Why Hybrid models are the way to go for assessing climate policies

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1. Introduction

Mitigation costs and strategies are of a particular interest for policy reasons: As the Stern Report (Stern, 2006) and the Fourth Assessment Report of the IPCC (IPCC-AR4) have argued, even ambitious emission reductions which are in accordance with low stabilization levels are technically feasible and economically affordable. However, these estimations and scenarios are based either on tow-down (TD) or bottom up (BU) models. As the Innovation Model Comparison Project (IMCP, Edenhofer et al. 2006) has shown, both approaches have several serious shortcomings. In the light of the discussion about mitigating climate change, where simultaneously an in-depth analysis of the energy system and a macro-economic view of the costs of such a transformation of the energy system are required, new modeling approaches are strongly needed.

As suggested by Hourcade et al. (2006) for this challenge three dimensions of modeling have to be combined: technical explicitness, as given e.g. in energy system models, macro-economic completeness, as given e.g. in dynamic CGE models or optimal growth models, and macro-economic realism as the capacity to reproduce crucial stylized facts e. g. by a realistic representation of the interplay between energy system and marco-economy. In the last two years, hybrid models have been designed to combine technical explicitness with crucial macro-economic features. Moreover, the aspect of induced technological change plays an important role in modeling mitigation policies.

We illustrate the basic needs of an Integrated Assessment model and further aspects concerning the overall design of scenarios. We show results from the global model REMIND-G and the global multi-region hybrid model REMIND-R that covers all three dimensions of modeling. We present results concerning the possible mitigation pathways and concentrate on the role of costs of resources, the role of discounting, of trade and of

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spillovers. We conclude that only hybrid models are – among the available methods – well equipped to meet the challenges of a full assessment of mitigation options and costs.

The paper is structured as follows: in section 2 we introduce the dimensions of Integrated Assessment (IA) modeling with the focus on model design and design of business-as-usual and policy scenarios. We will figure out the basic need of an IA model to be able to calculate mitigation pathways adequately. In section 3 the results from the hybrid model REMIND are presented. Conclusions are given in section 4.

2. The dimensions of IA modeling

2.1. How to build IA models

In this section we argue that a more realistic assessment of mitigation costs and strategies require a methodological effort to combine top-down and bottom-up models (Hourcade et al. 2006, Edenhofer et al. 2006). Conventional bottom-up models have described the competition of different energy technologies in detail, both on the demand- and on the supply side. These models are helpful for an understanding of technological choice. However, they have rightly been criticized for omitted macro-economic feedback loops of different policy scenarios and economic boundary conditions like the impact of endogenously determined interest rates on the choice of technologies. The conventional top-down models have addressed the macro-economic feedback loops of different policy scenarios, like the role of expectations or the impact of endogenous interest rates, prices and wages on investments in the energy sector. In top-down models energy production plays only a minor part in the economic system compared to other factors of production like labor and capital. Therefore, the structural change within the energy system seems to have relative little impact on macro-economic growth patterns. Moreover, top-down models have a tendency to model technological change as a continuous improvement of energy efficiency or a smooth substitution process of the different factors used in the macro-economic production function. These aspects do not take into account path dependencies or a limited possibility of substitution. Therefore, these models might be much more optimistic in calculating mitigation costs than conventional bottom up models. On the other hand, top-down models could be too pessimistic as they do not allow for market imperfections that could be sorted out by climate policy.

Based on a suggestion by Hourcade et al. (2006) the three dimensions of Integrated Assessment modeling are along (1) technical explicitness, (2) macroeconomic completeness and (3) macroeconomic realism (see Figure 1). For the representation of technical explicitness in a model long-term technical trajectories, a relevant portfolio of technologies and the mapping of the dynamic on the resource market are important. Macroeconomic completeness is figured by macroeconomic patterns such as trade, spillovers or game theoretical features of strategic behaviour versus price taker assumptions. Macroeconomic realism is given by a realistic representation of the interplay between energy system and macro-economy including a hard link (versus a soft link) between energy system and macro-economy. Moreover, stylized facts should be reproduced by the model to give a realistic picture.

We will extend these three dimensions of modeling by two important aspects: A first aspect of modeling design which is comprehensive to the top-down and bottom-up dichotomy is the role of endogenous technological change. Endogenous technological change is essential for describing reasonable business-as-usual (BAU) scenarios. The business-as-usual scenarios already define the features of technological change which can be induced by climate policy. Endogenous technological change in these models comprises at least two aspects: a) the number of technological options which can be invoked by policy instruments, b) the allowed endogenous efficiency improvements, like learning-by-doing and learning-by-searching.

A second aspect of modeling design refers to the time-horizon of investment decisions. Perfect foresight models enable investors to anticipate long-term changes and to control investment decisions accordingly, including externalities, resource scarcities and the dynamics of stock-pollutant problems. It can be assumed that models allowing for flexible investments achieve an equilibrium that can be characterized by low emissions and low mitigation costs.

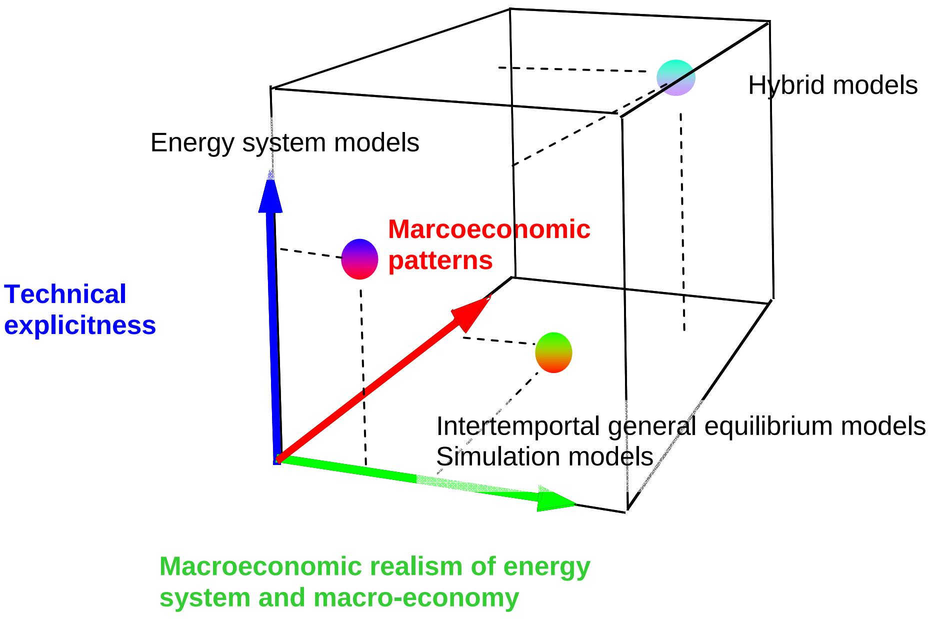
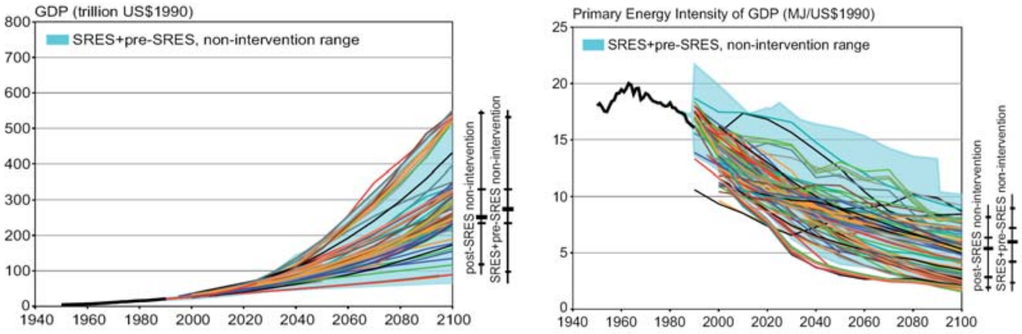


Figure 1: The three dimensions of Integrated Assessment modelling (graphic based on Hourcarde (2006), own modifications).

2.2. How to design business-as-usual and policy scenarios

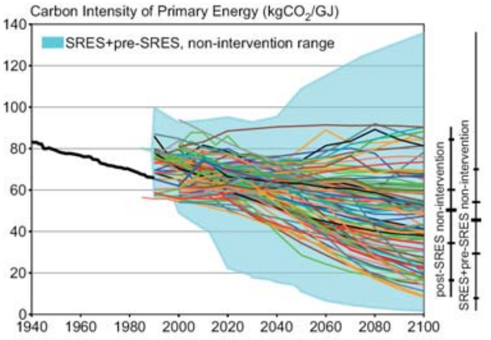
Not only the model itself but also the construction of the business-as-usual scenarios as well as the policy scenarios is an important aspect when assessing climate policies.

An extensive review of the recent long-term business-as-usual scenarios (Fisher et al., 2007) revealed that enhanced economic growth is expected to lead to a significant increase in the gross domestic product (GDP) during the 21st century (see Figure 2a) - throughout the world but especially in the developing countries and emerging markets. The expected rise in prosperity will reveal itself in a significant increase in the demand for energy services. Motivated by the first oil crisis, humankind was able to reduce the primary energy input required to produce one GDP unit (the so-called primary energy intensity) and is expected to do so in the future (see Figure 2b). Unfortunately, the historical improvements in energy intensities were not sufficient to fully offset the GDP growth resulting in increased energy consumption.



a) GDP

b) energy intensity



c) carbon intensity

Figure 2: Projections of a) economic growth and changes in b) primary energy intensity and c) carbon intensity, Source: Fisher et al. (2007), Fig. 3.2, p. 180 and Fig. 3.6, p. 184.

The respective increase in energy efficiency in the scenarios is also more than compensated by the huge economic growth anticipated. In the business-as-usual case, the demand for global primary energy therefore is projected to increase substantially during the 21st century.

Similarly to the development of the primary energy intensity, the carbon intensity (the amount of CO_2 emissions per unit of primary energy) is - with few exceptions - projected to decrease as well (Figure 2c) - simply reflecting the global tendency to initially replace coal by oil and subsequently oil by gas, nuclear energy, and renewable energies. It can be concluded from Figure 2 that the reduction of energy intensity – and therefore the amount of endogenous technological change - is much more important in the majority of the IPCC scenarios than the reduction of carbon intensity.

To design a proper BAU scenario, two things are crucial: on the one hand the current projections, e.g. of declining carbon intensity, always have to be cross-checked with the observed trend. On the other hand, technological change has to become more endogenous in Integrated Assessment in order to realistically model and understand the autonomous technological change.

The crucial question for constructing policy scenarios is how much technological change at what costs can be induced by climate policy when stabilization scenarios should be achieved. Admittedly, the last IPCC report has highlighted the importance of induced technological change. Nevertheless, most of its reported models are relatively poor in representing induced technological change. Unfortunately, there is so far only one modeling comparison exercise in the literature comparing integrated assessment models with respect to induced technological change (Edenhofer et al. 2006). However, the models compared in this exercise can only be seen as a first step in developing more appropriate tools for exploring mitigation costs and strategies. In order to identify the impact of induced technological change on mitigation strategies the business-as-usual scenario has to comprise all components of endogenous technological change potentially. A policy scenario refers to a scenario in which additional endogenous technological change is induced by climate policy (Edenhofer et al. 2006, 69). Therefore, the modelers have to know all potential policy options otherwise technological change cannot be induced by climate policy in the considered model scenario. We will now summarize the real-world components which can be induced by climate policy.

Achieving deep emissions reductions requires a comprehensive global mitigation effort, including a further tightening of existing climate protection strategies in industrialized countries and a simultaneous participation of developing countries, where most of the increase in greenhouse gas emissions is expected in the coming decades (Fisher et al., 2007, p. 199). Fortunately, there are numerous options available that can be induced by climate policy based on the technological knowledge which is already available:

- Energy efficiency improvement
- Fuel switching between fossil fuels (e.g., replacement of coal by gas)
- Zero- or low-carbon energy conversion technologies
- Carbon capture from fossil fuels and storage, probably combined with biomass
- Reduction of non-CO_2 greenhouse gases (multi-gas strategy)
- Land-use related mitigation options (e.g., reduced deforestation and afforestation).

The efficiency of these technology options can be enhanced in the models by different ways of implementing induced technological change (ITC):

- Learning by doing
- Learning by searching
- R&D investments
- Spillover effects
- Substitution of production factors

It is obvious that the model have to include at least some of the above mentioned features to be able to simulate mitigation pathways adequately.

2.3. How to calculate mitigation costs

From an economic point of view, mitigation costs should be calculated as the discounted welfare losses between the business-as-usual scenario and the policy scenario. However, not all models are able to calculate welfare losses. Different concepts of mitigation costs are associated with different model designs and should be distinguished:

Welfare costs: The ultimate goal of economic activities is human welfare. Until recently, many models used within the integrated assessment community have used per capita consumption as an index for human welfare. However, the utility losses calculated by intertemporal optimization models can neither be compared nor interpreted in an economic meaningful way. Therefore, Stern (2006) has proposed the concept of Balanced Growth Equivalent (BGE) as an indicator which on the one hand takes into account the non-linear relationship between consumption and utility and on the other hand translates welfare losses into consumption losses. Unfortunately, this indicator is not used within the IPCC report.

Macroeconomic costs: The mostly used indicator within the IPCC report reflect the impact of a given mitigation strategy on the level of gross domestic product (GDP) and its components. At this level of analysis, feedbacks between sectors and the macroeconomic environment are accounted for. Such general equilibrium effects can be calculated by models which encompass either the whole economy, or coupled models of specific sectors and macro-economy.

Economic costs for a specific sector are computed in partial-equilibrium models allowing for the integration of a multitude of mitigation options. For example, energy system models assess the sectoral costs of the energy sector. However, the macro-economic feedbacks are omitted. Nevertheless, some studies used within the IPCC have expressed their energy system costs as a share of their exogenous GDP path. From a methodological point of view this is not satisfying. Nevertheless, it is used by the modelers in order to make their results comparable.

Direct engineering costs of specific technologies: These numbers provide some information about the costs of a specific technology, like photovoltaic or coal-power plants. These cost estimates are mainly derived from engineering process-based studies of these technologies. Examples of these cost curves are static mitigation costs curves derived from existing technology options, current relative prices and income. Most bottom-up approaches are using this cost concept, omitting partial equilibrium effects and also macroeconomic feedback loops.

All these cost concepts have on common that they compare business-as-usual scenarios with policy scenarios. The IPCC AR4 and also the Stern Report (2006) basically have reported the macroeconomic costs or energy system costs measured as a share on GDP.

3. Model demands and results

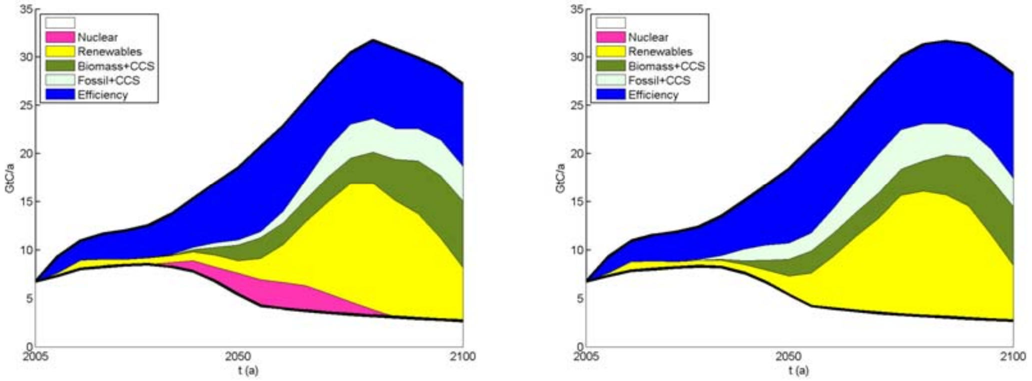
In the following we will show exemplary results from the model REMIND that illustrate the demands of IA models. We analyse the model in terms of the three dimensions of modeling.

For the development of the REMIND model at the Potsdam Institute for Climate Impact Research (PIK), we include a bottom-up energy system model within an intertemporal macro-economic general equilibrium model. Moreover, technological change is basically determined endogenously at different levels like overall energy efficiency and learning-by doing driven by endogenous determined installed capacities in the energy system. The efficiency and growth rates in the macroeconomic production function are, however, exogenously. The REMIND model exists in two versions. One version represents the world economy as one-world region (REMIND-G, a documentation of this model is under preparation). In a second version (REMIND-R), it comprises nine world regions allowing for trade in goods, capital, labour and energy (for a description see Leimbach et al. 2008).

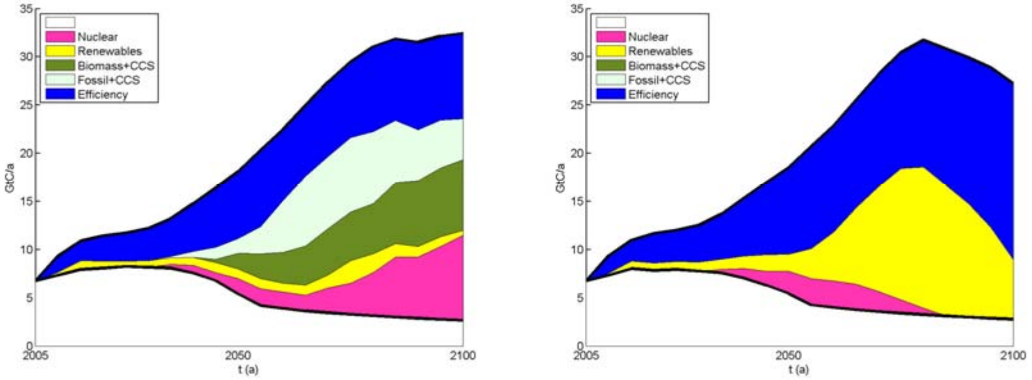
3.1. *Modelling technical explicitness*

Figure 3 reveals the relative importance of different emission mitigation options in achieving a stabilisation of the carbon dioxide concentration at 450ppm. The upper boundary of the corridor shows the business-as-usual emission trajectory, the lower boundary marks the stabilisation target.

By excluding a certain technology, the models show a high flexibility to reach the emission target without that very technology: the model can achieve the target when either renewables, nuclear or CCS are not available as a mitigation option.



a) all options b) no nuclear



c) no solar d) no CCS

Figure 3: Emission pathways (black) and technology wedges. The upper path corresponds to the BAU emissions, the lower path to the stabilisation scenario. Wedges are given comparing the "all options" scenario to scenarios where options are restricted to their respective usage in the business-as-usual scenario for a) "all options", b) "no nuclear", c) "no solar", and d) "no CCS". In the "all options" scenario, all greenhouse gas mitigation opportunities (energy efficiency improvement combined with fuel shifting, renewables, nuclear energy and the application of CCS) are taken into consideration irrespective of their business-as-usual usage.

Whereas in the business-as-usual scenario the energy mix is dominated by fossil energy, the energy mix of under climate policy shows more flexibility (not shown here). For policy implication this means that a dominant technology, without that mitigation would not be possible, cannot be figured out: a mix of options is needed and the best strategy seems to be to support a broad portfolio of energy carriers.

This result shows that the model is flexible enough to reconstruct the energy system with respect to the needs of climate policy, what is needed for representing the first dimension of *technical explicitness* (see Figure 1).

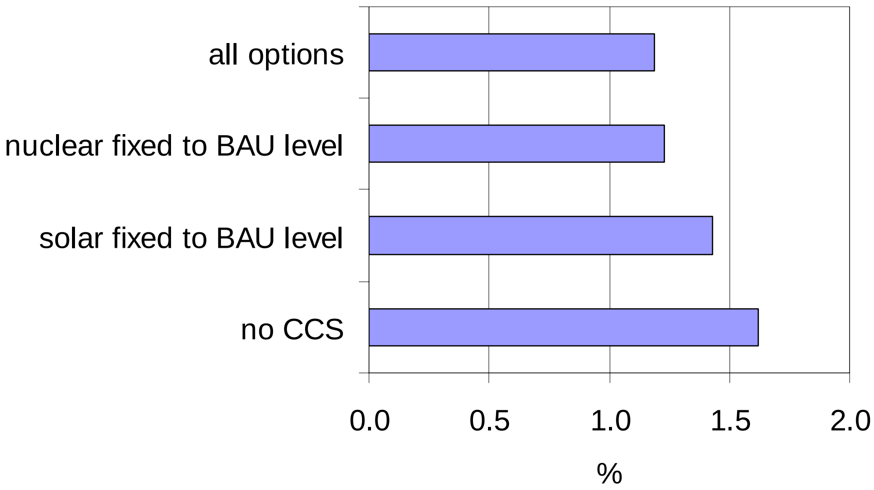


Figure 4: Consumption differences (business-as-usual - stabilisation), comparing the "all options" scenario to scenarios where options are restricted to their respective usage in the business-as-usual scenario. In the "all options" scenario, all greenhouse gas mitigation opportunities (energy efficiency improvement combined with fuel shifting, renewables, nuclear energy and the application of CCS) are taken into consideration irrespective of their business-as-usual usage. In the other scenarios, the technologies are fixed to BAU level.

Figure 4 shows the influence of excluding some of the different low-carbon technologies on the mitigation costs. As can be clearly seen, the exclusion of CCS technologies would result in a significant increase in the emission mitigation costs. Abstaining from applying solar energy sources in order to combat global climate change would also have an influence on the costs. In contrast to this, fixing nuclear energy to the business-as-usual case would result in additional costs that are almost negligible compared to the overall mitigation burden.

In contrast to the AR4 of the IPCC, this calculation clearly shows that there are more and less important options. The IPCC has calculated emission reduction potentials of different mitigation options (IPCC 2007, 17). This reduction potential is however derived for a specific scenario. Obviously, it neglects that multiple local optima may occur for non-marginal changes. In the case of multiple optima, switching-off an option may force the system to find another optimum. In the case switching off of nuclear power, a new equilibrium with similar welfare effects might be attainable; in the case of CCS, the costs will increase substantially if this option is not available.

3.2. Modelling macroeconomic realism

The second dimension of macroeconomic realisms (Figure 1) includes e.g. a realistic representation of the interplay between energy system and macro-economy. In REMIND this is covered by a hard link versus a soft link between the macroeconomic module and the energy system.

The energy system module depends on the one hand on the macroeconomic output which is used for financing investments into energy transformation capacities, fuel costs spendings and expenditures for operation and maintenance. It provides on the other hand final energy that is used in the macro-economy. This means that technological change in the energy sector is embedded in a macroeconomic environment that by means of investments and trade decisions governs regional developments.

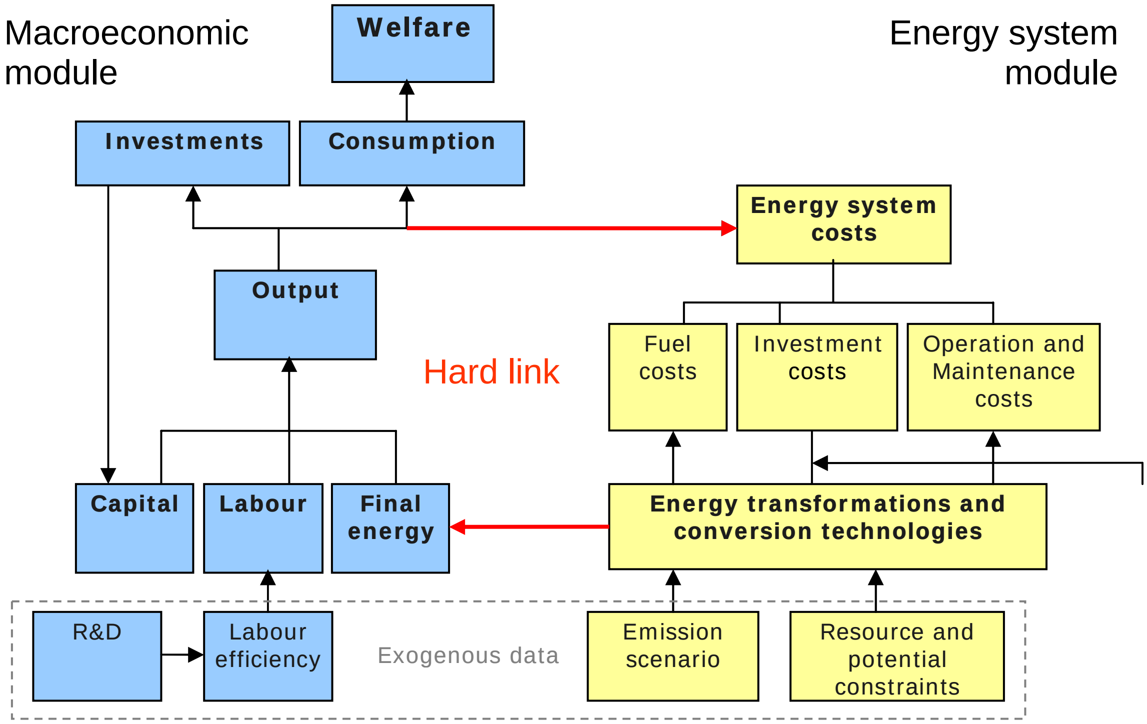


Figure 5: Example of a hard link between the macroeconomic module and the energy system in REMIND.

3.3. Modelling macroeconomic patterns

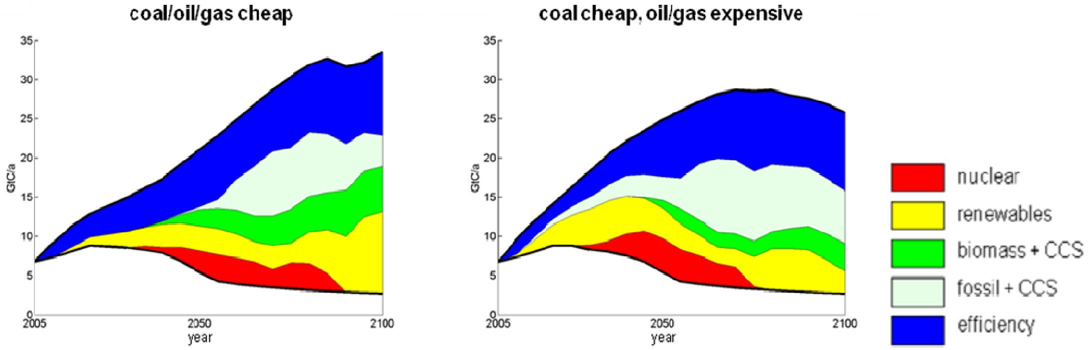
We have seen that some model features are crucial in order to fully picture the mitigation options. In this section we will indicate further characteristics that play an important role when discussing mitigation pathways. Here we will focus on the third modeling dimension of *macroeconomic patterns* that are essential for macroeconomic completeness. In detail this means e. g. the role of oil and gas prices, the role of discounting, and the role of international trade.

The hybrid model REMIND explains the impact of fossil fuel prices on mitigation costs and strategies. Moreover, we highlight the role of discounting on the choice of technologies which has been widely neglected by the current debate about climate policy. Both parameters influence the mitigation gap and therefore, the costs of mitigation. Further we argue that international trade is an important aspect in mitigation strategies and mitigation costs.

3.3.1. The role of oil/gas prices

Figure 6 reveals the relative importance of different emission mitigation options in achieving a stabilization of the carbon dioxide concentration at 450ppm as it was obtained with the model REMIND-G. The upper boundary of the corridor shows the business-as-usual emission trajectory which is dependent on the costs of fossil fuels. It is noteworthy that the increase of oil and gas prices does not alter the portfolio of mitigation substantially but shifts the importance of the respective options and particularly widens the mitigation gap.

The impact of increasing oil and gas prices, and especially the expectation of persistency of high prices, on technological change has three aspects: First, it fosters additional investments in exploring and exploiting the new and more costly oil fields including those holding non-conventional oil. Second, the increasing oil price makes options like coal-to-liquid a profitable one if coal is relatively abundant and cheap. In a climate protection scenario, the extensive use of coal can only become an option if it is combined with CCS. In the scenario assuming relatively cheap coal and expensive oil and gas, the clean coal option becomes more important compared to a scenario exhibiting low costs for all fossil fuels (see Figure 6). Third, high oil prices may also improve overall energy efficiency reducing the emissions until the end of the century even in the scenarios without any explicit mitigation policies and measures. It should be noted that long-term price trajectories of fossil fuels are quite uncertain. However, it is less uncertain that prices of oil and gas will increase faster than the price of coal because of the large coal reserves. Nevertheless, large negative externalities associated with coal production and use are likely to increase coal cost in the long run.



a) b)

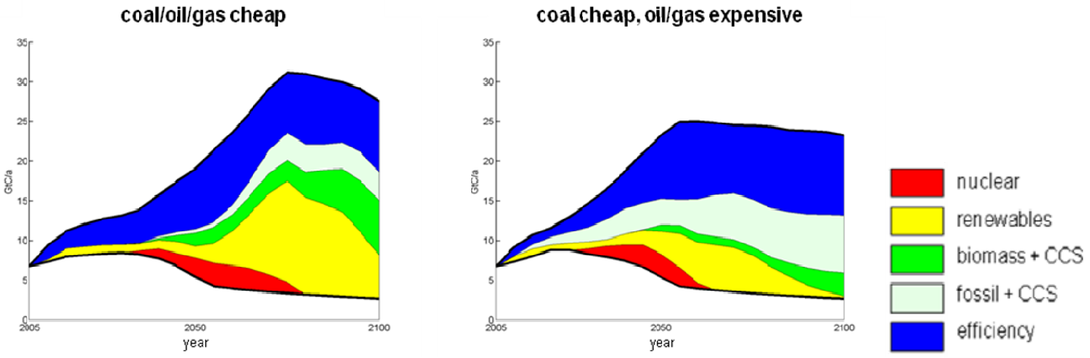
Figure 6: REMIND-G results (3%/a pure time preference rate) for the emission pathways and technology wedges for a) cheap coal/oil/gas and b) cheap coal and expensive oil/gas.

3.3.2. The role of discounting

The Stern Report (2006) has launched an exciting debate about the appropriate pure time preference rate. The Report has argued that the pure time preference rate is an ethical value judgment about the weight and importance of future generations in current investment decisions. It points out that there is no ethical reason why future generations should be regarded less important in current investment decisions than the current generation. However, the pure time preference rates observed on capital markets are much higher than the rate derived from ethical considerations. There is some evidence that the pure time preference rate of 3 % is appropriate when models are calibrated according to the empirically observed behavior on capital markets.

Designing adequate policy instruments could enable decision makers to reduce the discount rates of private firms and investors. It should be noted that lowering discount rates will not only affect the emission pathways and the costs of mitigation but also the mix of mitigation options.

This can be illustrated by implementing a lower time preference rate in the model. Assuming a lower pure time preference rate (1%/a) favors the application of emerging technologies (especially renewables, compare Figure 6 and Figure 7, also for the different price paths for fossil resources) for using renewable energies while reducing, in part, the necessity to use CCS technologies.



a) b)

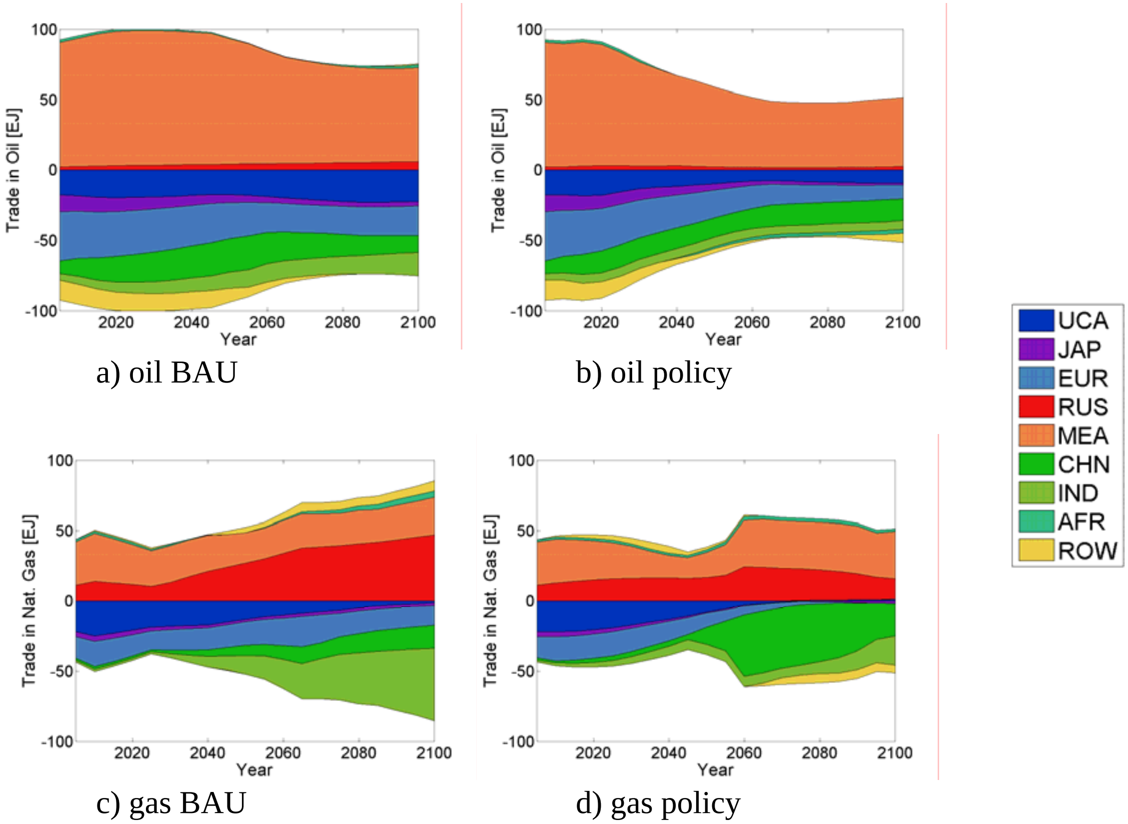
Figure 7: REMIND-G results (1%/a pure time preference rate) for the emission pathways and technology wedges for a) cheap coal/oil/gas and b) cheap coal and expensive oil/gas.

3.3.3. The role of trade

Economists should embed pathways of decarbonisation and induced technological change much more in the context of international trade and globalisation.

For exploring the impact of different allocation schemes of CO_2 emissions on mitigation costs and strategies, we have developed a framework comprising several desirable features. First, it allows agents to take into account the full intertemporal dimensions of the economic environment. The intertemporal optimisation framework is suitable for evaluating long-term problems like climate policy. Second, by being based on utility maximisation, it provides a framework allowing for analysing the welfare implications of climate policy or other structural changes. Third, the intertemporal market equilibrium derived in this context serves as a natural benchmark from which deviations can be measured that are caused by externalities, spillovers or irrational expectations. We want to point out here that models used in the context of climate policy have to take into account problems of international trade and globalisation much more seriously.

We have undertaken first steps in this direction. Admittedly, the focus on long-term optimisation may induce trade patterns which are in some cases not always consistent with empirical observation. However, this is not an objection against the framework. It should be seen more as a hint to identify hidden mechanisms. Irrespective of these problems, the results show that trade patterns are crucial for determining mitigation costs and mitigation strategies. Therefore, more empirical research, more modelling experiments and more modelling comparison exercises are needed in order to make the models more appropriate for policy advice.



a) oil BAU

b) oil policy

c) gas BAU

d) gas policy

Figure 8: Trade of oil and gas in the reference and in the policy scenario for REMIND-R. UCA (USA, Canada, Australia), JAP (Japan), EUR (Europe), RUS (Russia), MEA (Middle East and North Africa), CHN (China), IND (India), AFR (Africa), ROW (Rest of the World).

It turns out that setting a global emission cap (here exemplarily with a contraction and convergence allocation scheme where equal per capita distribution of emissions is achieved by 2050) strongly influences the trade balance in primary and secondary energy carriers. For example, oil exports from the Middle East region (MEA) are suppressed substantially (see Figure 8a,b) which results in high mitigation costs.

Also gas exports from Russia are reduced considerably (see Figure 8c,d). The gas and oil exporting regions like Middle East and Russia suffer from decreasing resource prices. The oil price, for example, is reduced to almost 50% in the long run compared to the reference scenario because there is no option to use oil emission-free.

4. Conclusions

In this paper we have illustrated the features that are essential to give a complete, a realistic and an explicit picture of the mitigation options. On the one hand this relates to a careful design of business-as-usual and policy scenarios. On the other hand, the models must include a number of characteristics in order to be able to adequately model the mitigation options and pathways. The model characteristics were analysed along the three dimensions of modeling that were suggested by Hourcade et al. (2006): technical explicitness, macro-economic realism and macroeconomic completeness. Moreover the effect of endogenous technological change is an overarching particularity when modeling the economic impacts of climate change. Illustrating results were given for the REMIND model.

It becomes clear that for Integrated Assessment modeling a number of model features are crucial in order to figure mitigation options and implications adequately and to give a complete picture of policy options. Not only the technical explicitness and the inclusion of a broad portfolio of technological options is important, but also the impact e.g. of high oil prices on the economy. Mitigation pathways also bring about a substantial change of the trade structure that has to be kept in mind in view of climate negotiations.

It should be clear that due to the different design of the models, a careful analysis of the structural uncertainties is important. An important issue would therefore be the conduction of advanced model comparison exercises, as started with the IMCP (Edenhofer et al., 2006), e.g. with the focus on the role of different technologies or on different assumptions on the price of resources. Moreover, the investigation of different policy options, such as emissions trading, universal and fragmented regimes, or the implementation of technology protocols has to be analysed in the light of model comparisons. By doing so, the structural model uncertainties can be captured and robust results for assessing climate policies can be extracted.

Acknowledgments

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