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The Impact of Uncertainty in Climate Targets and CO_2 Storage Availability on Long-Term Emissions Abatement

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Abstract A major characteristic of our global interactive climate-energy system is the large uncertainty that exists with respect to both future environmental requirements and the means available for fulfilling these. Potentially, a key technology for leading the transition from the current fossil fuel-dominated energy system to a more sustainable one is carbon dioxide capture and storage. Uncertainties exist, however, concerning the large-scale implementability of this technology, such as related to the regional availability of storage sites for the captured CO_2. We analyze these uncertainties from an integrated assessment perspective by using the bottom-up model TIAM-ECN and by studying a set of scenarios that cover a range of different climate targets and technology futures. Our study consists of two main approaches: (1) a sensitivity analysis through the investigation of a number of scenarios under perfect foresight decision making and (2) a stochastic programming exercise that allows for simultaneously considering a set of potential future states-of-the-world. We find that, if a stringent climate (forcing) target is a possibility, it dominates the solution: if deep CO_2 emission reductions are not started as soon as possible, the target may become unreachable. Attaining a stringent climate target comes in any case at a disproportionally high price, which indicates that adaptation measures or climate damages might be preferable to the high mitigation costs such a target implies.

Keywords Climate change · Energy system modeling · Carbon dioxide capture and storage (CCS) · Mitigation target · Storage potential · Uncertainty

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1 Introduction

The challenge of climate change is characterized by its overarching time span, with actions taken today having long-lasting impacts and directly contributing to the technological and environmental conditions we are likely to experience decades or even centuries from now. Since the transition from the current fossil fuel-dominated power production system to a more sustainable energy supply portfolio will be long, and in the meantime, deep CO_2 emission reductions are required on a much shorter time scale, technologies that bridge the gap between the present and future energy system are urgently needed. One potential technology to help us start decarbonizing the energy system, without the need to completely overhaul today's production paradigm overnight, is carbon dioxide capture and storage (CCS).

In this study, we concentrate on assessing the role CCS could play in a climate mitigation regime. We focus our attention especially on the uncertainty concerning regional storage availability for captured CO_2. Although substantial information has been gathered on the global availability of geological storage formations (see e.g., but surely not excluded to, [6, 11]), for CCS to become a major component of a comprehensive climate strategy it would need to be implemented on such a large scale that uncertainty with regards to the feasibility of using a selection of storage types becomes a key element. Furthermore, the yet-to-be-determined level of our climate control ambition is likely to play a fundamental role in defining how critical it is to have access to large CO_2 storage reservoirs. The interplay between these two uncertain features of our global climate-energy system may, to a large extent, define the future prospects of CCS technology.

We investigate this relationship first through a sensitivity analysis, by constructing and comparing a set of scenarios with increasing levels of climate control. In this analysis, we assess how the global climate target impacts the mitigation portfolio, as well as the costs and timing of CO_2 emission reduction efforts, if CCS turns out to involve only limited CO_2 storage capacity. In this sensitivity study, we also compare our results with those of a more optimistic scenario, in which additional storage types become available in 2050.

The strategies emerging from these scenarios portray decisions that are made under certainty, i.e., when it is known whether the CO_2 storage potential is low or high. In reality, however, uncertainty is a key characteristic of the decision-making process. Features of uncertainty become more relevant and apparent by the fact that both climate and energy systems inherently possess a high level of inertia, so that the impacts of decisions made today are still felt decades later. This mechanism applies for instance to the availability of geological CO_2 storage options if their cumulative volume is unknown at the moment of decision making. Therefore, decisions should be made with all possible future developments in mind. Public planning should thus (a) take into account the possibility of CCS having only limited practical use, (b) consider the option that, alternatively, it might become a major contributor to climate change mitigation until the end of the century, and (c) reflect the uncertain stringency of mankind's climate control ambition. We endogenize these uncertainties by introducing "diverging worlds" [13] in TIAM-ECN, which is an adaptation of the original TIAM model (for a description of the latter, see [18, 19]). Each state-of-the-world is given a likelihood and represents a unique combination of climate target and estimate for the global CO_2 storage potential. This framework of diverging worlds allows for solutions in which all state-of-the-worlds are considered simultaneously, and a balanced optimal mitigation strategy is drawn for the period leading up to 2050, when uncertainty is assumed to be resolved.

The literature on the economic modeling of energy systems including CCS has been growing rapidly over recent years, as exemplified notably by the adoption of this subject in broadly referenced publications like the IEA-ETP [9], IEA-WEO [10] and GEA [4]. CO_2 storage capacities have not been a major modeling focus over the past few years, but quite some attention has been paid to another uncertain aspect of CCS: uncertainty regarding storage integrity and risks of gradual leakage. Herzog et al. [7] proposed a definition for the effectiveness of temporary CO_2 storage (through any means) involving the net present value of the total stream of avoided CO_2 emissions. In an update of earlier work on CCS with the DEMETER model, van der Zwaan and Gerlagh expanded this top-down integrated assessment model by implementing an effectiveness expression similar to Herzog et al. [7] and applying it to geological storage of CO_2 in leaky reservoirs [5, 29]. Under different leakage models, they found that CCS remains a valuable option even with CO_2 leakage of a few %/yr, which is well above the maximum seepage rates that are thought to be likely from a geo-scientific point of view for well-chosen and well-designed CO_2 storage sites. The conclusions of van der Zwaan and Gerlagh [29] are in line with those reported in van der Zwaan and Smekens [30] based on the detailed bottom-up energy systems model MARKAL, but the former involve a higher allowable upper limit of leakage than the 0.5%/yr calculated in the latter.

Other CCS-related uncertainties that have recently been subject of analysis in the context of energy and climate scenarios development are incertitudes associated with the economic learning potential of CCS technology assumed in energy-climate models [26]. Possible learning-by-doing and experience curves are phenomena closely intertwined with the economics of CCS implementation, as are possible risks for leakage.

Labriet et al. [16], Syri et al. [27] and Loulou et al. [20] have used the same stochastic framework as we do in the present paper for their investigation of an uncertain temperature target and climate sensitivity. Other approaches for the analysis of uncertain climate futures include work by Keppo et al. [14], who conducted an ex-post probabilistic study of the temperature consequences of a set of greenhouse gas scenarios, and O'Neill et al. [25], who used a myopic framework for studying the relationship between initially unknown long-term targets and fixed-mid-century targets.

The purpose of the present work is to complement these studies with an investigation of uncertainties with regard to CCS-related storage potentials. Rather than assuming that mankind is going to use CCS on a large scale for sure, and that incomplete certainty remains as to whether the stored CO_2 will stay safely underground, we here suppose that one only deploys CCS technology if sufficient geological storage integrity can be guaranteed but that it is yet to be seen how large the global storage capacity free of leakage risks is. Section 2 of this article concisely recapitulates some of the main features of CCS as relevant to our central research question. In Section 3 we describe our methodology and particularly, the characteristics of the TIAM-ECN model version we use to undertake our scenario analysis. In Section 4 we report our main results, in terms of emission (reduction) efforts, CCS deployment, primary energy resource use and CO_2 emission prices. We end in Section 5 by summarizing our conclusions and formulating several recommendations.

2 Carbon Dioxide Capture and Storage

The capture of CO_2 before or after the combustion of fossil fuels (or any other carbon-intensive fuel, such as peat or biomass) and its subsequent storage in geological formations, or alternatively its industrial use or chemical fixation, is today considered one of the promising means to start addressing the problem of climate change in the near term [11]. The decarbonization of fossil-based energy through CCS application has the potential to contribute significantly to reducing CO_2 emissions. Pre-, post- and oxyfuel-combustion CO_2 capture technologies exist for power stations, and pre-combustion ones for fuel cell applications, while CO_2 capture techniques operate today in a number of large industrial processes. Technologies for CO_2 compression and transportation to storage sites via pipelines or with tankers are well known. The injection of CO_2 underground is technically straightforward in many geographical locations and geological storage formations abound. The global CO_2 storage capacity, in depleted oil and gas fields as well as aquifers, is likely to be large.

Still, much is left to be understood about several technical, economic, and political dimensions of CCS. Important questions remain in particular regarding possible environmental externalities and safety risks associated with the storage of CO_2 underground (see e.g., [11, 31]). The presence of large quantities of oil, natural gas (and CO_2) trapped in geological formations implies that in sedimentary basins impermeable cap-rocks are available with sufficient quality to confine fluids and gases for long periods of time. Since oil and natural gas fields have a proven containment integrity record for millions of years, there is good reason to believe that CO_2 can also be stored artificially without noteworthy leakage, at least in depleted oil and natural gas fields, for time frames compatible with the natural CO_2 cycle. On the other hand, plenty examples exist of natural leakage of CO_2 and other gases from the geological underground, notably resulting from volcanic activity. Several instances of leakage also exist associated with gases stored underground artificially. Furthermore, many fossil fuel-retaining reservoirs that subsisted long ago have probably disappeared over time as a result of dissipation and dispersion phenomena [1].

These observations confirm that the containment integrity of artificially stored CO_2 is a subject that deserves attention in the context of climate change mitigation strategies. We here take the approach that depleted oil and natural gas fields are candidate storage formations in which CO_2 can be contained with high probability for periods long enough to control our climate. For aquifers, however, no such high likelihood has yet been demonstrated. Through research and development we may learn over the coming decades whether or not aquifers can be considered safe enough and should therefore be included in the set of fully reliable CO_2 storage options. Before this uncertainty will have been resolved, however, substantial incertitude continues to exist with regards to the total global CO_2 storage potential. Indeed, while depleted oil and gas fields may provide highly certain CO_2 storage pockets, their total capacity is limited in climate control terms—yet for aquifers the situation is quite the opposite: their potential storage capacity is in principle large enough for many centuries worth of anthropogenic CO_2 emissions, but how long CO_2 can be contained there safely is still uncertain.

3 Methodology and Scenario Analysis

The methodology used to evaluate the impacts uncertainty concerning CCS may have on climate mitigation strategies affects the outcome of our analysis. Below, we therefore describe in detail the modeling framework of TIAM-ECN that we employ for our assessment, the set-up of our representation of CCS, the stochastic features of our model, and some of the main assumptions we implemented for our scenario runs.

3.1 Modeling Framework

We conduct our study using a version of the technology-rich bottom-up energy systems model TIAM (as described in detail in [18, 19]). This linear optimization model simulates the development of our global energy system from resource extraction to final energy use over a long period of time, typically of about 100 years. TIAM's original regional disaggregation, used also in our version of the model, separates the world in 15 distinct geographical areas: Africa, Australia–New Zealand, Canada, Central and South America, China, Middle-East, Other Developing Asia, South Korea, United States, Western Europe, Eastern Europe, Former Soviet Union, India, Japan and Mexico. Our altered version, TIAM-ECN, keeps all the main characteristics and many of the details of TIAM, but includes several modifications and simplifications. Most of the changes made relate to revised and updated input data, additional growth and decline constraints, as well as more aggregated sectoral and technological details.

The objective function of TIAM consists of the sum of the total discounted costs over the full time horizon, aggregated across all regions. Running scenarios with TIAM involve minimizing this objective function. The main cost components included in the objective function are investment costs and fixed and variable operation and maintenance costs. In addition to these, smaller cost components, such as decommissioning costs are also accounted for. Since the model is based on a partial equilibrium approach, with end-use demands responding to end-use prices, the implied costs (or gains) of demand changes are also represented in the objective function. For a detailed description of all simulated cost components, see Loulou et al. [17] and Loulou [19].

The database associated with TIAM is extensive and includes hundreds of technologies for a broad set of different sectors. Interregional trade is available for all relevant fossil fuels, as well as for emission permits. Fuel prices are determined endogenously (as shadow prices) by the model and are therefore not inputs to, but outputs of model runs. The exogenously defined demands for energy services are modeled with price elasticities, so that they react to price changes. Figure 1 shows a simplified sketch of the TIAM-ECN reference energy system.

In addition to energy flows and conversion technologies, environmental variables such as greenhouse gas emissions of all energy processes are modeled. TIAM-ECN includes in principle all sources of the main greenhouse gases, i.e., CO_2, CH_4 and N_2O, but currently excludes emissions of pollutants such as SO_x and NO_x. Energy-related greenhouse gases are modeled endogenously, whereas non-energy-related greenhouse gases are included as exogenously given emission paths. The latter are based on generic assumptions concerning their underlying drivers. Mitigation technologies are available for some of these non-energy-related emissions. For example, mitigation options are available for N_2O emissions from nitric and adipic acid production, as well as for CH_4 emissions from landfills and manure. For some sources of greenhouse gases, such as CO_2 emissions from land use change, CH_4 emissions from enteric fermentation, rice production and waste water, as well as N_2O emissions from agriculture, only exogenous emission paths are given without availability of mitigation technology. The endogenous climate module of TIAM has a 3-box representation for CO_2, while a 1-box representation is used for N_2O and CH_4 each (see [27], for a detailed description of the climate module). Emissions that affect our climate, but which are not directly included in TIAM, are represented through an exogenous forcing component in the model's climate module. Our modeling runs exclude the impact of aerosols and we assume that the forcing effect of all the remaining non-modeled forcing agents reduces linearly from today's values to a level of 0.1 W/m^2 by 2100.

A large number of mitigation options are modeled for the energy sector. The main clusters of alternatives are: (1) a reduction in the carbon intensity of fuels (such as a switch

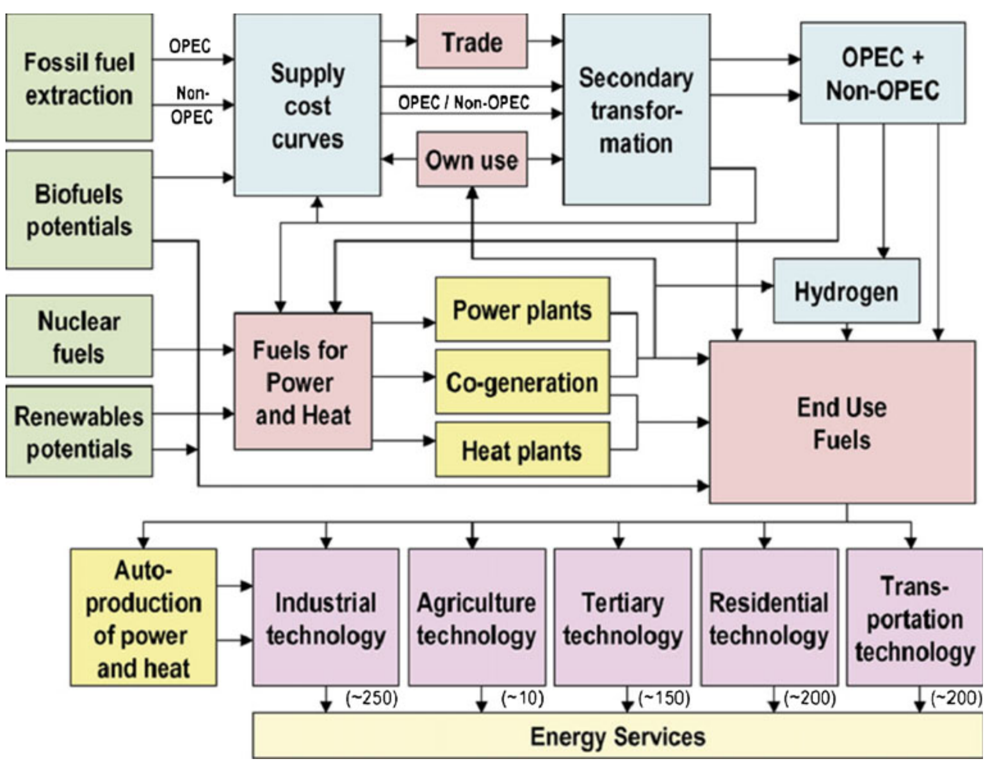

Fig. 1 Structure of the TIAM-ECN reference energy system [27]. *N.B. Numbers in parenthesis* indicate the approximate number of end-use technologies per demand sector

from coal to gas, or from fossil fuels to renewables or nuclear energy), (2) a reduction in energy consumption (including the application of more efficient conversion techniques on the supply side and demand reductions at the end-use level), and (3) add-on greenhouse gas reduction technologies (such as CCS, or CH_4 emission reduction technologies in oil, gas and coal production). Most of these climate change mitigation options emerge from TIAM's detailed description of the energy system. As CO_2 emission constraints are implemented, the energy sources with low-carbon content become more competitive, as do technologies that require less fuel input to provide the same energy service (and therefore in relative terms involve lower emission levels). A climate constraint will also increase the price of energy services, which leads to a lower overall demand for energy.

Assumptions regarding the respective potentials of carbon-free or low-carbon fuels, as well as the range of available efficiency improvements, may limit the use of these options. As mitigation options they are also limited by their baseline use: if a carbon-free option is assumed to have a large potential, but this potential is almost completely used already in the baseline scenario, then its potential for mitigation is low. CCS is available in the power sector, for synthetic fuel production (including H_2 generation from coal and natural gas, as well as methanol and Fischer–Tropsch liquids from coal), and (stylistically and only up to a limited potential) for upstream fossil fuel supply processes. A large number of storage options are simulated for the captured CO_2. There are a number of combinations available between CO_2 capture technologies and coal and natural gas-based power plants. CCS as applied to the combustion of biofuels is currently not included in our model: while this technology offers a promising possibility for "negative emissions", it remains to be seen to what extent it can be applied given possible logistical and spatial constraints. If this technology does become commercially feasible on a large scale, however, it could offer increased flexibility for reducing emissions rapidly.

3.2 Modeling CCS in TIAM-ECN

CCS is modeled in TIAM-ECN through the representation of two distinct components: (1) the CO_2 capture process and (2) the transport and storage of the captured CO_2 to a final storage site. Power generation is, by far, the most important sector in which CCS is supposed to be readily implementable. It is assumed that equipping existing power plants with CO_2 capture technology is not economic, not even as a flexibility option, so that in practice only facilities are built in which CCS is pre-integrated in the power plant. Since the characteristics of power plants designed from the start to include CCS technology significantly deviate from conventional existing plants, the differences between modeled power plants with and without CCS go beyond the mere addition of capture technology. For instance, some energy technologies that are favorable for CCS application (such as fuel cells that use gasified coal as input) are only included in the model with complete CCS technology integration.

For coal-fueled power plants, the technologies modeled in TIAM-ECN are post-combustion capture (combined with conventional pulverized coal power plants, with initial investment costs ranging regionally from 1,800 to 3,150 $/kW), pre-combustion capture (combined with integrated gasification combined cycles, or IGCCs, with costs of 1,840–3,220 $/kW) and oxyfueling (applied to pulverized coal power plants, with costs of 1,920–3,360 $/kW). For gas-fired power plants the simulated options only include post-combustion capture and oxyfueling (with costs of 800–1,750 $/kW), both in connection with natural gas combined cycles (NGCCs). Solid oxide fuel cells (SOFCs) operating in conjunction with CCS technology are assumed to become available a couple of decades from now (with investment costs of 1,280–3,080 $/kW). Hence, they start being deployed only around 2030, whereas 2010 is the typical introduction time for most other new technologies.

Potential CO_2 storage sites include depleted oil and gas fields (with offshore and onshore as separate alternatives, with a total global potential, including depleted and currently remaining fields, up to 1,000 Gton of CO_2), enhanced oil recovery fields (150 Gton of CO_2), coal seams (with shallow sites and formations deeper than 1 km given separately, amounting to 265 Gton of CO_2 in total) and saline aquifers (235 Gton of CO_2). Regional potential estimates by storage type are mainly based on Hendriks et al. [6]. Corresponding cost estimates are obtained from a number of sources, including Hendriks et al. [6] and IPCC [11]. For our more optimistic storage scenario we assume that half of the presently estimated gas and oil fields are available for use immediately, while the other half becomes available in 2050. The other storage options in this scenario will only become available in 2050. For our more pessimistic scenario no additional storage potential becomes available in 2050: in other words, only storage in gas and oil fields remains feasible, with just half of the potential currently estimated to be susceptible for CO_2 storage. In our stochastic scenario we stipulate that it is uncertain whether additional potential will become available in 2050 or not. The model therefore has to take both scenarios into account and suggest, accordingly, strategies for the first half of this century.

3.3 Stochastic Version of TIAM-ECN

The TIAM family of models possesses a built-in option to use the program in a stochastic mode. Hereby the future can be described in terms of alternative “states-of-the-world”, of which the branching points, likelihoods and characteristics are known entities ([18], for ETSAP-TIAM; see also [22], for another approach). The objective function is altered for this purpose, so that the costs of alternative states, each holding a distinct set of result variables after the branching point, are weighted according to their probabilities. This approach leads to cost minimization of expected costs under uncertainty.

The stochastic method of TIAM differs from “myopic” approaches [15, 21, 24], in which unknown futures are completely ignored in the model’s decision-making algorithm. It also is different from methodologies in which uncertainty is assumed to persist and e.g., Monte Carlo techniques are integrated in the overall analysis (as in [23]). Figure 2 visualizes the stochastic set-up of TIAM.

The example shown in Fig. 2 depicts one branching point, in 2040, for two types of characteristics, related to respectively a target (e.g. regarding climate, security of supply or sustainability) and a technology (e.g. its cost or associated limit on resource use). We adopt three alternatives for the target and two possibilities for how the technological characteristic may evolve. Although distinct uncertainties could be assumed to be revealed at different points in time, in Fig. 2 we suppose that all uncertainties are revealed simultaneously. Before the uncertainty regarding these two variables is resolved, the model needs to prepare for all possible states-of-the-world and take each into account according to the probabilities assigned to their respective realizations. Such diversification strategy, however, focuses mainly on the expected costs of alternative states-of-the-world. If there is question regarding model runs’ feasibility in terms of e.g. remaining under an uncertain climate target or below an uncertain cumulative bound on resource use such as CO_2 storage activity (as in our present case), the most stringent possible world might dominate and no cost-related diversification can be made. The reason is that no matter how low the probability for its realization, the model still needs to be able to cope with the circumstances and constraints described by that world. Since the basic decision-making principle of TIAM assumes a single “social planner”, the results of our stochastic analysis should also be seen in this context. Individual heterogeneous actors might well choose strategies that imply different results on the macro level (see [3], for a real option based approach).

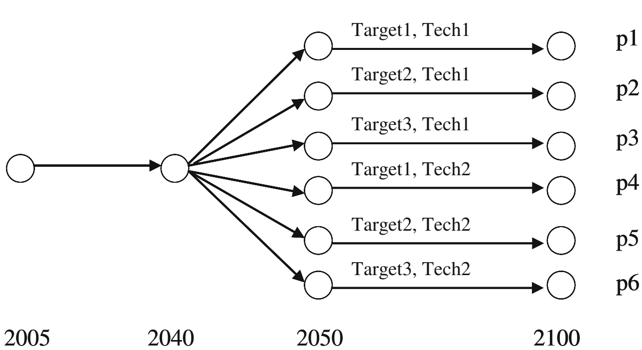

Fig. 2 An example of the stochastic set-up used in TIAM

Figure 2 reflects fully our stochastic case, in which only one resolution point exists, in 2040, and six alternative states-of-the-world are assumed for the time periods after 2040. Consequently, our research findings up to and including 2040 describe the strategy the model suggests under the uncertainty faced concerning the developments after the resolution point. One of the reasons we kept the size of the branching event tree fairly modest is that the computational requirements increase fast with higher levels of complexity. The restrictive set-up presented here proves to largely fulfill our purposes. Results from 2050 onwards describe conditional results, that is, actions that will be taken *if* we find ourselves in 2050 in a particular world. This implies that, although we retrieve only one set of results until 2040, from 2050 onwards we obtain six distinctive ones, one for each alternative state-of-the-world. In this paper, we mainly focus on the outcomes up to 2040, since these describe decisions taken under uncertainty - the main focus of our analysis. In some cases, however, knowledge of developments during the second half of the century is necessary for understanding pre-2040 results; we therefore extend our analysis until 2100 for certain indicators.

3.4 Scenarios and Assumptions

We construct a set of scenarios that cover a range of variations for the value of the climate target. Subsequently, we run alternative cases for each of these scenarios in which assumptions regarding the CO_2 storage capacity are either optimistic or pessimistic, thus yielding either opportunity or limits to the use of CCS technology, at least in some regions of the world. We also construct a stochastic scenario that considers all these cases simultaneously. For this scenario we attach probabilities to each of the possible future states-of-the-world. Our stochastic scenario only accounts for the uncertainties explicitly included, while taking all the other parameters as known. Of course, we therefore far from cover the full range of uncertainties that are being faced in reality, from concerning the trends of the drivers behind energy demand (e.g. population and economic growth) to the details of the development of individual technologies. Our study should therefore be taken as a sensitivity analysis of one particular kind, in which the implied decision maker considers alternative developments for only a few characteristics of the system simultaneously, while relying on scenario-based approaches for all other variables.

We define our climate targets in terms of maximum additional radiative forcing, which is comparable to upper limit for the atmospheric concentration of greenhouse gases. Since we do not explicitly constrain temperature change, we do not need to make assumptions concerning the wide range of possible values for the climate sensitivity. For studies concentrating on uncertainty regarding the latter, see for example van der Zwaan and Gerlagh [28], Keppo et al. [14] and Labriet et al. [16]. Different radiative forcing limits can, however, be interpreted as representing the same temperature target, under different assumptions concerning the climate sensitivity—this was systematically done in e.g., Loulou et al. [20]. We define three alternative radiative forcing targets: 5.5 W/m^2, 4.0 W/m^2, and 3.2 W/m^2. Since 3.2 W/m^2 is a fairly stringent upper level and might dominate our modeling outcomes, we study in particular how sensitive the stochastic results are to the choice of the most ambitious target considered possible. We do this by changing the value of the lowest climate change target from 3.2 to 3.6 W/m^2. We use this variation mainly in our sensitivity analysis and do not include it as an independent additional target in our stochastic study, for which we assume either the 3.2 or 3.6 W/m^2 target, not both.

In order to interpret these radiative forcing targets, Fig. 3 shows their consequences in terms of probabilistic temperature increases in long-term atmospheric equilibrium conditions. The climate sensitivity is the only parameter assumed uncertain behind this histogram, for which we use the probability density function as determined by Forest et al. [2]. This probability density function relies on uniform first priors. Figure 3 shows that the median temperature increase in the baseline is a bit below 5°C, whereas with a 3.2 W/m^2 target it is approximately 2.5°C. Even with our most stringent climate target, it thus seems unlikely that the global average surface temperature increase will stay below 2°C.

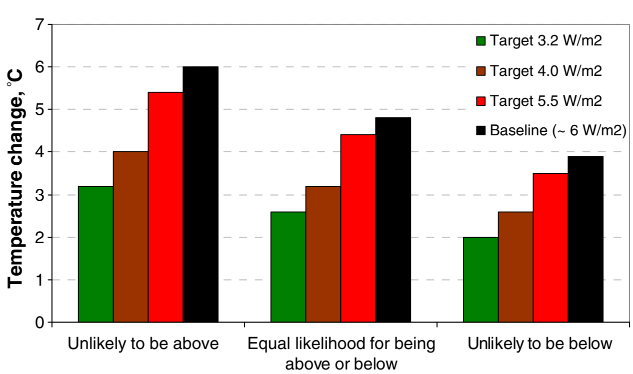

Fig. 3 Radiative forcing targets and related temperature outcomes. N.B. Terminology as in IPCC [12]: a probability>66% is considered "likely" and < 33% "unlikely"

The stochastic scenario includes all three climate targets (3.2, 4.0, and 5.5 W/m^2) as well as the two possible futures for the accessible CO_2 storage volume. The corresponding six different combinations of climate targets and storage capacities are exclusive, that is, only one of them materializes in 2050. Probabilities are assigned to each of these six states-of-the-world post-2050. Since it is highly uncertain what level of eventually allowed temperature increase strikes the best balance between mitigation, adaptation and damage costs—not to mention the non-monetary consequences of this increase (such as related to the potential climate-induced loss of natural habitats or migration of people)—these probabilities cannot be evaluated scientifically, at least not today. We have therefore chosen them rather arbitrarily. As a result of computational limitations the probability distribution function we employ is necessarily rather restricted, and in any case discrete. The basis and outcome of our analysis should therefore not be seen as absolute, but instead considered as a typical example of how the inclusion of uncertainty can affect optimal decisions for the long-term development of our global energy system. Table 1 lists the probabilities we have chosen for the alternative states-of-the-world. The probability for an agreed climate target of 5.5 W/m^2 is assumed to be 25%, for 4.0 W/m^2 45%, and for 3.2 W/m^2 (and 3.6 W/m^2 in the variant case) 30%, meant to represent roughly a failed, middle-of-the-road and ambitious climate policy regime respectively. The CO_2 storage capacity is assumed to be only partially available with a likelihood of 70%, while we suppose it is fully usable with a probability of 30%.

For the CO_2 storage potentials, the qualitative logic behind the chosen probabilities is that it would likely be difficult to determine conclusively whether the presently more unknown storage methods will become technically, economically and socially robust enough for widespread commercial operation. In combination with issues concerning public perception of CO_2 storage (see e.g. [8]), this leads us to assume that the likelihood of the more pessimistic CO_2 storage scenario is higher than that of the more optimistic one. The likelihoods for the climate target are, as mentioned, also highly debatable. Our reasoning is roughly that a medium target (4.0 W/m^2) is more likely than a very stringent one (3.2 W/m^2), since the latter would be more costly and more difficult to agree upon globally. We have given the lowest likelihood for the case in which little mitigation is required (5.5 W/m^2), which reflects that a corresponding median temperature increase of almost 4.5°C (see Table 1, calculated as for Fig. 3) is not likely to be acceptable. We recognize that it would be easy to argue for different parameter values and we therefore do not want to suggest that our choices should be interpreted as approximations, but merely as a "scenario of probabilities".

Table 1 Probability matrix for the resolution of climate target and storage volume values. Additional derived climate indicators are given in italics

Likelihood of scenario			Climate target	
Forcing target, W/m^2	CO_2 eq. concentration, ppm	Median temperature increase, °C	Low CO_2 storage potential (%)	High CO_2 storage potential (%)
5.5	*781*	*4.4*	17.5	7.5
4	*589*	*3.2*	31.5	13.5
3.2	*507*	*2.6*	21.0	9.0

4 Results

4.1 Mitigation and Emissions

The imposition of a radiative forcing target, without additional requirements for where or when to mitigate, allows our model to optimally determine at what place and time to materialize CO_2 emission reductions. The only overall constraint is that the global radiative forcing target is not exceeded. If there was a single marginal mitigation cost that stays constant throughout the time frame studied, postponement of mitigation would be preferable as a result of the 5% discount rate used in TIAM-ECN for devaluating future costs. If, however, it is assumed that the mitigation potential reduces in the future and correspondingly costs increase, action needs to be taken already early on. These types of dynamics can be clearly distinguished in the CO_2 emission results shown in Fig. 4.

Figure 4 shows the development of CO_2 emissions for the perfect foresight (PF) scenarios during the entire century. The steady linear increase of emissions in the baseline is abandoned from as early as 2020 if the stabilized climate target is 4.0 W/m^2 or below. If the target is higher (e.g. 5.5 W/m^2), emissions may stay close to the baseline for decades to come (until the middle of the century in the 5.5 W/m^2 case, after which they level off around 2080). A target of 4.0 W/m^2 yields a quick leveling off of CO_2 emissions (around 2020) and a steady decrease that starts around 2060. The stringent target of 3.2 W/m^2 requires CO_2 emissions to start decreasing from today onwards, with the steepness of the decrease gradually declining until leveling off close to the end of the century.

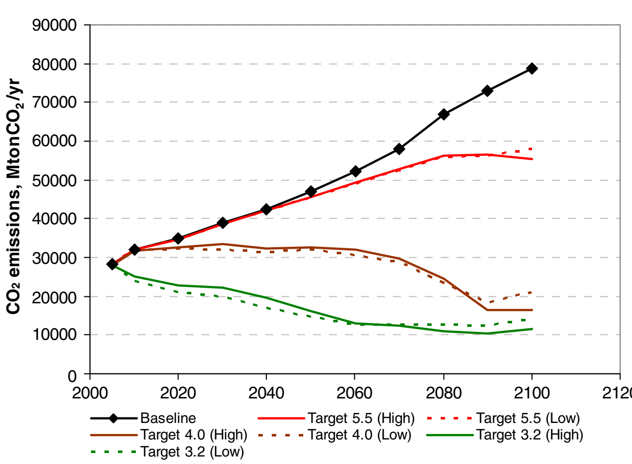

Fig. 4 Long-term CO_2 emissions for the baseline and the deterministic mitigation scenarios. Scenarios with a low assumption concerning the CO_2 storage availability are shown with *dashed lines*

The mid-term CO_2 emission paths show that, as one can expect, a more stringent target leads to higher mitigation needs in the near term. If the CO_2 storage potential for CCS is assumed to be low, large-scale mitigation with CCS is no longer possible by the end of the century, so that deeper reductions are needed already before 2050. As Fig. 4 also demonstrates, the impact of available CO_2 storage capacity is emphasized by the stringency of the climate target associated with the respective scenarios.

It is also clear from Fig. 4 that the climate target has a much larger impact on CO_2 emissions and the timing of mitigation, than the storage capacity does. As we later show, however, for a given climate target the use of CCS across the century differs significantly as a function of assumed storage capacity. This indicates that the fairly similar emission paths for the same climate targets are derived using, at least partially, different mitigation means. Figure 5 shows how uncertain targets and storage potentials are reflected in the CO_2 emission results for the stochastic scenario.

From Fig. 5 we conclude that if there is a possibility that the climate target is very stringent—so stringent that most of the reasonably cost-efficient mitigation measures need to be taken as soon as possible—the result of the stochastic scenario approaches that of this deep CO_2 reduction (i.e., strong mitigation) scenario. Under essentially any realistic probability it proves to matter fairly little how likely this scenario is: if the likelihood is above zero, the model needs to be able to stay below the constraints imposed also by this particular state-of-the-world.

The left panel of Fig. 5 shows how the climate target of 3.2 W/m^2 approaches the limits of mitigation options available in the model: the stochastic emission path is very close to that of the perfect foresight scenario with the 3.2 W/m^2 target. This suggests that the feasibility of reaching this target, if it happens to come into force in 2050, dominates the solution and issues of economic timing of mitigation become less relevant. This conclusion is

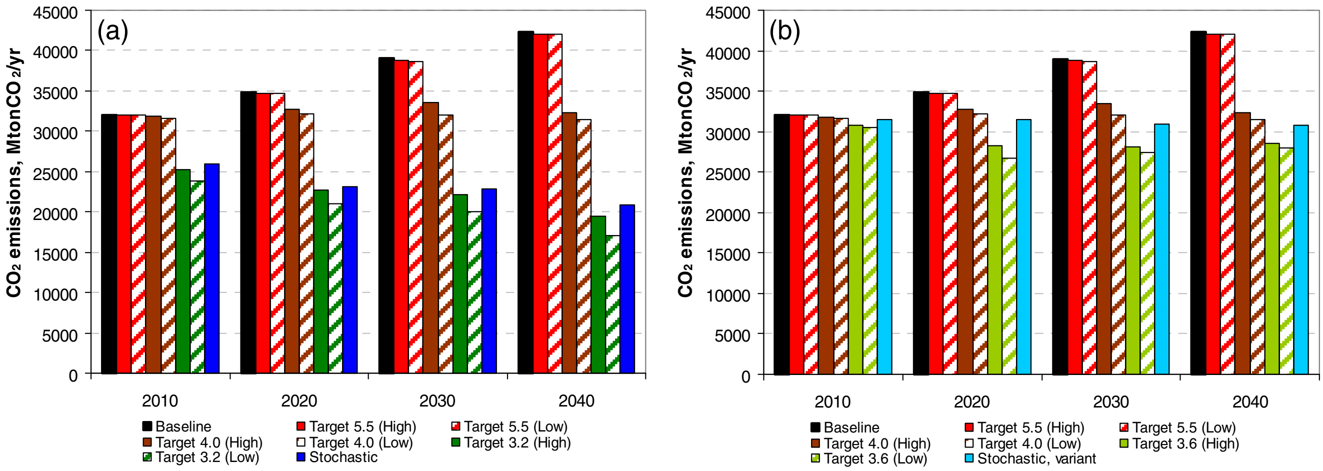

Fig. 5 Mid-term CO_2 emissions and the impact of uncertainty: **a** with 3.2 W/m^2 and **b** with 3.6 W/m^2 for the lowest level of climate target. Scenarios with a low assumption concerning the CO_2 storage availability are shown with *striped bars*

confirmed by panel b of Fig. 5: if the most stringent target considered possible is changed to 3.6 W/m^2, the result of the stochastic scenario diverges more clearly from the perfect foresight path of the 3.6 W/m^2 scenario and is closer to the result of the 4.0 W/m^2 PF scenario. This indicates that, in this case, the model is able to concentrate on the economics of mitigation across uncertain futures, whereas with a more stringent target the focus needs to be on reaching feasible results. Figure 6 illustrates this by showing how the emission paths change after uncertainty is resolved.

Figure 6 further demonstrates the impact the lowest possible target has on our stochastic analysis. The panel on the left indicates that unless the 3.2 W/m^2 target is revealed in 2040 in the stochastic scenario, emissions increase rapidly after the resolution of uncertainty. This implies rather high stranded climate investments for the pre-2040 timeframe. If the lowest possible target is relaxed to 3.6 W/m^2, emissions increase after uncertainty resolution only if the relaxed target of 5.5 W/m^2 is implemented—even then the increase is less steep than what is observed if a 3.2 W/m^2 target is a possibility. It can also be noted that there is no immediate deep decline of emissions observable after 2040 in the right panel, which indicates that the model is capable of reaching even the most stringent long-term climate target without drastic actions needed after the uncertainty has been resolved.

5 CO_2 Capture and Storage

In a climate-constrained world CCS offers a possibility for relying longer on existing production structures dominated by the combustion of fossil fuels, before a transition to carbon-free primary energy sources is achieved. Several aspects of CCS, however, remain intrinsically uncertain, concerning e.g. CO_2 storage potentials and leakage phenomena. An additional caveat of CCS applied to power

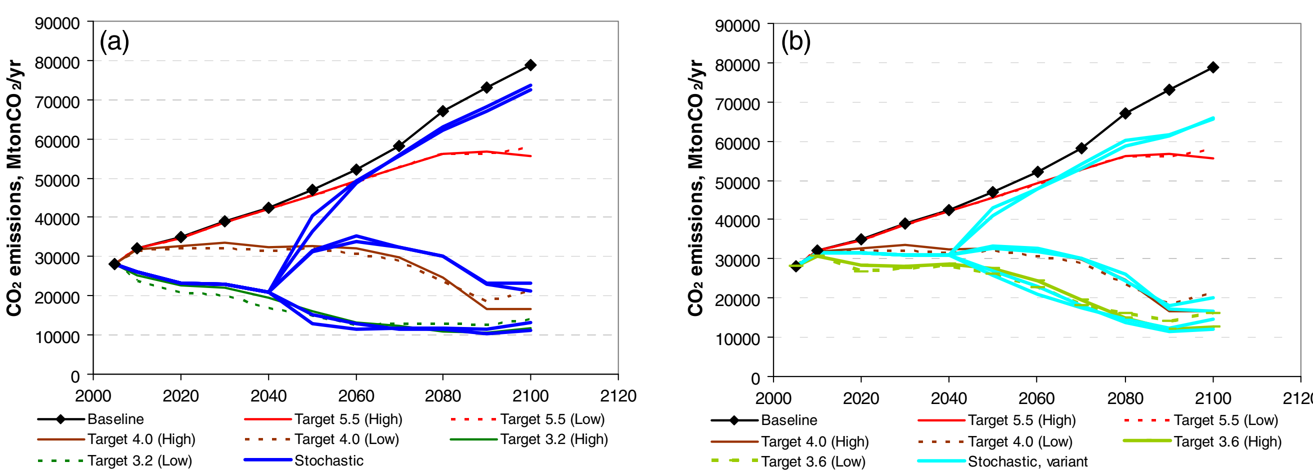

Fig. 6 Long-term CO_2 emissions: **a** with 3.2 W/m^2 and **b** with 3.6 W/m^2 for the lowest level of the climate target

plants is that the capture rate is typically only about 90% (since the costs of CCS increase exponentially with higher capture rates). Figure 7 illustrates the extent to which CCS technology is used in our TIAM-ECN model runs.

The first noticeable feature of Fig. 7 (panel a) is that the level of climate control plays a key role for the diffusion of CCS technology. If the target is assumed to be 5.5 W/m^2, practically no CCS is implemented before 2050. If the target is 4.0 W/m^2 some 500–600 Mton of CO_2 is captured each year around 2040. This CCS deployment level is more than doubled if it is either known or considered possible that a 3.2-W/m^2 climate target has to be reached. We see that the stochastic strategy involves more diversification across the different PF targets if the most stringent target considered possible is relaxed to 3.6 W/m^2 (panel b in Fig. 7): the stochastic result then lies somewhere around the middle between the PF 3.6 and 4.0 W/m^2 outcomes, rather than close to the 3.6 W/m^2 result. Generally speaking the use of CCS is likely to be reduced, even in the short term, if storage capacity is expected to become an issue later during the century. In practice, however, as demonstrated in Fig. 7, this effect does not prove to play out, or can even switch sign, until 2050. The reason is that until then the storage capacity does not become a constraining factor (at least not on the global level). This, however, is no longer true, when results are analyzed up to 2100.

Although for a given climate target the use of CCS follows very similar paths up to 2050, after 2050 our assumptions concerning storage potentials start to play a major role. As can be seen in panel a of Fig. 8, even if the target is the relatively lax 5.5 W/m^2, reduced storage potential estimates play an important role during the second half of the century: they halve the projected use of CCS by 2100. Panel b further illustrates the strong divergence of paths during the second half of the century: The more stringent the climate target, the larger the share of total cumulative CCS activity across the century that takes place before 2050. A lack of storage capacity has a similar effect: it shifts this share to earlier decades and the impact of this mechanism is stronger the tighter the climate target.

Noteworthy is also that although before 2050 the use of CCS is strongest in the 3.2 W/m^2 PF scenario, the cumulative use of CCS over the whole twenty-first century is most widespread in the PF scenario with the 3.6 W/m^2 target. A likely reason for this is that by the end of the century staying below the 3.2 W/m^2 target requires essentially completely carbon-free energy options, rather than techniques that still involve modest emission levels (which disfavors CCS, as a result of the assumed 90% capture rate). Figure 9 further elaborates on the relative importance of CCS by showing the share of cumulative CO_2 reductions achieved through CCS.

Immediately visible in Fig. 9 is that, although CCS contributes significantly to overall mitigation, its role remains supplementary throughout the century. Only at the end of the century in the PF 5.5 W/m^2 case with large CO_2 storage potential does CCS cover more than 15% of total cumulative CO_2 mitigation. By 2040, CCS covers no more than 5% of total mitigation, no matter which scenario is examined. Noteworthy is that, if the CO_2 storage assumptions are not optimistic, the relative contribution of CCS to overall mitigation peaks before the end of the century under all PF targets except for the 5.5 W/m^2 case. Stochastic scenarios follow the qualitative trends of the PF scenarios fairly closely.

Moving on to the technologies for which CCS applied, Fig. 10 shows the cumulative use of CCS from 2010 until 2040.

A few policy-relevant observations can be made from Fig. 10. First, it appears that at least in the mid-term the upstream fossil fuel sector offers cost-effective means for CCS application, even while the eventual total potential for

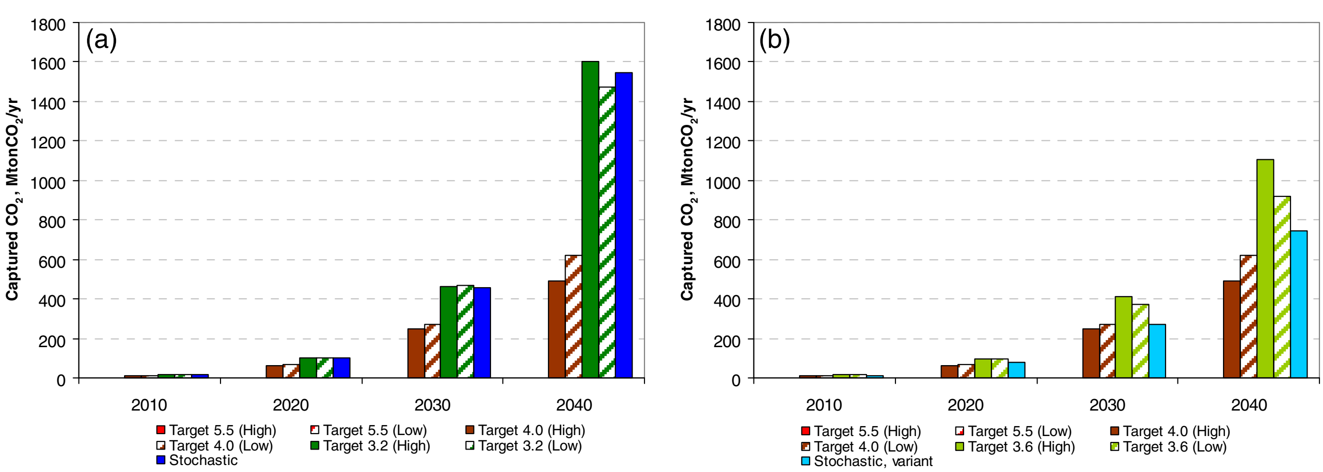

Fig. 7 The use of CO_2 capture and storage in TIAM-ECN: **b** replaces the 3.2 by a 3.6 W/m^2 climate target

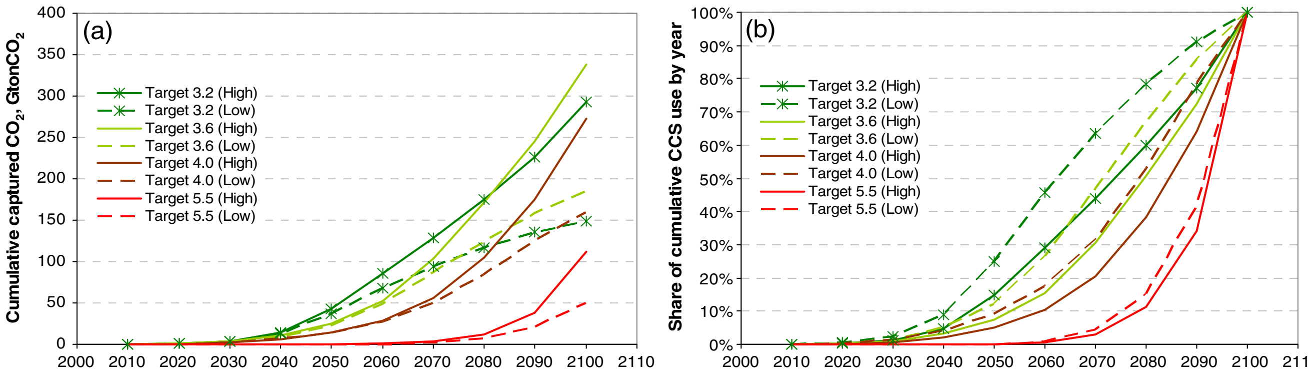

Fig. 8 Cumulative use (**a**) and relative timing (**b**) of CCS implementation

mitigation in this sector is rather limited. Some CO_2 capture is introduced for synthetic fuel production under the 4.0 W/m^2 climate target, but CO_2 capture from upstream emissions clearly dominates. Second, in case of a more stringent climate target CCS applied to power plants becomes the second option for CCS deployment. CCS is then mostly applied to gas-based power production rather than coal-fired power plants. Third, CO_2 capture from synthetic fuel production becomes lucrative if the climate target is stringent, but not otherwise (that is, the 3.2 W/m^2 climate target leads to sizeable CO_2 capture from synthetic liquid production, whereas the 3.6 W/m^2 induces little of such additional activity in comparison to the 4.0 W/m^2 target). Furthermore, if the climate target is stringent and the storage capacity for CO_2 is expected to be low, the use of synthetic fuels (such as hydrogen produced via steam methane reforming) during early decades is significantly expanded. Storage restrictions start affecting the modeling results during the latter half of the century: over the full-time frame of our study cumulative CO_2 capture from synthetic fuel production is higher if the storage potential is assumed to be larger.

5.1 Energy Resources

Figure 11 shows the development over the twenty-first century of the various types of primary energy use in the baseline, as well as the changes introduced in 2040 as a result of climate policy (in comparison to the baseline) across the set of our simulated scenarios.

As can be seen from Fig. 11, primary energy use climbs steadily in the baseline, approaches approximately 1100 EJ in 2050 and increases to about 1800 EJ by the end of the century. Although the use of carbon-free resources is substantially enhanced in absolute terms, the consumption of coal, oil and natural gas increases in a similar fashion, leading to an almost constant share for the use of fossil fuels throughout the century (at a level of around 86%). Climate change mitigation yields two main changes in total primary energy consumption. Not only is energy use significantly reduced, but the carbon intensity of the remaining portfolio is also substantially lowered. Both these changes become stronger, the tighter the climate target. Further modifications in the same direction are observed if CO_2 storage for CCS proves not to be available

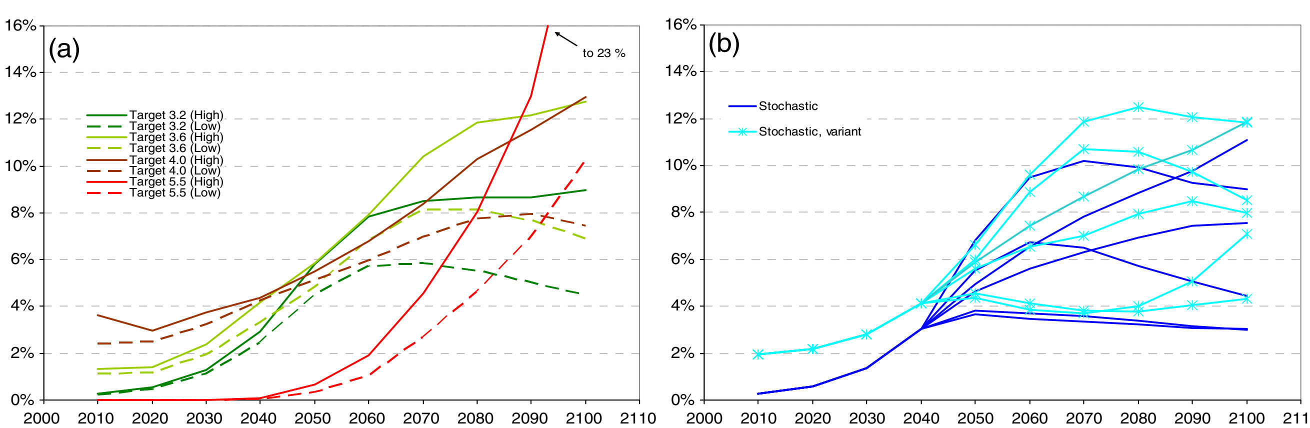

Fig. 9 Relative contribution of CCS to cumulative mitigation of CO_2

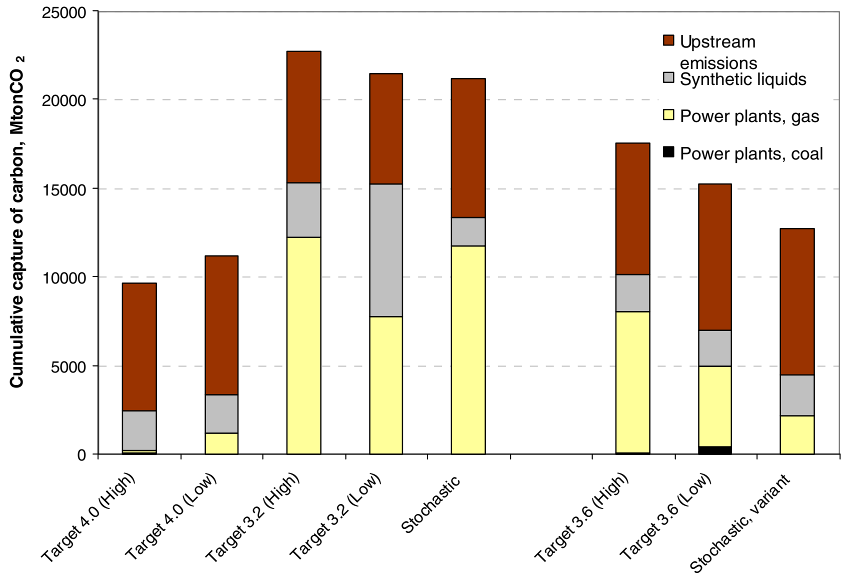

Fig. 10 Cumulative capture of CO_2 until 2040, given by energy technology to which CCS is applied. Scenarios with insignificant CCS deployment are excluded

up to its full theoretical potential. Not all fossil fuels are reduced in usage: all mitigation scenarios actually *increase* the use of natural gas, thereby complementing the surge in carbon-free energy resources. As before, the scenario with a loose 5.5 W/m^2 climate target does not alter the energy system before 2050.

Our findings in terms of primary energy use in the stochastic scenarios follow the same pattern as with the results for CO_2 emissions. If a 3.2 W/m^2 climate target is assumed to be a possibility, preparing for this extreme outcome proves to be the preferred strategy. In other words, in this case a precautionary approach is taken that disproportionally internalizes the worst case realization. Note that the primary energy portfolio of the (first) stochastic case resembles that of the PF 3.2 W/m^2 climate target scenario with *high* CCS potential. This indicates that hedging against a probability of only low CO_2 storage opportunities is not considered a priority.

5.2 Emission Prices

Perhaps the clearest indicator for the total costs incurred by the implementation of a global climate mitigation regime is the shadow price of CO_2 that the model generates. This shadow price can be interpreted as a global carbon tax or, alternatively, the market price for CO_2 emission permits, under the assumption that a global mitigation and trading regime exists without transaction costs or limits to emissions trading. Figure 12 presents results from TIAM-ECN for this indicator.

Figure 12 confirms what we saw in results for other variables. If 3.2 W/m^2 is a certain climate target, or even only a possibility in a stochastic scenario, the value of CO_2 emission permits grows considerably more rapidly than in other scenarios. In a stochastic setting the model uses again a precautionary approach from the outset: if it does not "prepare for the worst" the CO_2 price could easily explode

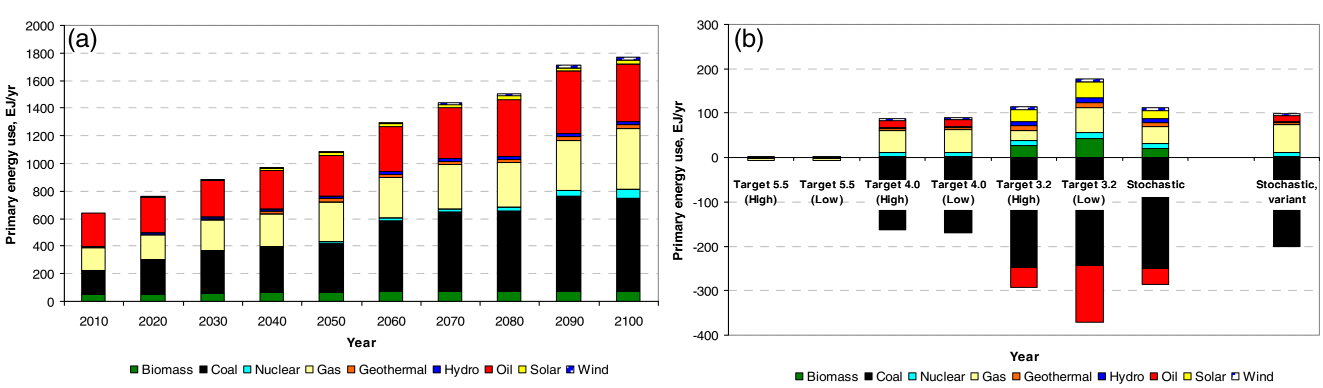

Fig. 11 Primary energy use in the baseline (**a**) and changes in consumption in 2040 as a result of climate policy (**b**)

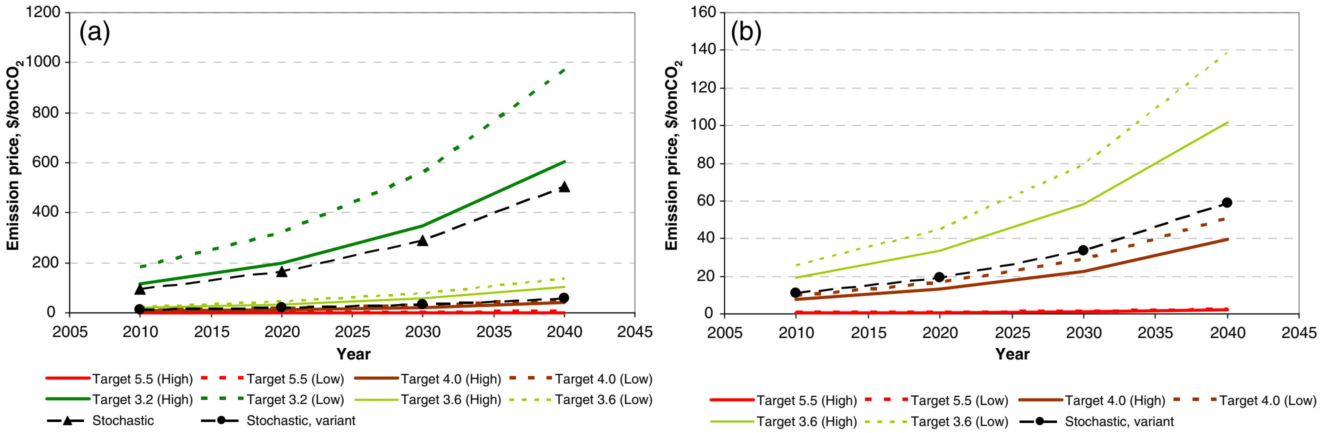

Fig. 12 Evolution of the CO_2 emission price: **b** excludes the 3.2 W/m^2 target

and approach infinity once the uncertainty has been resolved. The latter would, in other words, imply that reaching the climate target becomes infeasible. This indicates a high economic value for actions that would allow exceeding the 3.2 W/m^2 forcing target without sacrificing economic well-being, i.e. measures such as adaptation. The 5.5 W/m^2 scenario, on the other hand, leads to low emission prices of only approximately 50 \$/tonCO_2 in 2100 (a level reached in all other scenarios in or before 2050). Such low CO_2 prices are unlikely to lead to any significant changes in the energy system, even in the long term.

We conclude our analysis by showing how CO_2 prices develop in the stochastic scenarios, after uncertainty has been resolved. Results shown in Fig. 13 demonstrate the mechanism described above: Once the uncertainty has been removed and it is known that the 3.2 W/m^2 target needs to be reached, emission prices increase very rapidly. If it is also revealed that the CO_2 storage capacity is low, prices increase almost vertically and reach astronomical values in 2100. If, however, it turns out in 2040 that staying below 5.5 W/m^2 will be sufficient, the emission price drops to zero and stays there essentially until the end of our time horizon. Even if the revealed climate target turns out to be a moderate 4.0 W/m^2, CO_2 prices crash so deep after 2040 that they reach the level of 2040 again only some 50 years later. Such a significant drop in prices indicates that if the 3.2 W/m^2 target is not realized when uncertainty is resolved, many investments made prior to 2040 would, judged in hindsight, be uneconomic. All of the elements described above are clearly muted, if the 3.2 W/m^2 target is replaced with a 3.6 W/m^2 target in our stochastic analysis.

6 Conclusions

For the research presented in this article we used a stochastic version of the bottom-up energy systems model TIAM-ECN, which allowed us to study the impacts that uncertainty concerning the CCS storage potential and climate control target may have on mid-term energy transition strategies. In addition to a stochastic analysis we have run a set of scenarios with perfect foresight, in order to distill the changes caused by uncertainty in features or limitations of several parameters relevant for climate policy design. Our main focus was on the decision-making process during the first half of the twenty-first century.

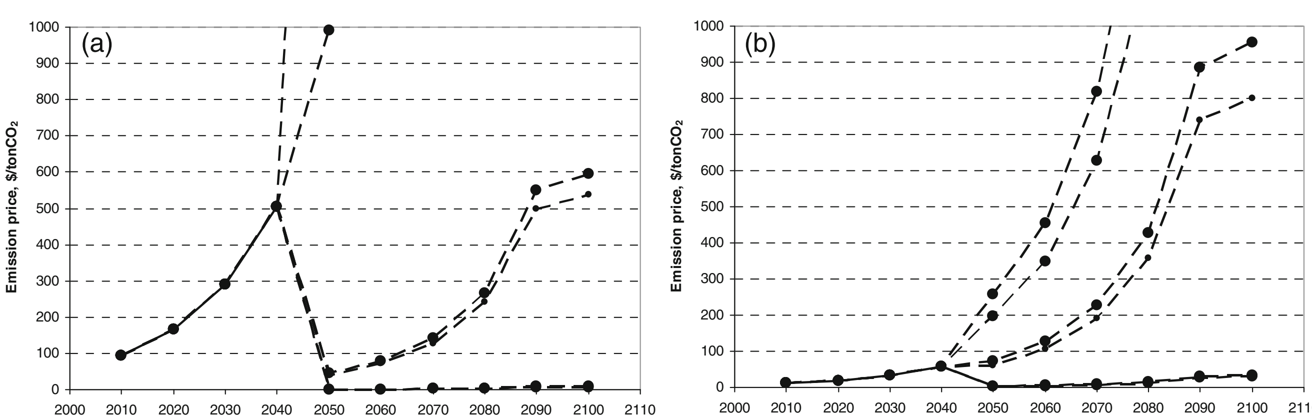

Fig. 13 Emission prices after the resolution of uncertainty, **a** with 3.2 W/m^2, **b** with 3.6 W/m^2 target included

We found that if it is a possibility that a stringent climate target needs to be reached, a strategy is required that emphasizes the most stringent potential mitigation goal. The latter then dominates the solution. The underlying reason is that the tightest climate target we inspected—3.2 W/m^2—is fairly close to what is feasible to reach for our model. Consequently, there is little room for the model to balance the economics of the energy system across possible future states-of-the-world. If the most stringent envisioned climate target is relaxed, the model puts forward a more balanced solution that takes into account all (in our case three) possible long-term targets, i.e. not only the most stringent one. This suggests that uncertainty with regards to the climate target has a much larger impact on mid-term results than incertitude in the size of the storage capacity. This implies that, at least on a global level, the available CO_2 storage capacity is unlikely to limit the use of CCS drastically prior to 2050, that is, the lack of such capacity might not increase mitigation costs considerably. In the long term, however, lack of CO_2 storage capacity can lead to increased climate mitigation costs and to a relative decrease in the importance of CCS as a mitigation option.

Despite the above, CCS remains a relatively important option for global climate mitigation. In the mid-term (before 2050) its use is higher the more stringent the climate target, or has a possibility to be. During the latter half of the century, however, the most stringent climate target does not lead to the highest deployment of CCS technology. The most likely reason for this is the fraction of CO_2 emissions that remains with a 90% capture rate. CCS can therefore be characterized as a good supplementary option for CO_2 emission reductions until the next generation of carbon-free energy technologies becomes cost-effective. In some cases, CCS could stay an important contributor to climate change mitigation even in the long term, but it may be subject to deployment limitations in case of an ambitious climate target or CO_2 storage limitations.

Costs of mitigation are mostly determined by the expected climate target, although when in the long term also CO_2 storage limitations start to become constraining clear differences in CO_2 emission prices can be observed between cases with similar climate targets but alternative CO_2 storage capacities. For example, a change in the climate target from 4.0 W/m^2 down to 3.6 W/m^2 increases the CO_2 emission price in 2040 by some 150%. Meanwhile the impact of the CO_2 storage potential is not insignificant: a substantial reduction in the assumed CO_2 storage capacity increases the emission price in the 3.6 W/m^2 scenario by some 40%.

The scenarios in which a stringent climate target is a possibility lead to high CO_2 emission prices. This indicates that adaptation measures could also possess considerable economic value and may "take pressure off" from mitigation efforts—the latter are clearly close to the maximum level considered feasible by our model. Another observation for possible further investigation is that the stochastic scenario that considers the 3.2 W/m^2 climate target possible experiences a drastic crash in CO_2 price levels if this target does not come into force in 2050. This phenomenon makes a considerable number of prior mitigation investments inefficient.

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