Betting on negative emissions

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Bioenergy with carbon capture and storage could be used to remove CO_2 from the atmosphere, thereby achieving 'negative emissions'. But its credibility as a climate-change mitigation option is unproven and its widespread deployment in climate stabilization scenarios might become a dangerous distraction.

Future warming will depend strongly on the cumulative CO_2 emissions released through to the end of this century[1,2]. A finite quota of CO_2 emissions, no more than 1,200 $GtCO_2$, is needed from 2015 onwards in order to stabilize climate below a global average of 2°C above pre-industrial conditions by 2100 with a likelihood of 66%. This corresponds to about 30 years at current emissions levels[3]. However, during the past decade, emissions from fossil fuel combustion and cement production have increased substantially to 36.1 ± 1.8 Gt CO_2/year in 2013, projected to reach 37.0 (34.8-39.3) Gt CO_2/year in 2014[3,4,5] , 65% above their 1990 level. Staying within the 2°C limit in a cost-effective way will require strong mitigation action across all sectors, with greater effort needed the further mitigation is delayed.

Actions that could stabilize climate as desired include the deliberate removal of CO_2 from the atmosphere by human intervention – called here 'negative emissions'. Along with afforestation, the production of sustainable bioenergy with carbon capture and storage (BECCS) is explicitly being put forth as an important mitigation option by a majority of Integrated Assessment Models' (IAMs) scenarios aiming at keeping warming below 2°C in the IPCC's Fifth Assessment Report (AR5)[6]. Indeed, in these scenarios, IAMs often foresee absorption of CO_2 via BECCS up to (and in some cases exceeding) 1,000 $GtCO_2$ cumulative over the course of the century[7], effectively doubling the available carbon quota.

BECCS is the negative emissions technology most widely selected by IAMs to meet the requirements of temperature limits of 2°C and below. It is based on assumed carbon-neutral bioenergy (i.e. the same amount of CO_2 is sequestered at steady state by biomass feedstock growth as is released during energy generation), combined with capture of CO_2 produced by combustion and its subsequent storage in geological or ocean repositories. In other words, BECCS is a net transfer of CO_2 from the atmosphere, through the biosphere, into geological layers, providing in addition a non-fossil fuel source of energy. Other options include afforestation, direct air capture, and increases in soil carbon storage. Afforestation and increased soil carbon storage differ from BECCS in that these land use and management changes are associated with a saturation of CO_2-removal over time, and in that the sequestration is reversible with terrestrial carbon stocks inherently vulnerable to disturbance[8].

The need for negative emissions

The IPCC's Working Group 3 (WG3) considered in AR5 over 1,000 emission pathways to 2100 (Fig. 1a). Most scenarios (101 of 116) leading to concentration levels of 430–480 ppm CO_2-equivalent (CO_2eq), consistent with limiting warming below 2°C, require global net negative emissions in the second half of this century, as do many scenarios (235 of 653) that reach between 480 and 720 ppm CO_2eq in 2100 (Fig. 1b, scenarios below zero). About half of the scenarios feature BECCS exceeding 5% of primary energy supply. Many of those (252 of 581) have net positive emissions in 2100 (Fig. 1b). Thus, BECCS does not ensure net negative emissions (i.e., its use need not completely offset all positive emissions). BECCS is an important mitigation technology especially as the stabilization level is lowered, and if near-term mitigation is delayed. By eventually requiring deeper emissions reductions, BECCS can help reconciling higher interim CO_2-eq concentrations with low long-term stabilization targets, particularly if overshooting of concentrations is allowed. Taking into account the full scenario range, global net negative emissions would need to set in around 2070 for the most challenging scenarios and progressively later for higher-temperature stabilization levels.

IAMs[6] and Earth system models (ESMs[2]) provide different but complementary approaches for quantifying negative emissions requirements. ESMs simulate the compatible net CO_2 emissions based on mass balance between atmospheric changes in CO_2 and land and ocean carbon sinks. A model intercomparison of 10 ESMs found that two-thirds of the models required net negative emissions in the second half of the century[9], but the ESMs make no assumption on how this is technically achieved. For IAMs, negative emissions are an outcome of an economic optimization driven by a choice between reducing emissions and BECCS (gross negative emissions). Both approaches model the link between CO_2 emissions, atmospheric concentrations and subsequent climate change. Importantly, some of the non-CO_2 emissions (e.g., CH_4 and N_2O from agriculture) will be very difficult to mitigate completely, as will some CO_2 emissions from industry and transportation below which mitigation will be economically and technically very difficult[10]. Therefore, to reach long-term climate stabilization under 2°C, there is likely to be a requirement for gross negative CO_2 emissions (i.e. at the project level) and likely also for net negative emissions (i.e. the global net balance).

The challenges ahead

The deployment of large-scale bioenergy faces biophysical, technical, and social challenges[11], and CCS is yet to be implemented widely. Four major uncertainties need to be resolved: (1) the physical constraints on BECCS, including sustainability of large-scale deployment relative to other land and biomass needs, such as food security and biodiversity conservation, and the presence of safe, long-term storage capacity for carbon; (2) the response of natural land and ocean carbon sinks to negative emissions; (3) the costs and financing of an untested technology; and (4) socio-institutional barriers such as public acceptance of new technologies and the related deployment policies. In the IAM scenarios in AR5[5] that are consistent with warming of less than 2°C, the requirement for BECCS ranges between 2–10 $GtCO_2$ annually in 2050, corresponding to 5–25% of 2010 CO_2 emissions and 4–22% of baseline 2050 CO_2 emissions. Huge upscaling efforts will be needed to reach this level. By comparison, the current global mean removal of CO_2 by the ocean and terrestrial carbon sinks is 9.2 ± 1.8 $GtCO_2$ and 10.3 ± 2.9 $GtCO_2$, respectively[5,12]. Concerning the capture and storage portion of the BECCS chain, the International Energy Agency's CCS roadmap clearly illustrates that huge efforts would be needed to achieve the scale of CCS (both fossil fuel emissions CCS and BECCS) foreseen in current stabilization scenarios, as publicly supported demonstration programs are still struggling to deliver actual large-scale projects[13].

It is difficult to estimate the actual costs of BECCS, as it is partially in competition for resources (land, biomass, and storage capacity and cost of CCS) used in other mitigation options and for objectives beyond climate stabilization. However, while negative emissions might appear more expensive than established mitigation options including fossil fuel emissions CCS, the mitigation pathways to 2100 excluding negative emission technologies are all substantially more expensive than the pathways including those technologies[6,14,15].

Policymakers will need a much more complete picture of negative emissions than what is currently at hand. Issues of governance and behavioral transformations need to be better understood. The reliance of current scenarios on negative emissions, despite very limited knowledge, calls for a major new transdisciplinary research agenda to (1) examine consistent narratives for the potential of implementing and managing negative emissions, (2) estimate uncertainties and feedbacks within the socio-institutional, techno-economic and Earth system dimensions, and (3) offer guidance on how to act under the remaining uncertainties. Similarly, technological and institutional roadmaps, and rapid implementation of pilot projects are needed to test feasibility and understand the barriers to technological development.

In addition to characterizing the potential for negative emissions more reliably and geographically explicitly[16,17], the tradeoffs related with the use of negative emissions need to be further assessed.

Some recent collaborative modeling efforts have provided important insights on such potential tradeoffs (e.g. ref. 18). In the case of BECCS, tradeoffs are associated with (1) competition for land and possible conflicts with the objectives for food security, biodiversity conservation and the demand for water resources in different sectors (e.g. ref. 19), and (2) the existence of sufficient potential for secure and accessible storage of captured CO_2 in competition with fossil fuel CCS, uncertainties about the possibility to upscale negative emissions technologies quickly, and public acceptance.

A consistent narrative of negative emissions management therefore has four components (Fig. 2) relating to the key uncertainties. The first component refers to technological aspects: with BECCS being the negative emissions technology most widely applied by IAMs, the implied heavy demands for sustainable biomass availability are suggested to be at least 100 and up to more than 300 EJ per year of equivalent primary energy by 2050[20]. Also, CO_2 storage potential in geological layers (aquifers, depleted fossil carbon reservoirs) and other resources such as water and fertilizer in the face of increasing food demand will need to be addressed. Bioenergy and water recycling with solar-powered distillation, algae grown offshore and fertilized with previously captured CO_2, and other innovations are among possible technologies enabling negative emissions to be achieved with lower pressure on land biomass production. However, such technologies require significant new research and development.

The second component in Fig. 2 describes carbon cycle uncertainties and dynamics in the Earth system. If negative emissions options such as BECCS are used only after significant climate change, then the response of the global carbon cycle can make the necessary amount of negative emissions even larger than for a scenario where the future CO_2 trajectory is contained below 430–480 ppm. This could occur through decreasing terrestrial and ocean sink efficiencies due to climate change, and net releases of CO_2 by the land and ocean reservoirs due to CO_2 removal over several decades[6,12,21,22,6].

The third component acknowledges that negative emissions will be part of a wider mitigation effort and their deployment will depend on the cost, risks and timing profile of other options. The spectrum ranges from more established mitigation technologies – for which it might then be too late – to solar radiation management geo-engineering options, which are quicker and cheaper to ramp up, but which embody a much larger scale of mostly unknown risks[23] and are not able to deal with other consequences of increased CO_2 concentrations such as the ocean acidification. This emphasizes that we are not in a position to discard the negative emissions option easily despite the above challenges. The fact that negative emissions solutions like BECCS will require time to achieve sufficient scale confirms that the future option space depends strongly on today's decisions.

The final component is concerned with institutional and policy challenges. CO_2 removal will be expensive and contentious, whereas emissions will remain cheap in the absence of strong climate policies. Therefore, any CO_2 removal strategy requires an extraordinary global regulatory framework taking into account national economic conditions. In the absence of a global climate agreement requiring stringent mitigation efforts and given the asymmetric distribution of mitigation potentials, negative emissions could help to offset emissions from countries that might not participate in reduction efforts or have less capacity to do so. This could open new perspectives on global climate management. Rigorous monitoring, reporting and verification will be needed to facilitate these options.

The development of consistent negative emission narratives is not a call for large-scale BECCS deployment, but a call to carefully and quickly assess all dimensions of its use for climate stabilization. Determining how safe it is to bet on negative emissions in the second half of this century to avoid dangerous climate change should be among our top priorities.

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Contributions

All authors contributed to the planning of the paper. S.F. led the work together with J.G.C. and prepared Figure 2 including description of the framework benefitting from discussions with all authors. G.P.P., R.M.A. and M.T. prepared Figure 1 and/or provided the associated analysis. All authors contributed to writing the paper, providing comments to the framework and input in terms of numbers and references backing the analysis.

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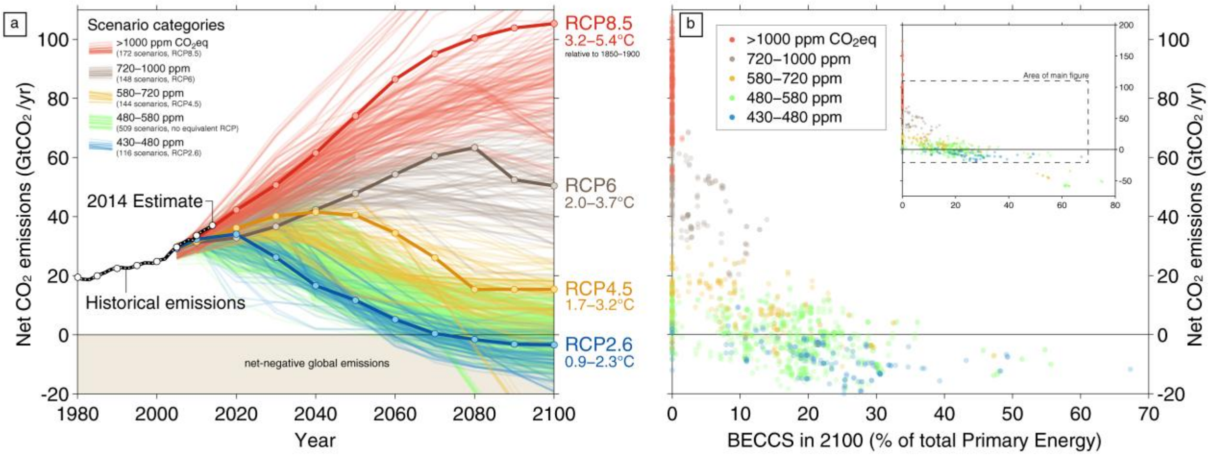

Figure 1: CO_2 emission pathways until 2100 and the extent of net negative emissions and BECCS in 2100. Historical emissions from fossil-fuel combustion and industry (black) are primarily from the Carbon Dioxide Information Analysis Center[4,6]. They are compared with the IPCC- AR5-WG3 emissions scenarios (pale colours) and to the four Representative Concentration Pathways (RCPs) used to project climate change in the IPCC-AR5-WG1 (dark colours) (**a**). The emission scenarios have been grouped into climate categories[5] measured in ppm CO_2-equivalent in 2100 (legend) from all components and linked to the most relevant RCP. The temperature increase (right of Fig. 1a) refers to the warming in the late 21st century (2081 –2100 average) relative to the 1850–1900 average[24]. Only scenarios assigned to climate categories are shown (1,089 of 1,184). Most scenarios that keep climate warming below 2°C use BECCS and many require net negative emissions (i.e. BECCS exceeding fossil fuel emissions) in 2100 (**b**). Data source: AR5 database and GCP/CDIAC.

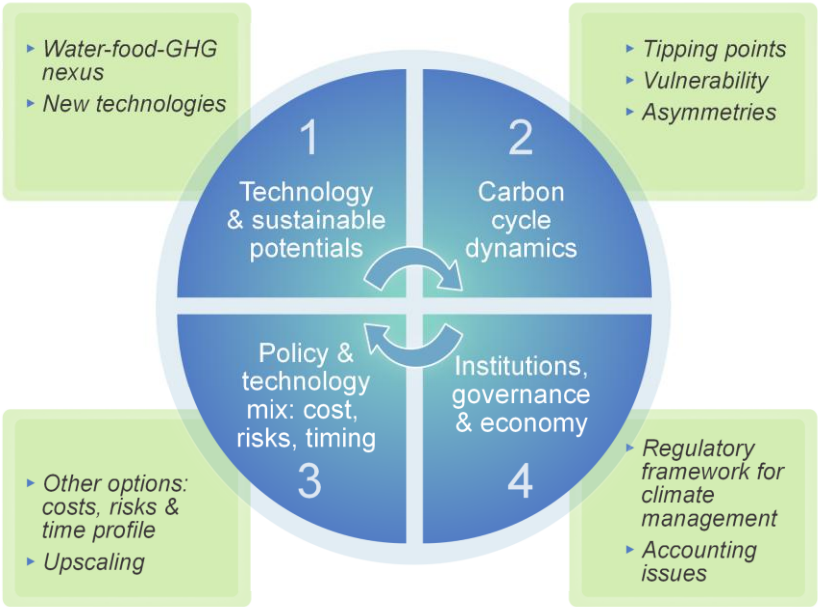

Figure 2: Four components of consistent negative emission narratives.