A critical assessment of energy-economy-climate models

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1. Introduction

Climate policy discussions involve complicated inter-linkages between the climate system, the energy system, the economic system, political processes and issues of fairness and justice. Furthermore, climate change involves actions that span and have consequences over several decades and centuries. For these reasons, among others, energy-economic models have been used for climate policy studies.

However, the use of models for studies of energy and environmental issues is not new. Groundbreaking steps related to this area of research were taken in the early Seventies with the publication of *The Limits to Growth*, Meadows et al. (1972), including the reactions to this study, and attempts to analyze the turmoil of the first oil crises. Novel theoretical research included articles by Dasgupta & Heal (1974), Solow (1974), Stiglitz (1974), and Salant (1976), while innovative numerical approaches to energy, resource, and environmental economic analysis were taken by Meadows et al. (1972), Nordhaus (1973), Nordhaus (1979), and Manne (1976). Although various models have been developed and improved during the last decades, much of the underlying theory behind these models and their conceptual modeling approach can be traced back to the 70's or even earlier.

This task, to study the interactions between the energy system, society and the climate system, is of course very complex, and it involves linkages that are not well known, especially those concerning socio-economic interactions that take place several decades into the future. Considering this level of complexity, one must interpret the results of models with care and be aware of the limitations of such models and their results regarding direct policy input. Models should be seen as tools for generating insights and offering plausible pictures on how the future may develop in internally consistent ways given a set of assumption of important driving factors such as climate policies, resources, technology progress, etc.

In this report we will examine nine different energy-economy models with various scope and theoretical backgrounds. We have selected examples of (i) partial equilibrium energy-economic models: MESSAGE, POLES, GAINS and GET, (ii) policy simulation models: MiniCAM, PRIMES, and TIMER (with IMAGE/FAIR), and (iii) two general equilibrium models: MERGE and GEM-E3.

First, we provide a framework for the kinds of questions these types of models usually address. Second, we provide an overall characterization of the models. Third, there is a discussion based on recent model comparisons in academic literature, followed by an assessment of the models in this study with a discussion on their strengths and weaknesses. Fourth, we include a discussion on how such models have been used as input to analyze emissions pathways compatible with long-term climate stabilization targets. In section five we offer a shortlist of, from our point of view, appropriate use of different models, and in section six we discuss the problems of choosing the “right” model. At the end we provide an Appendix with more detailed characterization of the chosen models.

2. Characterization and use of energy-economy-climate models

2.1 Utilization of energy-economy-climate models

Energy-economy-climate models are used to answer several different types of questions concerning how economy, technology and climate targets interact. Below are listed the most common types of questions addressed by energy system models:

1. Cost of climate stabilization (primarily the cost pertinent to the energy system). The models are used to estimate the cost, or the cost difference compared to a business-as-usual scenario, for the world or a region to reach a certain emissions or climate target.
2. Feasibility. Related to cost estimates are assessments on whether it is feasible to reach certain climate targets (primarily emissions, concentration or radiative forcing targets, as temperature targets are often assessed in a separate modeling step). In these cases assumptions on technology availability and diffusion rates are crucial.
3. Burden sharing. If the world strives to meet a climate target or an emissions target, questions arise on who will mitigate how much and who will pay for the mitigation. For this purpose different fairness principles may be used and then evaluated by regionalized energy-economy-climate models.
4. Role of technologies. Energy system models may be used to evaluate the potential role of certain technologies in a climate constrained future.
5. Exploring the future and baseline scenario construction. Models may be used to explore possible futures and how these futures may depend on aspects such as population growth, urbanization, economic development, resource constraints and technological development.

The answers to these questions depend critically on, among other things, the time span one utilizes in the modeling. Four different time perspectives are of interest for discussion:

1. *Years.* If one considers system development over only one or a few years, no large changes in the energy system emerge since most of the capital stock remains intact. In this perspective the probability for concluding sensible predictions is relatively high. Econometric based models and computable general equilibrium (CGE) models with short term elasticities may be applied to such questions, while energy system models are often less useful. The strength of energy system models is that they capture capital turnover and technical change in the energy system, which is a process too slow to have any significant impact over a time perspective of only a few years. CGE models

capture the change in the economy when it has been moved to a new equilibrium given change in, for example, tax schedules. To capture short term phenomena it is therefore vital to apply short-term elasticities.

2. *Decades.* For many questions connected to emissions negotiations and policy planning, a time span over one or a few decades may be considered, typically up to 2020 or 2030. For these time horizons the investigation of what role different technologies can play in meeting certain emissions targets becomes interesting, along with their associated costs and what impact climate policies may have on the economic structure of a country, region or on the global level. Detailed predictions are not possible. However, for example, one can with energy system models illustrate possible energy system development within several scenarios given different climate policies. For insights into how the general economy may be restructured given changes in policies, CGE models are typically suited for this time perspective. The analysis of such scenarios can provide important input to policy makers and their advisors. However, in scenarios with substantial reductions in emissions a relatively detailed model of the energy system must be designed so that possibilities for change in energy technologies and fuels are reflected. Furthermore, to predict the costs and feasibility of reaching certain climate targets, the representation of inertia and diffusion of new technologies in the energy system is essential. The applicability of CGE models depends on how large the required changes in the energy system must be to achieve relevant policy goals and if the model can account for the expansion of new energy technologies (i.e., if the CGE model is a hybrid CGE and energy system model or not). CGE models are typically based on a social accounting matrix[1] calibrated to a year in the recent past (say, 2005). If the scenario studied carries the economic system far off the conditions prevailing in the year for which the social accounting matrix was based on and if the model does not include the possibility of new technologies (which standard version CGE models do not) the results tend to become less relevant for scenarios aiming for, for example, large cuts in GHG emissions.

3. *Half a century/2050*. In climate policy discussions, benchmark emissions for 2050 are often discussed and used as targets in national and international planning (for example the EU's Roadmap 2050 & Swedish climate policies with zero net greenhouse gas emissions by 2050). On this time scale, CGE models (if not of the hybrid type) become less useful since the system is carried too far from the year for which the social accounting matrix is based on, while many energy system models may be more applicable. By 2050 the energy technologies in operation today will have likely been replaced, and large scale restructuring of the energy system is theoretically possible, although the decisions concerning energy system investment today is likely to have an impact in 2050.

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[1] A social accounting matrix is an input-output table of the economy in question and that includes input/output categories based on the resolution of the CGE model.

4. *Century.* A 100-year perspective is often considered in the discussion on energy and climate stabilization. Within this time horizon the whole energy system may be replaced two or three times, and for parts of it, like cars, even more. With this long time span the costs and feasibility of different technologies are inherently uncertain, and new energy technologies that are today not considered in these types of models may have been developed. Predictions are not possible. Rather, the aim with energy system models in this context is to get a qualitative and internally consistent picture of energy system development, as represented by different scenarios, and how it connects to climate change issues. One may also obtain an understanding of what role different known technologies can play in meeting emissions targets.

In the present report, we focus on the time horizons of decades to centuries, as this is of primary interest for policy issues related to climate change and a restructuring of the energy system.

2.2 Model characteristics

Different models have different characteristics that are important to take into account when interpreting the results from them and for understanding what questions the models are suitable to analyze. In Table 1 we have listed some important features of the models studied in this report. However, this characterization gives a crude picture of the models since there often exist versions with slightly different characteristics, and some important features may not be captured within the categories used here.

The first category in Table 1 is called “type,” in which the basic driving principle of the model is characterized. Many of the models covered in this study are optimization models, which mean that the system cost is minimized, or welfare maximized (if the model is a partial equilibrium model the consumer and producer surplus is typically maximized). In an ideal world this would be the outcome of a market economy without distortions and with full information. The optimization features may be used with various time dynamics. The optimization may either be done at each time step without knowledge about the future, through myopic optimization (a recursive dynamic model), or with rational expectations (a generalization of perfect foresight). Rational expectations mean that the model considers all future events such as prices and carbon constraints in the optimization. There are also model approaches that try to bridge the myopic and rational expectations approaches, for example, models with limited foresight. In limited foresight models the model optimizes over a time frame of some decades, i.e. the foresight is perfect, but only over a limited period of time. Even though the foresighted is limited to a few decades the model may be used to analyze the development over longer time horizon (Hedenus et al., 2006; Keppo and Strubegger, 2009). The optimization time horizon has some important implications. One may argue that it is unreasonable that the market would anticipate the future with perfect knowledge for the next hundred years as is assumed in a rational expectations model. However, a rational expectations model has on the other hand the possibility of presenting a prescriptive image. Thus, if we know the climate constraint and energy price or energy resources, or at least have a probability distribution of them, the model can find the energy system solution that is most cost-effective given the assumptions and constraints at hand. Another possible feature of an optimization model, assuming rational expectations, is the integration of a carbon cycle or simple climate model, so the climate target may be expressed in terms of greenhouse gas (GHG) concentrations, radiative forcing or global average surface temperature In simulation models that are used to assess the possibility of climate targets, the models are in general run with a GHG tax (or in some cases with annual emissions constraints), and the emissions path generated is tested ex post tested if it is compatible with the climate target at hand or not by using a simple climate model (often MAGICC).

In myopic optimization models (or dynamic recursive models) the market agents do not have any foresight or expectations of what happens beyond the time period the agents are in. This is also a highly idealized representation of real world decision making. Still, how well a model represents reality may be as dependent on the choice of parameters and other features in the model as the length of the foresight. New model approaches in which optimization and simulation are combined with agent-based modeling are under development, and some models of that type already exist, see, e.g., (Sassi et al, 2010), but none are part of our study.

In addition to the rational expectations and the myopic approaches discussed above, one of the models (TIMER) included in table 1 takes yet another approach. This model can be characterized as a system dynamics model. There is no rational forward looking behavior in the model but the agents the model strive to simulate are assumed using heuristic forecasting approaches for prices and other relevant variables when determining if an investment will be made or not. These heuristics are based on limited empirical data on how companies and consumers actually behave, but many parameters critical for the heuristically forecasting methods are based on expert estimates.

The next distinction made is between partial market and full market models. In cases where the models are based on optimization approaches, the division is often termed partial and general equilibrium models. In partial market (partial equilibrium) models the effect of price changes, resource base, policy instruments, etc., are studied within a part of the economy, often in the energy system and in some cases the land use system. In a general equilibrium model, also the effects to other sectors are considered, thus how increased energy prices may affect the service sector, labor market, etc., and in the end, GDP growth.

Most models considered here are bottom-up models, which mean that there is an explicit and relatively detailed representation of the energy system and in some cases other systems. From the model results one may analyze a certain technology using a certain fuel in a given sector. In top-down models, production functions or marginal abatement curves are used instead of detailed technological representation. These functions may either be calibrated with data from bottom-up models or through empirical data. Anyhow, one cannot obtain as detailed results of the energy system in a top-down model as in a bottom-up model. However, one may ask what does the level of detail mean; is it useful or not? The uncertainties are so large concerning a future energy system, and presenting detailed results on what could happen far off in the future is in general not suitable. Morgan and Keith (2008) argue that it may even be misleading for a user of the results since detailed results are often interpreted to be more reliable than results using less detail, even though the reliability of the results should be judged equally. However, this does not mean that one should avoid having a detailed representation in the models. Rather, the issue is related to how one presents the results. For example, under circumstances when the model improves with increased level of detail one should not refrain from adding a level of detail to the model. However there is no apparent reason why one should strive to present the model results at the most detailed level possible.

Table 1. Characteristics of the models studied

	Type	**Scope**	**Regions**	**Sectors**	**Time span**	**Gases included**
MERGE	Optimization, perfect foresight, general equilibrium	Whole economy, hard linked simple climate model.	9 world regions	2 energy sectors, one economy sector	2000-2100	Non land-use CO2, CH4 and N2O, sulfur aerosols.
MESSAGE	Bottom-up, perfect foresight optimization, partial equilibrium	Energy system, soft-linked to simple economic growth models.	11 world regions	6 demand sectors	2000-2100	Main GHGs
Mini-Cam	Bottom-up myopic optimization, partial equilibrium	Energy and land use.	14 world regions	3 energy demand sectors	1990-2095	15 GHG and aerosols
GET	Bottom-up, perfect foresight optimization, partial equilibrium	Energy, hard linked simple climate model	1 or 10 world regions	5 demand sectors	2000-2100	Non land-use CO2, MAC curves for CH4 and N2O
POLES	Bottom-up myopic optimization, partial equilibrium	Energy	47 world regions	22 energy demand sectors	2000-2100	Non land-use CO_2
TIMER	Bottom-up system dynamics	Energy, can be linked to include land use CGE.	17 or 26 world regions	5 demand sectors	2000-2100	Main GHGs and aerosols.
GAINS	Bottom-up, optimization	Energy, waste, agriculture	47 European regions	13 sectors	2000-2050	Non land-use CO_2, CH_4, N_2O, HFCs PFC, SF_6
GEM-E3	Top-down myopic optimization, general equilibrium	Whole economy	26 world regions or 15 European	4 energy sectors, and 14 other branches	2000-2050	Main GHGs
PRIMES	Bottom-up myopic optimization, partial equilibrium	Energy	27 EU countries	4 demand sectors	1990-2050	Non land-use CO_2, CH_4, N_2O, SO_2, VOC, PM

In the second category in Table 1, “scope,” the overall scope of the model, is indicated. In this column we try to capture in general what the models include, i.e., what is hard-linked and soft-linked in the model. Several of the models have in some studies been soft-linked or only loosely connected to other model parts that are not indicated in the Table 1. It is impossible to give a comprehensive picture of all co-runs of different soft-linked models, but we try to capture the main model parts. The categories “regions”, “sectors”, “time span”, and “gases included” indicate the level of detail for the geographical, temporal, sectoral, and emissions scope of the model.

In Table 2, further details of the models in addition to those in table 1 are presented. All bottom-up models have a relatively detailed representation of the supply side of the energy system. However, the extent that the demand side is represented varies. The response in the demand side may be represented by a price elastic demand function where demand reduces as energy prices increases, and vice versa. In this case behavioral changes (driving less, lower indoor temperatures), structural changes (more service based economy, relocation of housing) and technical changes (energy efficiency measures, better insulation) are lumped together. In other cases some important end-use technologies are represented, such as passive housing, energy efficient industrial processes, etc. In some cases a combination of the two methods are used.

As many models span over long periods of time, technological evolution becomes a pressing issue. In this category it is indicated whether models use endogenous or exogenous technological change. If technology evolution is represented exogenously, cost and performance change over time according to a pre-set schedule. In models with endogenous learning, performance and costs are improved as a result of investments. Thus, as agents in the system invest in a certain technology, the cost of this technology decreases; however if no investments are made, no or little improvement occurs.

Technology dynamics indicate how restrictions on technology diffusion are represented in the model. Technology diffusion becomes especially important if stringent climate targets should be reached within a short time frame; in these cases fast diffusion of new technologies are essential. Some models restrain the diffusion of a new technology by a certain percentage per year, an expansion constraint. The parameterization of these constraints is seldom made public since they are in general estimates based on expert knowledge. Other models use distribution functions that depend on relative prices of the technologies and fuels to allocate energy technologies within a sector. In an optimization model, without constraints, investment is solely made in the cheapest technology. Still, in most sectors in reality, investments are made in a diversity of technologies. To represent this, a distribution function can be used to allocate the investment among technologies with similar costs. Depending on the parameterization, this makes the sector more diverse than would otherwise have been the case in a linear programming type optimization model. These distribution functions also implicitly constrain the diffusion of new technologies. Some models also represent vintage capital, so that old capital in the model remains with a different (in general worse) performance than the new investments.

Table 2. Characteristics of the models studied

	Demand side	**Technology evolution**	**Technology dynamics**	**GDP representation**
MERGE	Energy can be substituted by capital and labor.	Endogenous (some versions)	Expansion constraints	Exogenous productivity improvement with endogenous growth or exogenous GDP, depending on version.
MESSAGE	Demand elasticities (in one version). Often a fixed demand is assumed.	Endogenous or exogenous	Expansion constraints	Exogenous GDP
Mini-Cam	Demand elasticities	Exogenous	Relative price dependent distribution functions	Exogenous GDP
GET	End-use technologies for transportation	Endogenous or exogenous	Expansion constraints	Exogenous GDP
POLES	Demand elasticities and end-use technologies	Endogenous	Relative price dependent distribution functions	Exogenous GDP
TIMER	End-use technologies and demand elastictities	Endogenous and exogenous	Relative price dependent distribution functions	Exogenous GDP
GAINS	End-use technologies	No	Capital turnover, data from PRIMES	Exogenous GDP
GEM-E3	Demand elasticities	Endogenous and exogenous	Capital turnover	Endogenous GDP
PRIMES	Demand elasticities and end-use technologies	Endogenous, economics of scale	Relative price dependent distribution functions vintage capital, perceived costs	Exogenous GDP

Finally GDP is in most bottom-up models exogenous. Thus, the development of the energy system does not affect the GDP growth. However, MERGE has exogenous productivity improvement, whereas GDP is affected by energy price increases. In GEM-E3, GDP growth is determined endogenously.

3 Critical issues and analysis of model results

3.1 Costs and feasibility of reaching stabilization targets

There are several studies in the academic literature in which models are compared. We have chosen to discuss a few of the more recent ones, namely the comparison projects ADAM and EMF-22. These studies include several of the models in our selection and analyses questions related to those we have for the present study.

3.1.1 ADAM

First, there is the study summarized in Edenhofer et al. (2010) which was part of the ADAM model comparison project. In the paper, five models are compared with respect to costs and mitigation strategies for meeting low CO_2 stabilization targets: MERGE, POLES, TIMER, REMIND, and E3MG (with the first three in common with our study). The E3MG model is a hybrid simulation model (Barker et al., 2006, Barker et al., 2008) that is salient in their study, both for its construction and in its strange performance.

One goal with their study is to make an assessment of the technological feasibility of reaching low CO_2-eq concentration targets and to estimate the associated costs. They select three targets: 550, 450 and 400 ppm CO_2-eq, all possibly consistent with a 2°C target but with different degrees of certainty. A goal of their study is to investigate technological barriers for the targets as well as the role of different technologies: How would the difficulty of reaching a certain target be affected by the availability of different technologies? These would include carbon capture and storage (CCS), CCS in combination with bioenergy (BECCS), large scale use of bioenergy and nuclear power. They claim that model comparison analysis can assist in finding possible scenarios or pathways to meet low CO_2 targets, and that it can provide a robustness test on the cost estimates as well as on the assessment of the importance of different technology options.

Assumptions on baseline scenarios are certainly of great importance when it comes to the assessment of technology options and costs for meeting low stabilization targets. In the study of Edenhofer et al (2010), there are in some respects significant differences between the models. For example, oil and coal prices differ by more than a factor of 4 between the most dissimilar baselines used. The E3GM model is noticeable for its declining oil price after 2050. One may still argue that comparisons between models with such wide differences between baselines (as well as among other assumptions) may be of value, since, if there are still results in common, the results indicate a certain degree of robustness. The authors argue also that an advantage in the variety of baselines exists as "The models are then able to cover a wide range of possible futures." We agree that could be the case if the baselines could be varied in a controlled way, but here there is a variation both in different baselines *and* different model structures at the same time.

When it comes to the results in terms of the primary energy scenarios generated, there are large differences among the models. In fact, the scenarios between 400 ppm and 550 ppm look more similar if they are produced by a single model than if one compares, e.g., two scenarios at 550 ppm but using different models.

The authors claim that the “first major result” of their analysis is that the models can “achieve the three stabilization targets.” This is certainly not a very strong result, and they also explain that some models had to be modified, i.e., equipped with CCS and BECCS, in order to achieve a feasible solution.

The value of a study of this type lies in the investigation of the role of different technologies for meeting low stabilization targets. But since there are relatively wide differences in cost estimates for a set of scenarios between the different models, one should conclude that the resulting qualitative picture and figures on costs should be viewed only with large error bars. A critical question is then whether one really needs such complicated models to make assessments of the role of different technologies. We think that for qualitative questions, one could and should use more simple models than those generally used in the literature.

It is worthwhile to notice that the models use very different strategies to achieve low CO_2 stabilization targets. POLES has an emphasis on end-use energy efficiency, as that is more explicit and detailed in that model. TIMER depends to a large extent on CCS of coal exhaust, and only allows BECCS for the more stringent targets (which is unclear to us why such a constraint should apply).

The position of oil in the transportation sector is also discussed, noting that except for the E3MG model, it dominates the transportation sector for a large part of the 21st century. This is a feature discussed extensively before, see, e.g., Azar et al. (2003), where the analysis is companioned with a sensitivity analysis (for details, see Azar et al. (2000)).

The reported costs for meeting different targets vary significantly among the models. The authors discuss the role of different baseline scenarios as a cause for this. The MERGE model has a large amount of coal in its baseline while REMIND initiates a large fraction of renewable energy. This results, for example in the 400 ppm scenario, in a cost of 2.5% and below 1% (of GDP), from MERGE and REMIND, respectively. (We leave E3MG outside this discussion as it reports a negative cost of 2% for the same target.)

To conclude, this model comparison clearly demonstrates how the results critically depend on model characteristics, including the choice of baseline scenario, yet in this paper, an investigation of parameter variations was not included, which we consider a very important part of a sensitivity and robustness analysis. It is clear that the results we get concerning energy system development and characteristics over a given century are very rough. This accentuates the question of whether we really need vast and complicated models for the analysis of a development over such a long time span. In fact, these models lack a transparency which we could gain from a suite of simpler models.

3.1.2 EMF-22

The EMF-22 project shares an aim with the ADAM project in that it attempts to assess the technological feasibility of reaching low CO_2-eq concentration targets and to estimate their associated costs. On the other hand, a difference between EMF-22 and the ADAM project is that in EMF-22 a delay in emissions reductions by emerging and developing countries is also analyzed. However, in our analysis of EMF-22 we focus on the scenario with global participation in reducing emissions of GHGs without a delay. For this effort, the following models were utilized: ETSAP-TIAM, FUND, GTEM, IMAGE (TIMER/FAIR), MERGE, MESSAGE, MiniCAM, POLES, SGM, WITCH. All baseline assumptions in the models differ, and they include different energy technology portfolios, while the only harmonized aspects were the stabilization targets and the delay in climate policies in the emerging and developing economies.

The EMF-22 project is summarized in (Calvin et al., 2009). The most stringent target assessed in EMF-22 is a global target of 450 ppm CO_2-eq (radiative forcing of 2.6 W/m^2 or approximately 390 ppm CO_2 only). Also, other, less stringent targets are included in the study: 550 ppm CO_2-equivalents and 650 CO_2-equivalents. The scenarios differ also whether an overshoot in radiative forcing is allowed during the 21st century or not. (Given that a 2ºC target should be met, an overshoot in the radiative forcing over the 21st century is a reasonable assumption due to the inertia caused by the world’s oceans.)

It can be worth observing that five of the ten models did not succeed in meeting the 450 ppm CO_2-equivalent target even with overshoot in radiative forcing. Of the models included in this report MERGE and POLES did not manage to meet this target, while MESSAGE, MiniCam and TIMER (given that BECCS is an option in TIMER) did. Only two of the ten models succeeded in meeting the 450 ppm CO_2 target without an overshoot in radiative forcing. However, it is not surprising that only a few models managed to meet this target since the current CO_2-equivalent concentration is already close 450 ppm CO_2-eq, which implies that emissions need to fall drastically during the coming years if this target is to be met. All ten models managed to meet the 550 ppm CO_2-equivalent scenarios, both with and without an overshoot.

The cost of meeting the climate stabilization target varies widely among the models. This large variation depends upon a range of factors such as baseline assumptions, carbon cycle/climate model applied, technology richness, etc. However, one relatively robust feature with the models included in the study is that the technology rich models (ETSAP_TIAM, IMAGE(TIMER), MESSAGE, MiniCAM) show a lower cost of meeting a 550 ppm CO_2-eq target without overshoot as compared to models with less technological details. These latter models also have their conceptual origin in a top down structure, Figure 1.

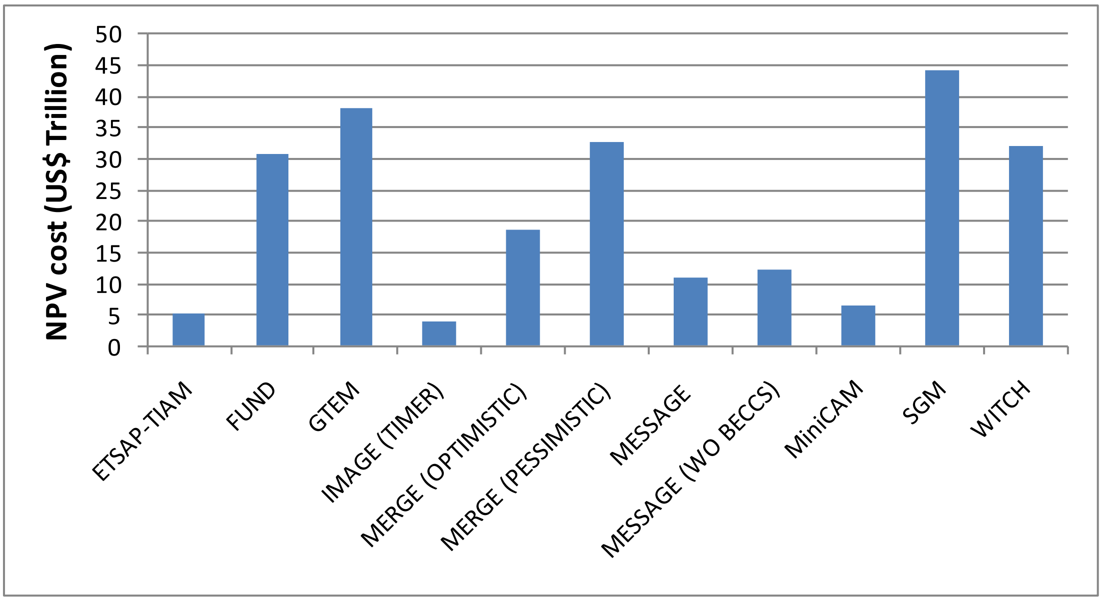

Figure 1. NPV cost of meeting a 550 ppm CO2-equvalent using a discount rate of 5%. About US$ 15 to 20 trillion corresponds to about 1% of the NPV GDP over the remaining part of this century in the scenarios that typically are used in this context.

As can be expected from cost results seen in Figure 1, the carbon price generated endogenously or applied exogenously varies considerably among the models. The prices at 2020 differ widely, from around 10 to 50 USD/ton CO_2 for stabilization at 550 ppm CO_2-equivalents without overshoot and between 15 and 260 USD/ton CO_2 for stabilization at 450 ppm CO_2-equivalents with radiative forcing overshoot before 2100. These numbers should be interpreted as the CO_2 price/tax needed globally in 2020 to be on a path towards stabilization at the target. The prices in 2095 in the 550 ppm CO_2-equivalent stabilization scenarios differ widely among the models, from around 200 to 2000 USD/ton CO_2. Typically the CO_2 price/tax grows close to (or slightly above) the rate of discount before the stabilization target is hit.

As for the ADAM modeling comparison, EMF-22 clearly demonstrates how the results critically depend on model characteristics. Also, it is clear in this study that the results one obtains concerning energy system development, stabilization pathways and costs of meeting climate targets are very rough estimates.

3.1.3 The EU 2050 roadmap

In the EU document “A Roadmap for Moving to a Competitive Low Carbon Economy in 2050,” (European Commission, 2011) four of the models discussed here were used — POLES, PRIMES in combination with GAINS, and GEM-E3 — together with two models for analysis of issues related to land use (agriculture and forestry) — G4M and GLOBIOM.

The report presents an impact assessment of European policies aimed at an 80% reduction of GHG emissions to 2050, which includes which technological and structural changes that are required to achieve this and the associated investments and costs. The starting point, based on current policies, is a reference scenario with projected emissions reductions as compared to

1990 by approximately 20% by 2020, 30% by 2030, and 40% by 2050. It is also assumed, as a base case scenario, that global oil and natural gas production will gradually increase from 2005 levels to accumulate an additional 20% by 2050. This includes assumptions on oil fields yet to be developed as well as unconventional oil.

The objective in the study is to investigate policies and the associated impacts leading to a low carbon EU economy by 2050. This also includes an analysis of global development under different assumptions, and an assessment whether the 2°C target can be met. For the EU, the emissions constraint on GHGs is set to –80% as compared to the 1990 level.

The chosen methodology is to create, characterize, and analyze a small number of scenarios with varying assumptions on technology development (delayed CCS, delayed electrification of transport sector), resource characteristics (oil price: shock, high/low), and whether the rest of the world adopts policies so that a global emissions reduction takes place (Global action vs Fragmented action scenarios). Five complementary models are used for the assessment, as mentioned above. For the global energy system scenarios POLES was used, while PRIMES in combination with GAINS was used for the European region. For impacts on GDP, employment and energy intensive industry, a global version of the GEM-E3 model was used.

It was concluded that the EU internal target of 80% emissions reductions is feasible, but that it requires stringent carbon prices across all sectors. In the case of the global action scenario, assuming global emissions by 2050 at 50% of the 1990 level, this is consistent with meeting the 2°C temperature target with a relatively high chance. In the fragmented action scenario, global emissions increases by more than 50%, and a larger temperature increase is to be expected (e.g., 3–4°C); the temperature response, of course, depends on the assumption of climate sensitivity and other uncertain geophysical factors.

The development of carbon prices shows levels around 50€ per ton CO_2-eq by 2030–35 for all scenarios (i.e., close to the reference scenario), but a large variety of price levels by 2040–2050 for the different scenarios, ranging from 100 to 500€ per ton CO_2-eq. The highest level is associated with the delayed CCS scenario, which indicates that the main scenarios rely on CCS to meet the 80% reduction target by 2050. It is also concluded that “despite significant variations in technological and fossil fuel price assumptions, results are quite robust in terms of the speed and magnitude of emission reductions over time.” But this is not unexpected since the 80% emissions reduction by 2050 is a given constraint, and changing the energy system takes time, implying that the emissions reduction will occur gradually over time. Most models, and most scenarios with such a target, would reproduce very similar emissions profiles, given the trajectory projected from current policies mentioned above. This emissions path surpasses reductions of 25% by 2020, 40% by 2030, and 60% by 2040.

On the cost side, the main conclusion is that the low carbon pathway leads to a shift from higher fuel expenses to large investments in new energy technologies. The investment increase approaches 300 billion € annually, which on average corresponds to 1.5% of GDP. Partial compensation may emerge in the form of decreased fuel costs. The global action scenario is particularly noteworthy for its projection of a price development of fossil fuels exhibiting a decline from 2030 and onwards. However, it must be noted that oil price development is subject to very high uncertainties due to resource availability, extraction costs and to the forces that determine market prices. A global action scenario could also be consistent with rising prices on oil in comparison to a reference scenario, see for example Johansson et al. (2009).

The chosen models are appropriate for the issues discussed. Some sensitivity analysis is done through the investigation of a small set of scenarios. The major conclusions regarding the energy system, its cost, and emissions are not unexpected.

3.2 Transaction costs, diffusion and learning

Most models take a cost-effectiveness approach, which means that the cheapest mitigation options are used first, and thereafter increasingly expensive ones are employed. This perspective, even though well-founded in economic theory, may cause problems under some circumstances as represented in a model. The cost of a technology is most often characterized by capital costs, fuel costs and operation and maintenance costs. These are the most important costs when comparing large scale facilities such as power plants. Hence, under these conditions the cost effectiveness principle is well founded. Energy efficient appliances (such as refrigerators, low energy light, etc.) are often found to be cost-effective from this perspective also. Still, in many cases, people tend not to invest as much in them despite their cost-effectiveness as described by a standard engineering based cost analysis. Economists have tried to explain this by pointing at other types of costs that are often omitted in these engineering based analyses. Transaction costs such as costs of seeking and processing information about new products are typically not included. Further, there may be risks associated with early adoption of a new technology as well as other hidden costs such as, for example, installation costs. Hence, the actual full cost will in general be larger than the engineering cost estimate. Finally, people tend not always to make the most cost-effective choice but act within “bounded rationality” (Nässen, 2007). In any case, if end-use appliances are introduced in a simulation model these costs and behavioral aspects, in addition to engineering costs, must be somehow considered. In other cases energy efficiency measures may be undertaken at a rate that has not been preceded in history.

POLES does represent end-use technologies and finds that half of the emissions reduction until 2030 consists of energy efficiency measures (Russ et al., 2009). This may be an indication that the transaction costs and intangible costs involved in energy efficiency measures are underestimated. This is of particular relevance, since POLES does not only try to point out technical potentials but also tries to simulate the development of the future.

Similar problems arise in GAINS, which is a bottom-up model that does not include transactions costs or hidden costs, but does allow the discount rate to be adjusted to represent risk aversion. In Winiwarter et al. (2010) they claim the mitigation potential for non-CO_2 greenhouse gases to be substantial and low cost. For a tax of 10 €/ton CO_2-eq, 36% of the mitigation will be of non-CO_2 GHGs, whereas they only constitute 18% of the total emissions in the baseline scenario. Non-CO_2 emissions are largely diffuse emissions and emerge from a set of smaller and larger actors. The problem here tend to be two-fold: First, there may be transaction costs and hidden costs associated with many mitigation options, especially in agriculture, and, secondly, it may be difficult to implement policy instruments that correspond to a certain carbon price level. This is less of a problem in GAINS as it is an optimization model that tries to point out cost-effective measures, and does not directly analyze measures that may take place for a given carbon price. However, since GAINS is also used in combination with simulation models such as POLES and PRIMES (i.e. European Commission, 2011), the results become difficult to interpret.

In European Commission (2011) the abatement of non-CO_2 gases in GAINS are rather modest, around 10% compared to the reference case. This corresponds relatively well to other estimates such as Beach et al. (2008) that estimated that the global emissions of methane and nitrous oxide from livestock could be reduced by 10-15% for a carbon price of €100 per ton CO_2-equivalents. Smith et al. (2008) estimated that the technical potential to reduce methane from livestock corresponds to 12% of present emissions. For nitrous oxide the technical reduction potential was estimated at 5% of current emissions.

Besides transaction costs and hidden costs, another factor, diffusion rates, may limit the diffusion of new cost-effective technologies. We discussed in section 2.2 different ways of handling diffusion in models. Distribution functions are a possible way of modeling a limited diffusion of new technologies and introducing heterogeneity in the system. A problem exists in calibrating the equations. For instance, in POLES' baseline scenario, plug-in hybrids, battery electric vehicles, hydrogen cars (both with internal combustion engines and fuel cells) as well as natural gas is present in 2100 (Kitous et al., 2010), even though the car market today is not very diversified. The reason the car market is not very diversified is related to a rather strong network externalities associated with a small scale distribution network of fuels. The large heterogeneity in the market found in (Kitous et al., 2010) may indicate that the parameter values give a too large heterogeneity.

Endogenous learning, the decrease in technological performance (primarily measured in costs) as a result of investments in the model, is introduced in some of the models we have studied here. Thus if large investments are made in wind power, the cost of wind power also decreases. This is rather realistic; however, the importance of introducing endogenous learning depends on other features of a model. The most used alternative to endogenous learning is exogenous learning, where costs decrease over time to a certain cost level. This long-term cost level can either be determined by engineering estimates or by extrapolation of learning curves. In a model with perfect foresight, the choice between endogenous and exogenous learning is of little importance for the technology mix and emissions targets. With endogenous learning one may see small shifts towards a larger share of technologies with a large learning potential at an earlier date than with a model with exogenous learning, although this difference depends much on the assumptions on diffusion rates (see above). Of major importance for model outcomes are the long-term cost level estimates of technologies. However, these do not depend on the choice between endogenous and exogenous learning (Hedenus et al., 2006). In myopic models, or models with limited foresight, how one deals with endogenous learning is of central importance. In such a model investments in new technologies do not appear for the reason that investments in the short-term leads to cost reductions in the long-term. In such models with no or limited foresight if and how technology policies are implemented in the models becomes central, hence one can study the effect of policies that induce investments.

Potential problems may emerge when distribution functions are combined with endogenous learning. In (Edenhofer, 2010), both wind power and decentralized photovoltaic (PV) production diffuse to their full technical potential also in the baseline scenario in the POLES model. This result is probably related to endogenous learning in combination with distribution functions. Even if a tiny amount of the technology is used in a time step (due to the distribution function), the cost will decrease in the next time step, which will allows for even larger diffusion. We cannot say for sure that wind power and solar PV will not diffuse to their full technical potential without climate policies, but it seems unlikely, and these results are most likely a clear example on their sensitive results may be due to the parameterization of the distribution functions and learning curves.

Furthermore, despite distribution functions, diffusion according to modeled outcomes may sometimes occur too rapid. In Russ et al., 2009, results from the POLES models show that in 2020 around 5% of the CO_2 emissions from the power sector are captured in the EU. The power sector in the EU-27 emits around 1300 Mton CO_2/yr (IEA, 2010), which corresponds to approximately 10 full scale coal CCS plants in 2020, which must be considered unrealistic (Hazeldine, 2009). These examples highlight that it is not necessarily the functions that determine whether the results become realistic or not, but the parameterization of the functions. However, given a frequent lack of data for parameterizing such functions, the parameter values must be based on educated guesses, which can lead modelers into two common errors. If a parameter is based on a guess and no reality check is performed on the results, they become irrelevant, or if the “right” results are seen as paramount, the model’s outcome can become pre-determined through the tuning of parameters. These potential problems are often experienced when only a limited number of scenarios are generated, which is often the case, rather than performing a thorough sensitivity analysis of crucial parameters, see for instance Bakker et al. (2009); while Azar et al. (2006) and Hedenus et al. (2010) for examples of more extensive sensitivity analyses.

3.3 Assessment of compatibility between short term emissions targets and long-term temperature targets – The cost-effectiveness versus feasibility

The concepts of cost-effectiveness and feasibility are connected in the analysis of climate targets. By feasibility we mean the achievability of meeting the target at hand, while cost-effectiveness refers to the way in which this target can be met at the lowest possible Net Present Value (NPV) cost. In the context of climate targets and emissions pathways an infinite number of emissions and technology pathways for meeting a target exist, given that the target can be met at all. Conversely, if the target is too stringent no pathway is feasible. Given a feasible climate target only one of the feasible pathways should be considered cost-effective, and this pathway will depend on the characteristics of the techno-economic model.

Determining the feasibility of emissions pathways is foremost dependent on the assumptions made regarding the geophysical system used in modeling. These assumptions include those of climate sensitivity, the parameterization of carbon cycle dynamics and parameterization of ocean heat uptake, among others. By considering only the geophysical system one would find the set of pathways that meets the constraints determined by the geophysical system, but leave out the constraints determined by the socio-techno-economic system. Adding characteristics on technologies, their costs and diffusion rates to the modeling would add information that could exclude some of the emissions pathways from the feasibility set that was based only on geophysical information. Hence, not necessarily all pathways that are feasible from a geophysical perspective are feasible from a techno-economic perspective.

One of these emissions pathways that is both geophysically and techno-economically feasible is the cost-effective pathway. This is practically how far one can get with the type of models considered in this report. However, not all of the pathways that are both geophysically and techno-economically feasible are feasible from a socio-political perspective. Hence, only a subset of the geophysically and techno-economically feasible pathways is socio-politically feasible, which cannot be assessed by techno-economic models. Potentially, none of the feasible pathways from a geophysical and techno-economical perspective are feasible from a socio-political perspective, And also, even if a few pathways are feasible from a socio-political perspective, these pathways may not necessarily include the pathway that is cost-effective.

In 2010, two policy oriented reports (Fee et al., 2010 and UNEP, 2010) focusing on the relation between emissions of GHGs in 2020 (and 2050) and the possibility of reaching long term temperature stabilization targets were released. The primary climate target that was analyzed in these reports was the target of stabilizing the global annual mean surface temperature below 2ºC above the preindustrial level. Central for the analysis in these reports were emissions scenarios taken from such models as those included in this report. For example, results from the ADAM and EMF-22 projects were central in both Fee et al (2010) and UNEP (2010) and contributed to a large share of the underlying emissions scenarios. The assessment of emissions level in 2020 (and 2050) and the likelihood of remaining below 2ºC above the preindustrial level were performed by using these emissions scenarios and running them in the simple climate model MAGICC (Meinshausen et al., 2011). Given certain assumptions on probability distributions for climate sensitivity, carbon cycle parameterization, parameterization of ocean heat uptake, etc., the likelihood of emissions scenarios leading to a global mean temperature change of less than 2ºC above the preindustrial level was assessed. The construction of such probability distributions is a very complex issue given very large uncertainties at hand. Although this issue is out of scope for this report, it is worth repeating.

When interpreting the numbers suggested as benchmark levels for emissions in 2020 and 2050 in Fee et al. (2010) and UNEP (2010) it is important to recognize that the underlying assessed emissions scenarios are in general constructed to generate the least cost solution for meeting a certain concentration or radiative forcing target. Hence, the emissions scenarios are not least cost scenarios for meeting the 2ºC limit with certain probability level. Also, the models that generated the emissions scenarios were in general not run to generate direct insights to some of the questions in focus in Fee et al. (2010) and UNEP (2010), which sought answers to questions such as the year of peak GHG emissions, the compatibility of GHG emissions levels in different years with stabilizing the annual global mean surface temperature below 2ºC above the preindustrial level, and the highest realistically achievable rate of emissions decline beyond the emissions peak. Hence, even though energy-economy-climate models can be set to analyze such questions, they are seldom used in that way. See O'Neill et al. (2010) for an exception where feasibility rather than cost-effectiveness is in focus for scenarios leading to different temperature targets. Also, given the rather subjective approaches used to model, for example, technology diffusion in the underlying models, the numbers presented in Fee et al. (2010) and UNEP (2010) should be interpreted with great care and seen as indicative numbers rather than strict levels.

4. Model Assessment

In this section we give a subjective assessment of the nine models' strengths and weaknesses.

MERGE: The model's strength does not lie in its rich description of energy technologies, neither in the rich description of the economic system nor in its description of the climate system, but in the combination of these three systems. With the use of a perfect foresight approach, the main driving mechanisms of the model are transparent in comparison with other models assessed in this report. Hence, the model should be seen as an important model for generating insights about the combined dynamics of the systems, but not for short term policy impact analysis.

IMAGE/FAIR/TIMER: This model package's strength lies in its ambition to actually simulate the evolution of the energy system. This model is thus relatively suitable for baseline scenario analysis and policy impact analysis. However, the ambition to simulate markets is also one of its main weaknesses since this approach makes the model rather non-transparent for outsiders. In addition, the models (TIMER-FAIR-IMAGE) are soft-linked in a way that obscures the implications of certain actions. Also, as in the case of many models, one may question the absence of some potentially import energy technologies in the simulation; in this case coal-to-liquids stands out as an important omission.

POLES: The model's strength lies in a detailed representation of the global energy system, including representation of end-use technologies. Several features are included that aim for a simulation approach. The model is sometimes linked to other models, such as IMAGE and GLOBIOM, which further reduces transparency.

PRIMES: A detailed representation of the European energy system, including representation of end-use technologies and non-monetary costs of new technologies, is the strength of PRIMES, which is also linked to POLES to generate global energy prices. Good documentation is lacking, and linkages to other models such as GAINS increases the lack of transparency.

GAINS: The model's strength lies in the richness of the number of technologies included and the simple decision criteria applied - cost minimization. Hence the model can be used to assess the technical potential of abatement options under stylized conditions. However, one may question the model's usefulness as a simulation of how the market may react to, for example, a new policy package.

GET: GET's overall simplicity yet fairly detailed description of technologies are its strongest advantages. These points make the model suitable for analyzing questions such as which climate targets may be feasible given assumptions of technology availability. Its weakness for short-term policy analysis corresponds to its rather weak ability to capture short-term aspects of energy system change.

MESSAGE: The model approach is very similar to the GET model, even though the model is more technology rich and gives a better regional representation. But overall the same comments we had of GET apply to MESSAGE as well.

MiniCAM: The model's strength lies in its detail regarding most important greenhouse gases and reflecting and absorbing aerosols together with both a land use model and its explicit connection a simple climate model. MiniCAM has a rich description of the energy system, from energy supply and transformation technologies to end-use.

GEM-E3: The foremost strength is its general equilibrium approach; its weakness is its crude description of energy technologies. The model is suitable for evaluating the impact policies could have on structural change in the economy in the short-term (less than 10–20 years) but less useful for long-term analysis. Since the energy system is not described in detail, the model should be used in combination with models with higher detail of the energy system for investigation of energy system issues.

5. Discussion

We have in this report tried to characterize and discuss several different energy-environment-economy models and results from such models. When these models and their results are used in a policy planning process, the presentation of quantitative results to motivate policy proposals is often considered important. Results that are often highlighted in such a context are the cost of meeting a certain climate or emissions target, the expected carbon price needed to achieve the targets, emissions levels for specific target years and the diffusion of certain technologies. As a researcher it may appear tempting to prescribe which models that can provide the most accurate numbers for policy makers. However, after a lengthy involvement in this research branch and the reading of numerous reports and papers based on various models, one firm conclusion is that no single model can be considered as more accurate than many others. Also, it is clear that the same model behaves quite differently in different studies. The reason is likely a combination of model development, different model versions, the choice of parameters and scenarios, etc. What one may say is that some models include a more realistic representation of diffusion and learning-by-doing, foresight by economic agents or economic-wide effects. However, the estimates based on these models are not necessarily more accurate than the numbers presented by a simpler model. The uncertainties involved are vast, and some important mechanisms operating in the real world may still be missing, causing results to be skewed in one way or the other.

Uncertainties in this context in general highlight the importance of sensitive analysis. This is most often absent both in policy reports as well as in academic literature. Sensitivity analysis can be made in several different ways. Most often some scenarios that differ in technologies available or fuel prices are tried. Such an analysis gives some insight into the uncertainties, but in general, only a very limited set of possible futures are examined. A more thorough analysis is robustness analyses, but this is seldom done. In such an analysis the robustness of the main results are tested with respect to changes in parameters such as technology costs, diffusion rates or resource availability. This kind of analysis may provide a much deeper understanding of the model and the results, but these kinds of analysis are rare also in the academic literature as it many times requires extensive programming.

Sensitivity analysis can also be made by using Monte Carlo methods, where some parameters are randomized given a specific probability distribution for each parameter in a large number of model runs. With this analysis one may get both an assessment of the uncertainty range of the variable studied (carbon price for instance) as well as an assessment of which parameters that are important to the results. A Monte Carlo analysis typically requires at least 100 to 1000 models runs, and thus to be possible, the model cannot have too long running time. Here emerges a trade-off in model development. A more advanced model may capture more interlinkages but creates on the other hand difficulties for performing a Monte Carlo analysis.

A yet different form of sensitivity analysis is the variation of some structural characteristics of the model. This could include running the model with or without endogenous learning, with longer or shorter foresight, with or without a hard link to a simple climate model and with or without a hard link to the land use system for instance.

One alternative to structural sensitivity analysis is a multi-model assembly in which several different models are used to analyze a mutual question. This is done on a regular basis and two such studies were discussed above in section 3.1 (ADAM and EMF-22). However, such model results are generally compared, and little effort is made to explain and analyze the difference in the model outcome, which makes the results to have limitations as policy inputs, see also O’Neill & Nakicenovic (2008), who share this view. However, a few papers exist in which differences in results from different models are analyzed in greater detail, see for example Grahn et al. (2007).

It may be less difficult under specific circumstances to assess which models can produce qualitative insights into different issues. For instance the study of long-term effects on technology specific policy instruments (like green certificates) in a prefect foresight model is not very useful, as the model anyhow can foresee cost reductions in the future. GAINS is relevant to estimate the techno-economic potential in different sectors, but may be not as good for studying the expected effects of a certain policy, as the behavioral representation is rather simple. Myopic models cannot be used to study cost-effective emission pathways; here perfect foresight is required.

Finally we would also like to raise the importance of the modeling team. As there are so many uncertainties at hand, and so many unknown parameters in the models, the modeling team must know the real underlying system they are studying as well as the model they are using. Knowledgeable researchers can with a very simple model offer important insights both for research and policy planning. Without a proper understanding of the real system one may easily make unrealistic assumptions or use the model for questions for which it was not intended to be used. However, our experience tells us that building and running a model is a good way of gaining insight in how the real world system works. Thus, just running a few scenarios on a readymade model, imposes a risk that odd results may be presented, and without actually gaining understanding of what may occur in the real world.

From this we can conclude that in general perhaps less focus should be put on which model is used, given that the model includes the basic characteristics that are needed to analyze the questions posed. More important for reliable and robust results that are usable for informing a policy process is that extensive sensitive analyses are performed and that the modeling is led by a skilled modeling team(s). The importance of details such as the number of demand sectors, regions, diffusion rates and if technological change is endogenous or exogenous tend to be relatively small when overall questions such as cost of stabilization, timing of emissions reductions or carbon prices are studied.

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Appendix: Model descriptions

MERGE

MERGE — a Model for Evaluating the Regional and Global Effects of greenhouse gas reduction policies — is an integrated energy-economy-climate model covering all three aspects. The model consists of:

- A two sector energy system model covering electricity production and non-electric energy;
- An aggregate economy model where production and consumption of one representative good is considered; and
- A simple climate model where calculations of the concentration, radiative forcing and temperature of the most important GHGs are considered.

The world is divided into nine geographical regions [USA, Western Europe, Japan, Canada-Australia-New Zealand, Eastern Europe and the former Soviet Union, China, India, Oil exporting countries, the rest of the world (Richels & Blanford, 2008)]. Trade in energy resources and the representative consumption good between the regions can take place.

The model is an intertemporal optimization model where savings, investments, non-renewable resource extraction and greenhouse gas emissions. These are determined by that one representative consumer in the each of the regions who maximizes his net present value utility. The impact of greenhouse gas emissions are either considered by the use of a climate damage function (in which market and non-market impacts are valued in economic terms) or by the inclusion of constraints on emissions, concentration, radiative forcing or global average surface temperature. Rational expectations, the generalization of perfect foresight, are assumed. The model has in several papers been used in stochastic optimization applications where hedging strategies for uncertain long-term climate targets or damages are analyzed (Manne & Richels, 1992).

Currently, the MERGE model is developed by two different research groups which seem to develop the model rather independently of each other, Electric Power Research Institute (EPRI) in the US (who develop and use MERGE) and the Energy Economics Group at the Paul Scherrer Institute in Switzerland (who develop and use MERGE-ETL). The basic structure of the two versions is the same, and the primary difference is that MERGE-ETL contains more energy technology options.

MERGE is not a technology rich model, although it represents different technologies and resources. It tracks the depletion of oil and natural gas but not coal, which is assumed to be present in such large amount that it is not necessary to track depletion. MERGE-ETL has a somewhat richer description of technologies than MERGE and does include for example biomass with CCS. This is one reason why lower climate stabilization levels are attainable in MERGE–ETL than in MERGE [compare for example Magne et al. (2010) for MERGE-ETL and Blanford et al. (2009) for MERGE.

The model has been used extensively to assess various aspects of climate policy and was one the first energy-economy-climate models that took into account climate policy constraints and their influence upon economic growth and the energy supply mix.

MERGE was used in the Energy Modeling Forum 22 focused on climate stabilization, or to be clear, radiative forcing stabilization at 2.6 W/m^2, 3.7 W/m^2 and 4.5 W/m^2, with delayed participation by developing countries (BRIC and other developing countries as two groups representing the developing countries). To summarize briefly, a 2.6 W/m^2 limit (without any overshoot) is not feasible, 3.7 W/m^2 is feasible under most conditions while 4.5 W/m^2 seems to be feasible given all conditions explored (Blandford et al., 2009). It is worth noting that under a no climate policy target case the energy system is very much dominated by coal during the second half of this century. In stabilization scenarios coal with CCS plays a significant role.

The baseline in MERGE-ETL is comparable to that of MERGE although wind expands heavily for electricity production while natural gas expands in the production of non-electric energy. In a 400 ppm CO_2-eq scenario all renewables sources of electricity expand rapidly above their baseline level, except wind which reaches its maximum potential already in the baseline (Magné et al, 2010). In the non-electric sector H_2 is the long run solution. Efficiency measures are not explicitly included, but energy demand is price responsive and as a result the demand for energy is cut when climate constraints are in place due to increased energy prices.

IMAGE/FAIR/TIMER

IMAGE is a group of linked and integrated models. The primary objective is to study long-term dynamics of global environmental change. The IMAGE group of models consists of a land use model; TIMER, an energy system model; FAIR-SIMCaP, a combined GHG abatement model and a simple climate model, SIMCaP (SIMCaP is in turn based on the simple climate model MAGICC, but also simulates emissions profiles compatible with various climate targets); and an IMAGE climate module also based in part on MAGICC. The models can either be used separately or in combination with each other. Most central for climate policy related discussions are the FAIR-SIMCaP and TIMER models.

TIMER

TIMER is a global energy system model based on a system dynamics approach. TIMER considers the demand and supply of 12 different energy carriers for 17 world regions (alternatively 26 world regions). Initially TIMER was originally developed as a globally aggregated model (called TIME) (Rotmans and De Vries, 1997)

The model is a simulation model where the dynamics of investment and fossil fuel depletion depends on defined algorithms and rules of thumb strategies but not on an optimization approach. Investments and non-renewable fuel depletion are determined by internally generated forecasts based on past development within the model and rules of thumb but without any foresight.

The model includes a range of primary energy options: oil, coal, natural gas, uranium, biomass, solar, wind, hydro and several potentially crucial abatement technologies such as CCS and H_2. The TIMER model explicitly tracks resource depletion of oil, natural gas and coal.

The TIMER model includes endogenous technological development based on ‘learning-by-doing’ as well as exogenous technological change.

Capital that is invested cannot be abandoned prematurely. This is an important aspect that limits rapid technological change as well as rapid cuts in emissions. Also carbon prices above \$1000 per ton C are not allowable within the model, since the technologies have not been evaluated for higher levels that this (van Vuuren et al., 2010).

The model utilizes a multinomial-logit function for representing cost heterogeneities that are present in the real world but missing in the model in order to avoid a single technology taking the whole market share within a specific market segment. Instead, the lowest cost technology takes the largest market share although not in general the whole share.

The TIMER model does include end-use technologies and the prospects for the use of more energy efficient end-use technologies. However, short payback periods are required for energy savings, in line with empirical estimates, and the model includes various premium values that reflect preference differences, environmental factors, etc., for different energy end-use alternatives.

For electricity production the model takes into account monthly load curves, the intermittency characteristics of many renewables and the requirement these place on the electric supply system.

The mode also includes the use of traditional biomass. The demand for traditional biomass decreases with increasing per capita income.

The potential for modern forms of biomass is determined by the land use model within IMAGE. The potential for dedicated bioenergy plantations is determined by land available to biomass production, which is determined by the amount of land that is classified as either abandoned crop land or part of natural grassland. Hence, the model uses a “food-first” approach and does not model competition for land between bioenergy and food production.

The TIMER model does not run towards any climate target, but rather a CO_2-eq tax profile is imputed, and whether the target is met is determined ex-post by running the generated emissions scenario in a climate model, often the IMAGE climate sub model or MAGICC. If the target is not met, a higher tax profile has to be imputed in TIMER.

FAIR-SIMCaP

FAIR is a simple model covering Kyoto GHGs and exogenous scenarios for other climate forces. The model can either be used as a standalone model to assess the costs and burden sharing of emissions targets or together with the SIMCaP model. SIMCaP is a simple climate model used to generate emissions pathways consistent with various climate targets (being concentration, radiative forcing, or temperature). The FAIR model does not generate baseline emissions scenarios; instead baseline scenarios must be taken from other sources, primarily TIMER, and emissions can be reduced by the use of marginal abatement cost functions. Hence no technology is represented within the model.

The regional marginal abatement cost functions used within FAIR for energy related CO_2 emissions are based on the TIMER model. The marginal abatement cost depends on the 30-year history of emissions prices in the model. Depending on the past CO_2 prices in FAIR suitable parameters for the marginal abatement cost function are picked from a database that is subsequently used for calculating the cost of abatement in a specific year. The parameters within the databases are generated by running TMER with different CO_2 emissions price paths (exponential growth, linear growth or constant prices) at different levels and at different growth rates. By allowing the abatement cost in FAIR to be dependent on past prices, the path dependency within the energy system is captured at least partially. In addition, constraints on how fast emissions may fall are implemented in FAIR in order to avoid unrealistic cuts in emissions. At what level this constraint is set depends on study, but usually about 3% of emissions in the year 2000 per year. Hence, the emissions decline at maximum rate of about 1.2 Gton CO_2-eq/year according to a linear path.

Estimates on the cost and potential for reducing non-CO_2 GHGs are from Lucas et al. (2007), while abatement cost functions for afforestation/reforestation are estimated from the land use module in IMAGE.

A demo version of FAIR is downloadable via:
http://themasites.pbl.nl/en/themasites/fair/download/index.html

POLES

Prospective Outlook on Long-term Energy Systems, POLES, was developed by the European Commission in the 1990s. POLES is a global partial equilibrium model with 47 regions, 22 energy demand sectors and around 40 energy technologies (Kitous et al., 2010; Russ and Criqui (2007). The model is rather technology rich in the supply side, with a large variety of technologies such as CCS, renewable energy of different kinds and nuclear energy. For a structural overview see (European Commission, 2010).

The overall economy is exogenous, whereas equilibrium is obtained in energy markets. Three regional gas and coal markets are simulated as well as one global oil market. The energy markets are assumed to not contain any market power, such as OPEC’s influence on the world market price of oil. The model is a recursive myopic optimization model that simulates the global energy supply from 2000 to 2100.

As POLES only considers the energy system and emission of CO_2, it can be soft-linked to other models to incorporate other aspects of climate mitigation. In Russ and van Ierland (2009), IMAGE was linked to POLES to estimate emissions from agriculture, GLOBIOM to consider deforestation and afforestation, and MAGICC to assess climate impact. In another study marginal abatement cost curves for non-CO_2 GHGs were included (Edenhofer, 2010).

Energy demand in POLES is derived from economic growth, autonomous technological trends as well as short- and long-term demand elasticities. Further end-use technologies are modeled to some extent such as more energy efficient buildings.

Electricity supply is modeled in detail through load curves over the year as well as the day. Technological diffusion is dependent on the return of investment, and the speed of diffusion is directly related to the profitability of a technology. Also the profitability affects the potential market share, as distribution functions are used to allocate market shares between competing technologies.

PRIMES

PRIMES is a simulation model for European energy policy analysis (Capros et al., 1999; European Commission) It covers EU-27 and has a detailed representation of different demand sectors and subsectors. Local air pollutants are included as well as CO_2, N_2O and CH_4. The model is myopic, optimizing for a time step of 5 years between 1990 and 2050.

PRIMES is soft-linked to GEM-E3 for macroeconomic and sectoral economic data, GAINS to assess the environmental impact of local pollutants, POLES and PROMETHEUS to determine world markets prices of energy and SCENES to simulate transport activities.

The model consists of detailed representation of the demand side. Demand for energy is calculated based on welfare optimization by agents, but also representation of habits, comfort, risk and inertia. Long- and short-run demand elasticities are applied at rather disaggregated level.

Ramsey-Boiteux methodology and mark-up prices are used to simulate energy prices.

The model is rather detailed in the electricity sector with representation of power flows and future interconnectors also. Economics of scale as well as learning effects are modeled as well as non-monetary costs such as the perceived cost of technologies and risk premiums. Further vintage capital is represented as well as inertia in the system.

It has a detailed bottom-up representation of technologies and fuels and also includes learning curves. Furthermore end-use technologies are included. Besides engineering costs of technologies, non-economic costs are included, for instance the perception of a technology to consumers.

GAINS

GAINS is a model developed at IIASA and is an extension from the model RAINS which focused on local air pollutants. GAINS is a bottom-up optimization model that finds cost-effective measures to mitigate GHGs as well as local pollutants. In the model the GHGs CO_2, CH_4, N_2O and three flouride gases are included as well as local pollutants NO_x, SO_2, volatile organic compounds (VOC), NH_3 and particulate matter (PM). The model is mainly used to assess co-benefits between GHG mitigation and local pollutants as well as to construct marginal abatement curves. GAINS is resolved in 5-year steps from 1990 to 2050. GAINS minimizes the cost to reach certain emissions levels. Investments are compared on the basis of levelized costs that include investment costs and variable and fixed operating costs.

There are many different regional versions of GAINS covering for instance China, India and Russia. In the European version of GAINS a high regional resolution of 47 regions (of which 5 are sea regions) comprises Europe including the European parts of Russia and Turkey. GAINS is also updated regularly with new data on national emissions inventories. A spatial resolution of 5000 grid cells is offered so the transportation diffusion of pollutants such as SO_2 may be studied.

The model assumes a free and fully integrated market for abatement technologies exists, thus the same cost applies for a new technology in all regions. However, the regions determine parameters such as average boiler size, utilization rates, emissions factors, fuel prices and labor cost. Costs on information and other transaction costs often associated with small scale scattered measures are not consistently included in the model.

GAINS has also a rather detailed sectoral representation, in which GHG mitigation can take place in 13 sectors for methane and for most energy use sectors for CO_2. However, CO_2 from land use change and forestry are not included. A large variety of mitigation options are represented, for instance mitigation options are described for different types of industries. In the transportation sector hydrogen is an available mitigation option, but not plug-in hybrids or battery vehicles.

The model takes a very engineering perspective on emissions mitigation. The diffusion of new practices and measures are estimated from a rather technical perspective. Thus inertia in technology diffusion processes is not modeled in an explicit way, but rather from assumptions and model input from national energy system models (Klaassen et al., 2005, p 24). Further potential for renewable energy in a certain year is derived from scenarios made with the PRIMES model (Klaassen et al. 2005, p 26). For methane often simple assumption are made, such that propionate precursors to reduce methane from ruminants that are at a research stage today could be applied to all roughage fed cattle in 2020, which to say the least is very optimistic (Höglund-Isaksson and Mechler, 2005, p 37).

In GAINS some options with negative costs are available (even with private discount rates), and this is well known for engineering cost estimates of energy efficiency measures. In GAINS these measures are automatically introduced in baseline projections, thus reducing emissions also in baseline scenarios. This indicates that the baseline projection are lower than what could actually be expected, as it is well known that cost-effective energy efficacy measures often are not introduced due to factors such as imperfect information and split incentives.

GET

GET is a global energy system model developed at Chalmers University of Technology (Azar et al., 2003; Azar et al., 2000). GET minimizes the cost of the energy system between 2000 and 2100 with perfect foresight. There are four end-use stationary energy sectors with exogenous energy demand: electricity, feed stock for the chemical industry, residential and commercial heat, and industrial process heat. The transportation demand, also exogenously given, is in turn divided into different modes: rail, aviation, road and sea, as well as into personal and freight transport (Hedenus, 2010). The model is technology rich and contains a large variety of technologies which are assumed to be at a mature cost level.

There are several versions of the model, such as a regionalized version (Grahn et al., 2008) or with limited foresight and endogenous learning (Hedenus et al., 2006). The model is mainly used to explore the long-term development of the energy system given stringent carbon constraints. The first and simplest version of the GET model is available via an interactive web interface, GETOnline[2].

MESSAGE

MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental impact, was developed at IIASA. It is a dynamic linear programming model of the energy system. Optimization based on minimization of the energy system costs determines the use and investments of different energy technologies.

MESSAGE III has 1990 as the base year, 10-year time steps, runs over 100 years, and an aim to be used for questions on a medium- or long-term time span. Variable time steps are possible. The model is well described, with user’s guides and mathematical descriptions available (Messner and Strubegger, 1995). MESSAGE is based on 11 world regions, and there are about 150 energy technologies in the model. Energy demand is exogenous. Three are three end-use sectors: industry, residential/commercial, and transport. The demand is elastic.

All major GHGs are considered by inclusion of emissions from all GHG emitting sectors even though they are not part of the optimization. Climate change effects can be modeled by connecting MESSAGE to MAGICC. The model also includes endogenous technology learning using mixed integer programming. A limited foresight version has also been tested (Keppo and Strubegger, 2009). The model can be connected to a macro-economic model, MESSAGE-MACRO (Messner and Schrattenholzer, 2000). MACRO is based on the MERGE series of models.

MiniCAM

The MiniCAM (Mini-Climate Assessment Model) model is an integrated assessment model involving economy, energy, land use systems and the climate system (Clarke et al., 2007). But since the economy system is only functioning as an input to the energy system, it is a partial equilibrium model that includes the energy system, agriculture and other forms of land use.

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[2] www.chalmers.se/ee/getonline

The model delivers projections for the sectors in focus: energy, agriculture, other land uses and emissions. There are three end-use sectors for energy: industry, buildings and transport. The characteristics of other sectors, or the economic system at large, are exogenous to optimization. The model involves supply-demand functions that determine market prices, making the model non-linear.

The model runs in 15-year time steps from 1990 to 2095, and it involves 14 geographical regions. Technology choices determined by “market competition” results in a fraction for each technology using a logit function. A price exponent parameter in the logit function determines how fast the use of different fuels changes in time as a response to price and policy changes. High technology detail and CCS are included for both fossil fuels and bioenergy. Technology improvement is treated exogenously. The model includes 15 GHGs and aerosols, and the MAGICC model is used for climate effects.

GEM-E3

The integrated assessment model GEM-E3, General Equilibrium Model for Energy-Economy-Environment interactions, is a recursive-dynamic general equilibrium model. The core mechanism is a CGE model (van Regemorter et al., 2004). The model covers 21 world regions in a global version or 15 primary European countries in a European version. The European version includes the rest of the world in a reduced form and also extends to include accession countries and Switzerland. Together with the POLES model, which holds a detailed description of the energy sector that is missing in GEM-E3, the model has been used by the EC for assessment of policies and their implications in the context of climate and energy. The model usually runs from 1995 to 2030, but examples of studies to 2050 and 2080 exist.

GEM-E3 considers four economic agents: households, firms, governments and foreign sectors and 18 productive branches covering agriculture, energy, manufactured goods and services. Under “energy” are four branches: solid fuels, crude oil and refined products, gas and electric power, while transportation is found under “services.” Without any detailed modeling of energy technologies and their characteristics, the focus is on the economy at large including an aggregate description of the energy sector.

GEM-E3 has been used to assess macro-economic impacts of various policies aimed at GHG reductions in the energy sector, including effects on GDP, private consumption and employment (European Commission, 2008).

Technological progress can be both endogenous and exogenous, as the production function depends on R&D expenditures. It should also be noted that GEM-E3 has a flavor of a hybrid model, since some detail in the energy sector is introduced by representation of market shares of 8 different power producing technologies (with different characteristics).