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Meeting global temperature targets—the role of bioenergy with carbon capture and storage

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Abstract
In order to meet stringent temperature targets, active removal of CO_2 from the atmosphere may be required in the long run. Such negative emissions can be materialized when well-performing bioenergy systems are combined with carbon capture and storage (BECCS). Here, we develop an integrated global energy system and climate model to evaluate the role of BECCS in reaching ambitious temperature targets. We present emission, concentration and temperature pathways towards 1.5 and 2 °C targets. Our model results demonstrate that BECCS makes it feasible to reach temperature targets that are otherwise out of reach, provided that a temporary overshoot of the target is accepted. Additionally, stringent temperature targets can be met at considerably lower cost if BECCS is available. However, the economic benefit of BECCS nearly vanishes if an overshoot of the temperature target is not allowed. Finally, the least-cost emission pathway over the next 50 years towards a 1.5 °C overshoot target with BECCS is almost identical to a pathway leading to a 2 °C ceiling target.

Keywords: climate change, energy systems, integrated assessment models, negative emissions

S Online supplementary data available from stacks.iop.org/ERL/8/034004/mmedia

1. Introduction

Without a change in prevailing energy and climate policies, the expected future greenhouse gas emissions will likely lead to an increase of global mean surface temperature above the 2 °C temperature limit endorsed by the UNFCCC in Cancún [1]. This calls for more ambitious policies as well as thorough investigations into options that may help to reverse global warming in the future. Bioenergy with carbon capture and storage (BECCS) is a technical option that could potentially generate sustained negative CO_2 emissions while simultaneously producing electricity, heat or liquid fuels such as ethanol. If a large-scale expansion of BECCS takes place while carbon emissions from the rest of the global energy system are nearly eliminated, net negative emissions on a global scale can be achieved. In this way, BECCS can contribute to reducing global mean surface temperature [2].

Previous studies using technology-oriented energy system models (including studies with a previous version of the model used here) have shown that stringent CO_2 concentration targets or radiative forcing targets can be reached at lower cost if BECCS is available [3–6], and that some concentration targets are only within reach if BECCS is available. For a given radiative forcing level or concentration target in year 2100, CO_2 emissions levels in 2020 and 2050 can be higher if BECCS is included in the technology portfolio [4, 7]. In this letter, we advance this work by integrating a temperature response model into an energy system optimization framework and by explicitly analysing the role of BECCS in meeting various temperature limits.

Two types of temperature limits are considered: a 'ceiling target' which may never be exceeded, and an 'overshoot target' which allows for a temporary overshoot in the temperature response, provided that the target is met in 2150. Temperature targets could also be constructed, for example, as 'peak and decline targets', in which a maximum temperature level is specified along with an aim to reduce temperature beyond the peak. This is related to overshoot targets, and for simplicity we do not discuss this option further.

The aim of this letter is thus to analyse the role of BECCS in meeting global temperature targets. Two key questions are addressed.

- How are cost-effective emission, concentration and temperature pathways towards various temperature targets affected by the availability of BECCS?
- How is the cost of meeting different temperature targets affected by the availability of BECCS under various assumptions about carbon storage capacity, biomass availability and climate sensitivity?

Results addressing these questions have not been reported earlier since previous studies have focused on analysing emission pathways towards concentration targets [3], radiative forcing targets [5] or cumulative CO_2-equivalent emission targets [8, 9]. When optimizing towards temperature targets the inertia of the climate system is explicitly taken into account, as opposed to when optimizing towards concentration, radiative forcing or cumulative emission targets. As discussed in den Elzen and van Vuuren [10] and Johansson [11], the energy uptake by the oceans has a profound impact on emission pathways towards climate stabilization.

The letter is structured as follows. In section 2, we present our method briefly. A more detailed description of the model is given in an appendix. In section 3, model results are presented. In section 4, a brief sensitivity analysis is offered. A more detailed sensitivity analysis is presented in the supplementary online material (available at stacks.iop.org/ERL/8/034004/mmedia). A combined discussion and conclusion is offered in the concluding section 5.

2. Method

We have developed an integrated energy–climate model, GET–climate, by merging a technology-oriented ('bottom-up') energy system model [4, 12, 13] with a reduced-complexity climate model [11, 14]. The energy and climate models are hard linked, which enables us to generate internally consistent least-cost scenarios for the global energy system, for a given energy demand scenario and temperature target. All major greenhouse gases as well as aerosols are included in the model. Our carbon cycle representation takes into account climate feedback and nonlinearities of the carbonate chemistry in the ocean and CO_2 fertilization in the terrestrial biosphere [15].

The scenarios generated by our model are based on a perfect foresight approach. This implies that costs of technologies, limits on expansion rates and future potential, and the dynamics of the climate response to emissions are known and taken into account in the optimization. This idealized approach gives us a consistent picture of the cost effectiveness of different technology options for meeting various temperature limits.

In section 3 we focus on eight combinations of technology availability and temperature limit formulations in order to illustrate the potential importance of BECCS under different conditions. We consider ceiling and overshoot targets, limits on the global mean surface temperature of 2 and 1.5 °C above the pre-industrial level, and we allow carbon capture and storage (CCS) either from only fossil fuels ('fossil CCS') or from both fossil fuels and biomass ('fossil CCS and BECCS'). Fossil fuels, nuclear power and renewable energy technologies are available in all scenarios.

Our separation between the 'fossil CCS' and 'fossil CCS and BECCS' cases should be seen as a constructed case in order to isolate the role of BECCS and negative emissions. There are no strong technical reasons why BECCS should not be a feasible option if CCS becomes one, given a certain supply of bioenergy. Similarly, our assumption that all available biomass can be used in BECCS facilities is idealized, and intended to clarify the quantitative links between biomass availability, potential for negative emissions and temperature reductions.

All results in the main letter are produced assuming mainstream estimates of global bioenergy availability (200 EJ yr^{-1}) [16, 17], carbon storage capacity (2000 $GtCO_2$) [18], and climate sensitivity (3 °C per doubling of CO_2 concentration) [19]. Results for variations of these parameters are presented in detail in the supplementary material (available at stacks.iop.org/ERL/8/034004/mmedia) and are discussed briefly in section 4 below. A more detailed description of the model and key assumptions is provided in the appendix.

3. Results

3.1. Emission and temperature pathways

Emission, concentration and temperature profiles for 2 and 1.5 °C ceiling and overshoot targets are shown in figure 1. In the 2 °C ceiling target scenarios, net CO_2 emissions linger close to zero once the temperature target is met. This is consistent with earlier findings that there is a strong relation between cumulative CO_2 emissions and peak temperature [20], and that the temperature response to a pulse emission of CO_2 is nearly constant over centuries [21–23]. This also explains why there are essentially no net negative emissions in the ceiling case with BECCS, since sustained global net negative emissions would lead to a continuous decrease in temperature. Even though no net negative emissions appear, the cost-effective emission pathway is somewhat higher in the near term (2020–50) when BECCS is available and lower in the long term (2060–100), see also [46]. Hence, BECCS enables a delay in emission reductions but keeps cumulative emissions approximately the same.

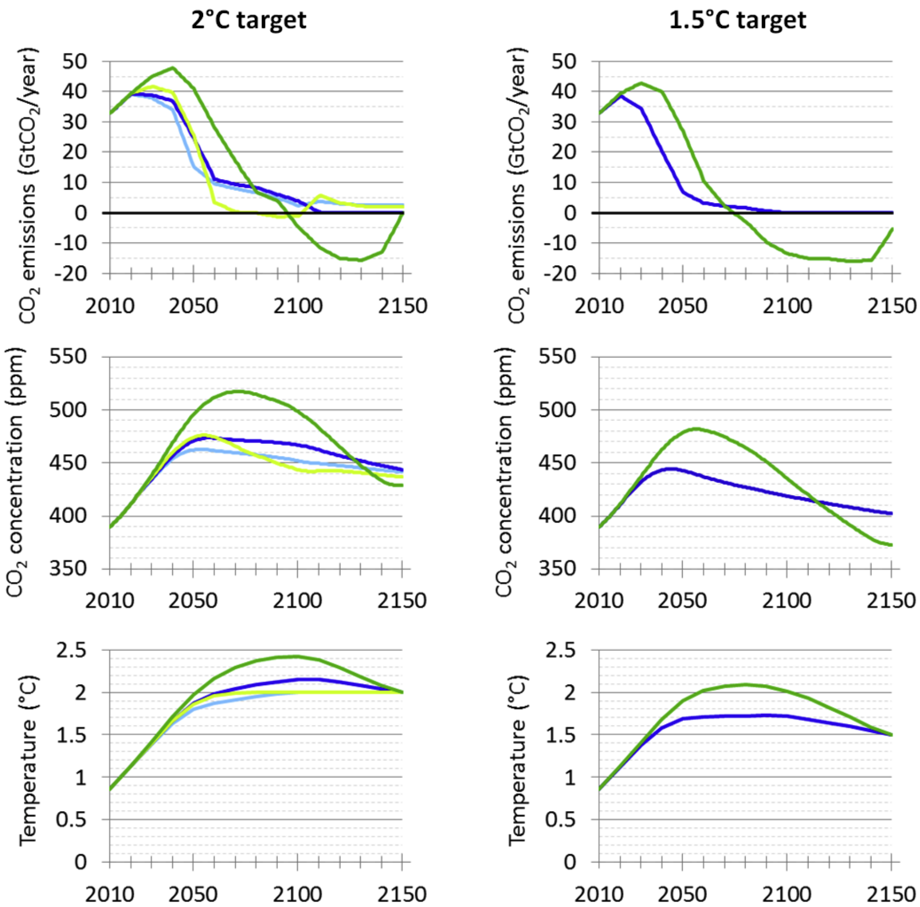

Figure 1. CO_2 emissions, CO_2 concentration and mean surface temperature increase, for 2 °C targets (left) and 1.5 °C targets (right). Cases shown are: fossil CCS with ceiling targets (light blue), fossil CCS with overshoot targets (dark blue), fossil CCS and BECCS with ceiling targets (light green) and fossil CCS and BECCS with overshoot targets (dark green). Ceiling cases for the 1.5 °C target are infeasible in our model.

(However, as shown in section 3.2, availability of BECCS does not have any significant impact on abatement costs of meeting ceiling targets.) Additionally, despite the temperature ceiling, there is room for a century-long overshoot in concentration (above the long term equilibrium level) due to inertia in the climate system [10, 11]. The 1.5 °C ceiling targets are not feasible in our model primarily due to constraints on technology expansion rates. This result is consistent with Ranger *et al* [24] and Rogelj *et al* [8, 9] who find that meeting the target without an overshoot is a significant challenge.

In the overshoot scenarios, carbon dioxide emissions are significantly higher during 2030–70 if BECCS is allowed; this is in line with model results based on radiative forcing targets in 2100 [7]. These higher emissions are compensated by global negative emissions in the subsequent 50–70 yr, reaching a minimum of nearly -16 $GtCO_2$ yr^{-1} for both targets. This implies that atmospheric CO_2 concentration peaks later and at a significantly higher level when BECCS is available. If BECCS is not available, temperatures are not able to decrease significantly after an overshoot. The observed minor temperature decrease in this case is caused primarily by abatement of methane (see supplementary material available at stacks.iop.org/ERL/8/034004/mmedia).

The average rate of decline of surface temperature in the BECCS overshoot scenarios towards a 2 °C target is 0.08 °C/decade between 2100 and 2150, and 0.1 °C/decade for the 1.5 °C target. In this estimate, the effect of abatement of other greenhouse gases, primarily methane, is included. The contribution of BECCS is about 0.06 °C/decade. This estimated rate of temperature decline is an order of magnitude larger than that of Friedlingstein *et al* [2]. However, they assume an arbitrary (and modest) negative emission level while ours is an estimate of the techno-economical potential through the use of BECCS. Per ton of sustained annual negative CO_2 emissions, our estimate of the temperature decline (0.4–0.5 mK yr^{-1} for each $GtCO_2$ of sustained annual negative emission) is comparable to that of Friedlingstein *et al* [2] and Zickfeld *et al* [25].

3.2. Abatement cost of meeting temperature targets

In figure 2, we present the abatement cost of meeting a wide range of temperature targets for the same scenarios of technology availability and target type as in section 3.1 (for comparison, we also add a 'no CCS' case). The abatement cost is defined as the difference in total discounted system costs between temperature target scenarios and an

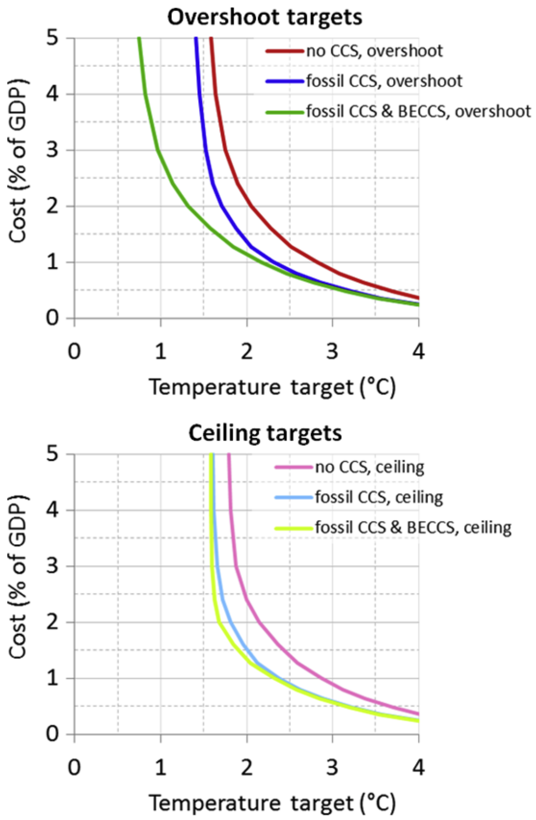

Figure 2. The value of BECCS with overshoot targets (top) and ceiling targets (bottom). Abatement costs in per cent of discounted future GDP as a function of temperature target for multiple model runs. Cases shown are: no CCS with overshoot targets (dark red), fossil CCS with overshoot targets (dark blue), fossil CCS and BECCS with overshoot targets (dark green), no CCS with ceiling targets (light red), fossil CCS with ceiling targets (light blue) and fossil CCS and BECCS with ceiling targets (light green).

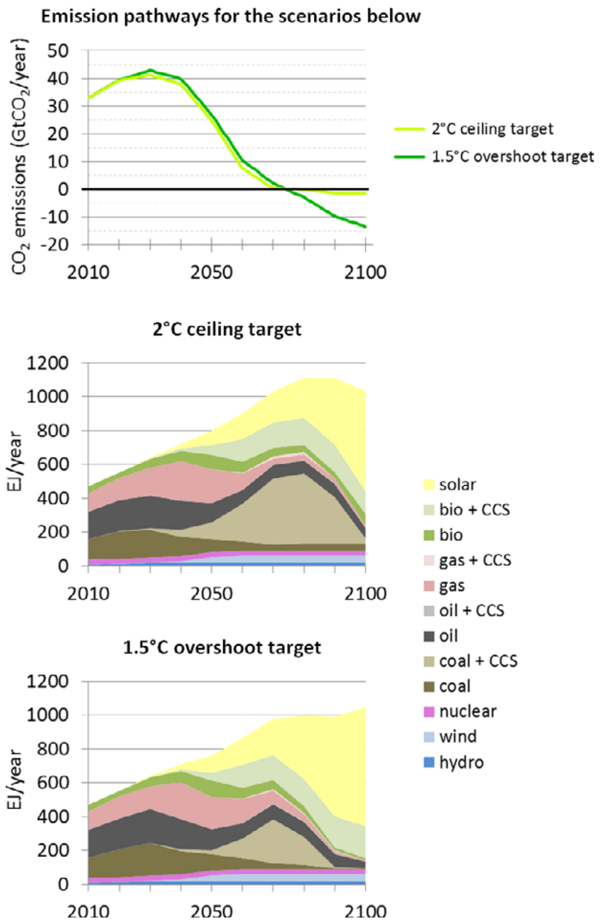

Figure 3. CO_2 emission pathways and primary energy supply to 2100. Emission pathways for the 2 °C ceiling target with BECCS (light green) and the 1.5 °C overshoot target with BECCS (dark green). Below, primary energy supply for the 2 °C ceiling target with BECCS (middle) and the 1.5 °C overshoot target with BECCS (bottom). Primary energy supply that has carbon capture applied is shown in lighter colour shades.

unconstrained business-as-usual scenario. Total system costs include energy system costs and emission reduction costs for methane and nitrous oxide.

When temperature target overshoot is allowed (figure 2, top), BECCS reduces the cost of meeting temperature targets below 2.5 °C (the benefit is higher the more ambitious the target is). It also brings significantly lower temperature targets within reach. However, for ceiling targets, allowing for BECCS only has a marginal impact on the cost (figure 2, bottom). This ultimately stems from the observation that for ceiling targets, there is little or no value in achieving global net negative emissions (because this would lead to a decrease in temperature, as noted above). However, BECCS is still used in the ceiling case so as to allow for larger fossil CO_2 emissions (cf figure 3). This, however, turns out to have no large impact on the mitigation costs in our model.

The main driver of lower costs in the cases in which BECCS is available and overshoot targets are accepted is that future negative emissions make it possible to defer near term emission reductions (see figure 1). Over the period 2010–50, cumulative emissions in the BECCS overshoot case towards the 2 °C target are 1690 $GtCO_2$, which can be compared to 1440 $GtCO_2$ without BECCS. Postponing the mitigation effort can be cost-effective when future costs are discounted, as pointed out by Wigley *et al* [26] in their analysis of the trade-offs involved when timing emission abatement efforts to meet a concentration target, although they did not include negative emissions from the energy system. In the long run, however, cumulative CO_2 emissions towards the same temperature target converge as expected [25]. In our model, this is slightly affected by the possibility to reduce methane and nitrous oxide at varying rates in the different scenarios (see supplementary material available at stacks.iop.org/ERL/8/034004/mmedia).

3.3. Comparing the 2 °C ceiling target with the 1.5 °C overshoot target

In figure 3, we compare the energy system development and the resulting emission pathways for the 2 °C ceiling target and the 1.5 °C overshoot target, both with BECCS. Strikingly, the emission pathways for the two temperature targets are almost identical until 2070; emissions in the 1.5 °C overshoot case are even slightly higher than in the 2 °C ceiling case.

This result may be contrasted to the conclusions by Meinshausen *et al* [27], who find that the probability of remaining below 2 °C (i.e. a ceiling target) strongly depends on cumulative emissions over the first half of the century, whereas our result requires BECCS with an overshoot target to 2150. However, Meinshausen *et al* primarily consider emission pathways without negative emissions.

As shown in figure 3, the development of the global energy system in both scenarios is similar over the first decades, but differences start to emerge around 2050. There is more coal with carbon capture and less solar energy for electricity and hydrogen production in the 2 °C ceiling case than in the 1.5 °C overshoot case. This is because in the overshoot case, limited carbon storage capacity is spared for BECCS, so as to enable net negative emissions beyond 2100 (see also figure 1). This is an intrinsic result of dynamic optimization models; scarce resources are used for the most beneficial purposes. However, in the real world, it may be difficult to ensure that scarce storage is spared for the future.

4. Sensitivity analysis

Our results are obtained with the assumption that 200 EJ yr^{-1} of biomass is available for bioenergy production [16, 17], that the carbon storage potential is 2000 $GtCO_2$ [18] and that the climate sensitivity is 3 °C per CO_2 doubling [19]. In the supplementary material (available at stacks.iop.org/ERL/8/034004/mmedia) we conduct sensitivity analyses in which we reproduce figures 1 and 2 for higher and lower values of these parameters. Additional sensitivity analyses are performed for the discount rate, the direct and indirect N_2O emissions associated with biomass production, the baseline energy demand scenario and the cost of carbon capture and storage. We find that one of our key results—that BECCS reduces costs for overshoot targets, but not much for ceiling targets—holds under significant changes to most of these parameters. In particular, the benefit of BECCS (assuming overshoot targets) increases significantly with the climate sensitivity.

For a biomass availability of 100 EJ yr^{-1} (i.e., the lower end of estimated bioenergy potential [16, 17]), the benefit of BECCS is significantly reduced. We find that halving the biomass supply reduces the global net negative emissions to a third of those in our base case with 200 EJ of biomass per year. When considering an increased biomass availability of 300 EJ yr^{-1}, the emissions reach a minimum of −25 $GtCO_2$ yr^{-1}. However, this does not have a great impact on costs because global net negative emissions become limited by carbon storage capacity. It is only when the limit on storage capacity is relaxed simultaneously that we see a greatly increased economic benefit of BECCS.

In an additional scenario variation, we examine the effects of requiring temperature overshoot targets to be met in 2100 instead of in 2150. We find that the maximum level of overshoot becomes significantly smaller due to the shorter time available for BECCS to induce temperature reductions. For some targets, e.g. the 2 °C overshoot case with BECCS, temperature overshoot virtually disappears. Consequently, cost reductions enabled by BECCS are also smaller.

Finally, we test a case in which we force the model to use at least 50 EJ yr^{-1} of coal without CCS. This could represent situations in which some countries do not join international climate agreements or if certain sectors cannot significantly reduce CO_2 emissions. We find that the benefit of having BECCS available now increases for ceiling targets. For overshoot targets, the benefit of BECCS is not strongly affected.

For more discussion and figures detailing these results, see the supplementary material (available at stacks.iop.org/ERL/8/034004/mmedia).

5. Discussion and conclusions

In this letter we report the following main results.

- If overshoot is allowed, BECCS may significantly reduce the cost of meeting a stringent temperature target, by delaying emission reduction efforts and using negative emissions to compensate for them later. Since future costs are discounted, postponing abatement leads to lower net present value costs. Additionally, by enabling net negative emissions from the global energy system, BECCS makes it possible to reach temperature targets that are otherwise not feasible.
- If overshoot is not allowed, the economic benefit of BECCS is considerably smaller. The reason for this can be understood as follows. BECCS can drive down the net present value of global abatement costs in two qualitatively different ways: either by enabling emission reduction efforts to be postponed or by lowering the overall marginal abatement cost curve at any given moment. For ceiling targets, the potential for delaying emission reductions is relatively small. Nevertheless, our model results indicate that BECCS can become competitive in scenarios with ceiling targets, and it may supply a significant fraction of global primary energy in the future.
- Emission pathways towards 2 and 1.5 °C targets are presented. Our model results indicate that emissions over the period 2020–50 are higher if BECCS is included in the technology portfolio, especially for temperature overshoot targets. This corroborates the results of Azar *et al* [4] and van Vuuren and Riahi [7] who find that near term emissions can be higher if BECCS is available when meeting concentration and radiative forcing targets.
- The rate of temperature decline is estimated to about 0.06 °C/decade for a large-scale implementation of BECCS (assuming near zero CO_2 emissions from the rest of the energy system, 200 EJ of biomass per year, and a climate sensitivity of 3 °C for a doubling of CO_2 concentration).
- For an overshoot target that must be met by the year 2100 instead of 2150 the value of BECCS becomes smaller. The reason for this is that for such a short period for overshoot, the target becomes more similar to a ceiling target.

- Under ceiling targets the economic value of BECCS is high when climate sensitivity is high or if it is very costly (or impossible) to drive down the fossil CO_2 emissions from the energy system to near zero levels.

A critical factor concerning the use of BECCS is the availability of biomass. Producing large amounts of bioenergy may have significant impacts on global food prices, biodiversity, water availability, etc [28]. A back-of-envelope estimate of global land requirements suggests that 200 EJ yr^{-1} of bioenergy may require around 500 Mha of land, or one third of global crop land (see calculation in the supplementary material available at stacks.iop.org/ERL/8/034004/mmedia). Also, climate change itself may impact the potential for bioenergy supply potential, although it is uncertain in which direction, at least for the global warming levels we consider in this letter [17]. If BECCS is severely limited by low biomass availability, other negative emission technologies such as direct air capture of CO_2 could conceivably play a role similar to that of BECCS in reducing atmospheric CO_2 concentrations [29].

The option of global negative emissions increases the possibility of meeting stringent overshoot temperature targets. This benefit of BECCS is also, somewhat paradoxically, its main political risk. The possibility of achieving negative emissions in the future may be perceived as a carte blanche for delaying emission abatement efforts. We caution against such an interpretation for a number of reasons. First, because of the long atmospheric lifetime of carbon dioxide, the less we emit in the near term, the more ambitious targets can be reached in the future. Second, the potential rate of temperature decline (about 0.6 °C per century) is too slow to act as an 'emergency brake' on short timescales, if climate damage becomes unacceptable. Third, the extent to which BECCS can be made available in the future is uncertain, due to uncertainties in land availability as well as technological constraints. Fourth, there are ecological and climate risks associated with the higher temperatures during the transient phase [30, 31]. This makes overshoot targets contentious, although they may be necessary in order to reach low temperature levels. Finally, to reach global negative emissions, other zero-carbon technologies need to be developed, nurtured to maturity by learning-by-doing in the marketplace and deployed at a very large scale [32]. This transition takes decades or more. Thus, near term emission reductions relative to business-as-usual scenarios take place and are cost-effective in all our model runs with temperature targets. In fact, by the end of the century, most of the abatement originates from technologies other than BECCS.

Author contributions

CA conceived the study and co-developed the GET energy system model. DJ co-developed the MiMiC climate model. NM developed the integrated energy–climate model based on GET and MiMiC, and performed the model runs. All authors planned the research, analysed the results and wrote the letter. Authors are listed alphabetically.

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Appendix

A.1. The GET–climate model

The GET–climate model is an integrated energy–climate model. It consists of a technology-oriented global energy system model hard linked with a reduced-complexity climate model that includes all major greenhouse gases and aerosols. Total annual system costs are calculated as a sum of energy system costs from the energy module and the abatement costs of non-energy-related greenhouse gas emissions. Optimal solutions can be found either by minimizing the net present value of total system costs given constraints on surface temperature, or by minimizing achievable temperature targets for a given limit on system costs. The model uses a discount rate of 5% yr^{-1}, and the time horizon extends to 2170. The long time horizon is necessary to analyse potentially scarce carbon storage capacity and estimate the long term temperature response of negative emission pathways.

GET–climate is written in GAMS and has roughly 100 000 variables and equations. Despite the entirely linear energy system module, the combined model is nonlinear due to nonlinear parameterizations of ocean and terrestrial carbon uptake and radiative forcing, temperature feedback on the carbon cycle, and a nonlinear component of the objective function arising from nonlinear MAC curves in the greenhouse gas emissions module. The model is solved using CONOPT 4, usually in less than 10 min on a modern laptop.

A.2. The energy system module

The energy system module is based on the single-region version of GET 7.0 [12, 13], with linear equations describing the global energy system from resource extraction via energy conversion to end use. The GET model has been used for studying various aspects of the energy system in scenarios with low CO_2 emissions [12, 13, 33]. In two papers, the GET model was used for studying BECCS for CO_2 concentration targets [3, 4]. In Azar *et al* [3], GET was compared with IMAGE/TIMER [5] and MESSAGE [34]. This study showed that all three models reach the same fundamental conclusion that introduction of BECCS reduces the cost to meet stringent CO_2 concentration targets. They also generate very similar CO_2 emission pathways.

There are five end use sectors, each with exogenous energy demand: electricity, residential and commercial heat, industrial feedstock, industrial process heat and transportation. Demand projections are based on the IIASA updated version of the SRES B2 baseline scenario [35].

The main energy carriers available to end use sectors or for conversion to other carriers are: coal, oil, natural gas, biomass, pellets, petroleum (generic carrier representing gasoline and diesel), synthetic fuels (generic carrier representing methanol, ethanol, dimethyl ether and Fischer–Tropsch diesel), hydrogen and electricity. Assumptions of technology cost and performance parameters correspond to a mature level of development for most technologies. Some developing technologies, e.g. solar PV, fuel cells and hydrogen production, have higher initial costs combined with exogenous cost reductions over time.

The direct contribution of intermittent electricity technologies such as solar PV and wind power is limited to a combined total of at most 30% of annual electricity generation. However, this limit can be circumvented using electricity storage technologies (e.g. pumped hydro, compressed air storage, batteries, or conversion to hydrogen and subsequent electricity generation in fuel cells), albeit at increased cost and with energy losses in the round-trip conversion.

We assume that carbon dioxide emissions can be captured from all large-scale fossil fuel and bioenergy conversion facilities, but emissions from small-scale fuel use in transport, local heating, etc, cannot be captured. Other important assumptions pertaining to the energy system include: onshore and offshore wind power limited to 40 EJ_{elec} yr^{-1}, hydropower limited to 20 EJ_{elec} yr^{-1}, nuclear power generation fixed at today's level (10 EJ_{elec} yr^{-1}), and baseload concentrating solar power (non-intermittent because of integrated heat storage) limited to 20% of total annual electricity generation.

A.3. Greenhouse gas emissions and MAC curves

Energy-related CO_2 emissions and abatement levels are determined endogenously by the technology choices made in the energy system module. CO_2 emissions from land use change follow projections in the IIASA B2 scenario [35].

Baseline emissions of energy-related methane are determined endogenously based on coal mining and extraction of oil and natural gas in the energy system module, while non-energy-related methane and nitrous oxide baselines are based on IIASA B2r projections. The model then chooses cost-effective emission reductions relative to these baselines based on marginal abatement cost (MAC) curves. In addition, nitrous oxide emissions resulting from nitrogen fertilizers used for biomass production and the intensification of agriculture following the higher demand for biomass are parameterized using Popp *et al* [36] (we assume 10 g N_2O–N per GJ of bioenergy).

Estimates of MAC curves for methane emissions were taken from a US EPA study [37]. Separate MAC curves were produced for emissions from natural gas use, coal and oil production, and non-energy sectors. Estimates of MAC curves for non-energy-related nitrous oxide emissions were taken from Reilly *et al* [38].

A.4. The climate module

The climate module in GET–climate originates from the MiMiC climate–economy model [11], but has been revised for this study. It can be characterized as a reduced-complexity climate model. Such models are capable of closely reproducing global average temperature responses of AOGCMs, given exogenous input of the climate sensitivity and other key parameters [39].

To model net ocean and terrestrial biosphere uptake of CO_2 from the atmosphere, we implement the nonlinear impulse response functions of Joos *et al* [15], which in turn are calibrated to the Princeton 3D carbon cycle model [40]. This approach captures the nonlinearities of the carbonate chemistry in the surface ocean (Revelle buffer factor) as well as those pertaining to CO_2 fertilization in the terrestrial biosphere. The resulting carbon fluxes are modified to include temperature feedback from increased respiration ($Q10 = 2$) and reduced solubility of CO_2 in seawater [41, 42].

Methane and nitrous oxide concentrations are calculated using one-box mass balance models (i.e. exponential decay), taking into account the feedback effect methane has on its own atmospheric lifetime. Nonlinear parameterizations of radiative forcing for methane and nitrous oxide are taken from the IPCC TAR [43]. The indirect effect of methane concentrations on stratospheric water vapour and tropospheric ozone concentrations is also included, using parameterizations from IPCC AR4 [19] and IPCC TAR [43], respectively. Radiative forcing contributions from halocarbons, changes in solar activity, volcanoes and land use change are taken from the RCP-3PD scenario [44].

An upwelling-diffusion energy balance model with polar overturning [11] is used to calculate the dynamic temperature response to the total radiative forcing.

The radiative forcing contribution from aerosols (including the indirect effect on cloud albedo) is taken from the RCP-3PD scenario [44]. It is scaled so that modelled temperatures match the historical temperature record for exogenously given values of the climate sensitivity [45]. Similarly, the fertilization parameter (β) is calibrated to reproduce historical concentrations.

In our analysis we do not make a probabilistic interpretation of how likely a certain emission pathway is to meet a certain temperature limit, as in e.g. Rogelj *et al* [46]. Instead, we use a single parameterization in the main part of the paper, along with results for different climate sensitivities in the supplementary material (available at stacks.iop.org/ERL/8/034004/mmedia).

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