284652

[19] A. Grunwald, Energy futures: Diversity and the need for assessment, Futures 43 (2011) 820-830.

[20] O. Amerighi, U. Ciorba and M.C. Tommasiono, Inventory and characterization of existing tools ATEsT Models Characterization, Report Deliverable D1.1, ENEA, Italy, October 2010. (available at www.atest-project.eu)

[21] N. van Beeck,:Classification of Energy Models, Tilburg University & Eindhoven University of Technology, May 1999. (available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.43.8055&rep=rep1&type=pdf)

[22] Nordic Energy Perspectives, Coordinated use of energy system models in energy and climate policy analysis - lessons learned from the Nordic Energy Perspectives project, Th. Unger (ed.), Elforsk, Stockholm, April 2010. (available at http://www.nordicenergyperspectives.org/modellrapport.pdf)

[23] C.G. Heaps, Integrated Energy-Environment Modeling and LEAP, PowerPoint presentation, SEI-Boston and Tellus Institute, November 18, 2002. (available at http://unfccc.int/resource/cd_roms/na1/mitigation/Module_5/Module_5_1/b_tools/LEAP/Training_Materials/LEAP_Slides.ppt)

[24] P. Bishop, A. Hines and T. Collins, The current state of scenario development: an overview of techniques, Foresight Vol. 9 Issue 1 (2007) 5-25.

[25] Intelligent Energy for Europe, The Pan European TIMES model for RES2020, Model description and definitions of Scenarios, Project no: EIA/06/170/SI2.442662, s.l., 2009 (available at www.res2020.eu)

[26] D. Devogelaer, J. Duerinck, D. Gusbin, Y. Marenne, W. Nijs, M. Orsini and M. Pairon, Towards 100% renewable energy in Belgium by 2050, VITO, Mol, April 2013. (available at https://www.vito.be/SiteCollectionDocuments/VITO/Documents/130419_Backcasting_FinalReport.pdf)

[27] I. Anable, C. Brand, N. Eyre, R.I Layberry, N.Bergman, N. Strachan, T. Fawcett and M. Tran, Lifestyle and Energy Consumption, Working paper, UKERC/WP/ED/2011/00, UK Energy Research Centre, Oxford, November 2011.

[28] J. Quist and Ph.J. Vergragt, Backcasting for Industrial Transformations and System Innovations Towards Sustainability: Relevance for Governance?, in: K. Jacob, M. Binder and A. Wieczorek (eds.), Governance for Industrial Transformation. Proceedings of the 2003 Berlin Conference on the Human Dimensions of Global Environmental Change, Environmental Policy Research Centre, Berlin, 2004. pp. 409 – 437. (available at http://userpage.fu-berlin.de/ffu/akumwelt/bc2003/proceedings/409%20-%20437%20quist.pdf)

[29] J. Quist and Ph. J. Vergragt, Past and future of backcasting: The shift to stakeholder participation and a proposal for a methodological framework, Futures 38 (2006) 1027-1045

[30] R. Friedrich, A. Rabl and J.V. Spadaro, Quantifying the Costs of Air Pollution: the ExtenE Project of the EC, Pollution Atmosphérique December (2001) 77-104.

[31] R.G. Richels, R.S.J. Tol and G.W. Yohe, Future scenarios for emissions need continual adjustment, Nature 453 8 May (2008) 155.

[32] T. Barker, The Macroeconomic Effects of the Transition to a Low-Carbon Economy, The Climate Group, University of Cambridge and Cambridge Econometrics, 2008. (available at http://www.theclimategroup.org/_assets/files/Macroeconomics-effects-of-the-Low-Carbon-Economy.pdf)

[33] M. Jaccard, J. Nyboer, C. Bataille and B. Sadownik, Modeling the Cost of Climate Policy: Distinguishing Between Alternative Cost Definitions and Long-Run Cost Dynamics, The Energy Journal Vol. 24 N° 1 (2003) 49-73.

[34] K. Allacker, F. De Troyer, K. Putzeys, A. Janssens, C. Spierinckx and A. Vercalsteren, Sustainability, Financial And Quality Evaluation of Dwelling Types “SUFIQUAD”. Final Report Phase 1 Summary, Belgian Science Policy, Brussels, 2009. (available at http://www.belspo.be/belspo/ssd/science/Reports/SuFiQuaD_Summary_Phase1_DEF.pdf)

[35] R. Kemp, J. Rotmans and D. Loorbach, Assessing the Dutch Energy Transition Policy: How Does it Deal with Dilemmas Of Managing Transitions?, Journal of Environmental Policy & Planning Vol. 9 N° 3-4 September-December (2007) 315-331.

[36] N. Bergman, N. Markusson, P. Connor, L. Middlemiss. and M. Ricci, Bottom-up, social innovation for addressing climate change, Working paper, Environmental Change Institute, University of Oxford. 2010. (available at http://www.eci.ox.ac.uk/research/energy/downloads/Bergman%20et%20al%20Social%20Innovation%20WP.pdf)

[37] K. Ehrhardt-Martinez, J.A. Laitner and K.M. Keating, Pursuing Energy-Efficient Behavior in a Regulatory Environment: Motivating Policymakers, Program Administrators and Program Implementers, California Institute for Energy and Environment CIEE, Berkeley, August 2009. (available at http://uc-ciee.org/downloads/Motivating_Policymakers_rev.pdf)

[38] J. Backhaus, S. Breukers, O. Mont, M. Paukovic and R. Mourik, Sustainable Lifestyles: Today's Facts & Tomorrow's Trends, D1.1 Sustainable lifestyles baseline report, Energy research Centre of the Netherlands, Amsterdam, 2012. (available at www.sustainable-lifestyles.eu)

[39] Detailed information on the GEM-E3 model is available at http://ipts.jrc.ec.europa.eu/activities/energy-and-transport/gem-e3/

[40] D. Van Regemorter, Assessment of the Macroeconomic Impacts of NEC Scenarios with GEM-E3, Study prepared for the DG Environment, European Commission, Brussels, April, 2008.

[41] J.R. Ravetz, The Science of 'What-If?", Futures Vol. 29 N° 6 (1997) 553-593.

[42] J.R. Ravetz, The post-normal science of precaution, Futures Vol. 36 N° 3 (2004) 347-357.

[43] A. Ruszczynski, Modeling Uncertainty, Options Summer (1995) 12-13.

[44] R. Lempert, S. Popper and S. Bankes, Shaping the next one hundred years: New methods for quantitative, long-term policy analysis, RAND report MR-1626, The RAND Pardee Center, Santa Monica, CA, 2003.

[45] D. Swanson, S. Barg, S. Tyler, H. Venema, S. Tomar, S. Bhadwl, S. Nair, D. Roy and J. Drexhage, Seven tools for creating adaptive policies, Technological Forecasting and Social Change 77 6 (2010) 924-939.

[46] E. Pruyt, J. Kwakkel, G. Yücel and C. Hamarat, Energy Transitions towards Sustainability I: A Staged Exploration of Complexity and Deep Uncertainty, paper presented at the 29th International Conference of the System Dynamics Society, Washington D.C, August 18, 2011. (available at http://www.systemdynamics.org/conferences/2011/proceed/papers/P1129.pdf)

[47] K.H. Dreborg, Essence of backcasting, Futures, Vol. 28 N° 9 Nov (1996) 813-828.

[48] J. Duerinck, Transition towards a low carbon society in 2050: Status of long term modelling in Belgium, VITO, Mol, April 2012. (available at http://www.klimaat.be/2050/files/5513/8323/2905/Models_final_report_.pdf)

[49] S. Jasanoff, *The Fifth Branch. Science Advisers as Policymakers*. Harvard University Press, Cambridge, MA, 1997.

[50] S. Jasanoff, Technologies of humility. Nature 450 (2007): 33.