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When are negative emissions negative emissions?†

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Negative emission technologies (NETs) have seen a recent surge of interest in both academic and popular media and have been hailed as both a saviour and false idol of global warming mitigation. Proponents hope NETs can prevent or reverse catastrophic climate change by permanently removing greenhouse gases from the atmosphere. But there is currently limited agreement on what "negative emissions" are. This paper highlights inconsistencies in negative emission accounting in recent NET literature, focusing on the influence of system boundary selection. A quantified step-by-step example provides a clear picture of the impact of system boundary choices on the estimated emissions of a NET system. Finally, this paper proposes a checklist of minimum qualifications that a NET system and its emission accounting should be able to satisfy to determine if it could result in negative emissions.

Broader context

If global greenhouse gas emissions are not rapidly and immediately abated, the possibility of limiting global warming to "well under" 2C may depend on the reduction of atmospheric greenhouse gas concentrations *via* the use of technologies that permanently remove of greenhouse gases from the atmosphere. These "negative emission" technologies have received rapidly increasing research, media, and political attention in the past few years. However, as this paper shows, the term "negative emissions" is used inconsistently in this conversation. If unresolved, those inconsistencies, while subtle, could result in unintended consequences, such as a "negative emission" technology that increases atmospheric greenhouse gas concentrations. This paper illustrates the potential impact of the different uses of the term "negative emissions", and proposes a checklist of "minimum" criteria to determine whether a technology could result in negative emissions.

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Introduction

Without immediate and comprehensive mitigation of anthropogenic greenhouse gas emissions, the prevention of

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catastrophic impacts from global warming may come to depend on the deliberate removal of massive quantities of greenhouse gases from the atmosphere. This concept of "negative emissions" gained increasing attention after its initial inclusion in the 4th IPCC assessment report in 2009 and then in the vast majority of integrated assessment models in the 5th report in 2014. The ambitious "well below 2 °C" target of the 2015 COP21 Paris climate agreement may already be unachievable without negative emissions.[1–4] Indeed, all modelling scenarios in the 2018 IPCC special report on limiting global warming to 1.5 °C rely on the removal of carbon dioxide from the atmosphere.[5] In a 2017 review,[6] all included 1.5 °C scenarios depended on permanently removing an annual 3 to 30 gigatonnes of CO_2 from the atmosphere—up to 80% of current global emissions—before the end of this century.

Some of the technologies designed to achieve negative emissions are based the encouragement of natural processes that uptake and store atmospheric carbon, such as afforestation (AF)[7,8] and soil carbon sequestration (SCS).[7,9] Other negative emission technologies (NETs) rely on human engineering, such as capture and storage of CO_2 from the combustion of biomass for energy (bioenergy with carbon capture and storage, BECCS),[7,10] or the chemical removal of CO_2 directly from air[7,11] and subsequent storage (direct air capture with storage, DAC-S).

Achieving massive-scale negative emissions requires an unprecedented fast-tracking of technological development and an unprecedented level of cooperation between political, industrial, and consumer stakeholders.[12,13] For while negative emission strategies are based on proven technological components, such as biomass cultivation, energy use, logistics, and gas storage, each of these components have financial costs, greenhouse gas emissions, and other environmental and social impacts. NETs rely on connecting these components into complex systems, further increasing risk and uncertainty.[13] An overarching necessity is to ensure that the total effect of all components within the complex system of a NET is the permanent removal of atmospheric greenhouse gases, and thereby a net decrease in the greenhouse gas concentration in the atmosphere.

If massive-scale negative emissions are to be achieved, a clear, comprehensive, and consistent definition of when negative emissions occur is a necessary prerequisite for the effective implementation of incentives, regulations, and accounting. However, this is not currently the case. The 2018 IPCC special report[5] defines "negative emissions" explicitly only as the "removal of [atmospheric] greenhouse gases", though long-term storage is a feature of all greenhouse gas removal technologies discussed. A recent report by the European chemical industry[14] argues that CO_2 use—including in fuels and other short-lived chemicals—can be counted as "negative emissions", regardless of the origin of the CO_2 or fate of the product. A proposed EU policy[15] for the emission accounting of manure-based biogas allows methane diverted from traditional waste treatment to be labeled "negative emissions". That is, even if the biogas is later combusted and the resulting CO_2 is released to the atmosphere, since the emissions were prevented from happening during the waste treatment process itself, they are considered "negative". The above examples each come from a document relevant to policy and industry decision makers and each example uses the term "negative emissions" to refer to a different concept, including the removal (and implicit storage of) atmospheric greenhouse gases, the utilization of greenhouse gases in products, and the prevention or delay of greenhouse gas emissions.

This paper shows that this lack of clear consensus is due to the use of different system boundaries when considering what to count as "negative emissions". This paper reviews the variations in the explicit and implicit usage of the term "negative emissions" and related terminology in studies from 2014 to 2018. To clarify the impact of system boundary selection on the perceived emission balance of a NET, a simplified example is used to illustrate the differences in emission accounting for a hypothetical NET when different system boundaries are used. Finally, we propose an operational set of minimum criteria for evaluating whether a system could result in negative emissions.

Literature review methods

Recent peer-reviewed academic literature on negative emissions was collected *via* a Web of Science topic search on the terms "negative emission", "negative CO_2", "negative greenhouse gas", "CO_2 negative", and "carbon negative" from 2014 through June 2018. This search resulted in 433 citations, of which 147 were neglected; 31 for lacking peer-review, 14 for being inaccessible, and 102 for being on unrelated topics, such as carbon electrode design or short-term natural carbon fluxes.

In the remaining 286 studies, the use of the term "negative emissions" was evaluated on whether the usage encompassed:

- the physical removal of greenhouse gases from the atmosphere,
- the storage of atmospheric greenhouse gases and whether the storage was specified to be permanent,
- whether the emissions associated with both the upstream and downstream supply chains of the negative emission technology (life cycle emissions) were considered, and
- whether other concepts were encompassed by the term, including the storage of non-atmospheric greenhouse gases, the re-emission of captured gases to the atmosphere, or the inclusion of avoided emissions.

Usage was evaluated first by any explicit definition provided and also by any clear implicit criteria. For example, if negative emissions were only referred to as resulting from technologies that store atmospheric greenhouse gases in geologic formations (*e.g.* BECCS, DAC-S), removal and permanent storage were assumed to be implicit criteria of that study's definition of negative emissions. Usage features for each paper were collected in a tally spreadsheet, which is provided in the ESI† to this paper.

Overview of the usage of negative emissions terminology in recent literature

Half of the 286 papers reviewed provided an explicit definition of the term "negative emissions" (or "negative CO_2",

Table 1 Summary of results from the literature review on the usage of the term "negative emissions"

Features of usage	Number of reviewed papers with feature	(% of total)
States that the goal of negative emissions[a] is to reduce global warming or the atmospheric concentration of greenhouse gases	199	(70%)
Provides an explicit definition of negative emissions[a] that includes:		
The removal of greenhouse gas from the atmosphere	143	(50%)
The storage of the removed gases	82	(29%)
And specifying permanent storage	58	(20%)
An accounting of greenhouse gas emissions to the atmosphere that result from the use of negative emission technology	5	(2%)
Uses the term negative emissions[a] to include:		
The capture and/or storage of non-atmospheric greenhouse gases (*e.g.* from the combustion of fossil fuels)	17	(6%)
Greenhouse gases that are explicitly re-emitted to the atmosphere	23	(9%)
Greenhouse gases that would be prevented from being emitted to the atmosphere when compared to a reference scenario (avoided emissions)[b]	16	(6%)

For the full article list with usage features marked per article, please refer to the ESI. [a] Including the alternate terms: "negative CO_2", "negative greenhouse gas", "CO_2 negative", and "carbon negative". [b] Including 11 of the 27 (41%) life cycle assessments papers that are in the literature review.

"negative greenhouse gas", "CO_2 negative", and/or "carbon negative"). Table 1 shows that these explicit definitions were not always consistent. 143 (50%) of studies specified the removal of atmospheric greenhouse gas, but only 82 (29%) specified any sort of storage of the greenhouse gas. 23 papers (9%) considered negative emissions to be generated from processes that explicitly re-release the gas into the atmosphere in the short term, such as *via* conversion to fuel. A further 33 studies (12%) also explicitly considered negative emissions to come from processes that do not remove greenhouse gases from the atmosphere, such as carbon capture and storage (CCS) of fossil fuel emissions or emission reduction technologies. The full list of papers reviewed, tagged with usage features is available in the ESI† as a sortable spreadsheet.

If implicit usage is also considered, a further 34% (84% of total) of the studies likely consider negative emissions to involve the removal of atmospheric greenhouse gases, and a further 44% (65% of total) likely include the permanent storage of greenhouse gases. However, there is high variance in how clearly these terms are used and, without an explicit definition, it is ambiguous whether these are intended as necessary or optional criteria of negative emissions.

The most consistent usage feature was that 70% (199) of papers state that purpose of negative emissions is to reduce global warming or, more specifically, to reduce atmospheric concentrations of greenhouse gases. Therefore, logically, the quantity of greenhouse gas in the atmosphere must be lower after NET use than before it. This requires not only that greenhouse gases are removed from and stored outside the atmosphere, but also ensuring that any greenhouse gases emissions that result from this process are not greater than the amount of greenhouse gases removed. Of the papers reviewed, only five[16–20] (2%) explicitly acknowledge that all emissions associated with the use of NETs, including those upstream and downstream of the removal process, are needed determine whether a technology actually results in an overall decrease of atmospheric greenhouse gases. The system boundary selection example below illustrates the potential importance of these upstream and downstream emissions on the overall GHG balance of an NET system.

Avoided emissions and enhanced oil recovery

In 11 of the 27 (41%) life cycle assessment (LCA) studies included in the literature review, avoided emissions are labelled as negative emissions. However, while calculations for avoided emissions can result in negative numbers, they are distinct from the physical removal of greenhouse gases from the atmosphere, and a brief clarification of the distinction is warranted.

Avoided emissions are an estimation of emissions that are assumed to be potentially prevented by switching from a system of reference to the system studied in the LCA, based on specific assumptions of future system behaviour. They are a feature of a method to account for the emission-reduction potential of co-products that are produced in a system analysed by an LCA, known as "displacement" or "system expansion".[21] As an example, in Beaudry *et al.* (2018),[22] a palm oil biorefinery is assumed to produce—among other products—ethanol and electricity. The study assumes that this ethanol and electricity directly replace gasoline and coal-based electricity, and therefore, if the biorefinery is in operation, these fossil fuels will not be used. It then follows that the greenhouse gas emissions attributable to the production and use of the gasoline and electricity from coal will also not be produced; these emissions are said to be "avoided". The study then subtracts these "avoided emissions" from the emissions of the biorefinery. As the resulting difference is a negative number, the biorefinery is said to result in negative emissions.

In short, the negative greenhouse gas emission numbers in these LCAs are not physical emissions. They are the potential reduction of emissions in a hypothetical scenario where a specific technology replaces another specific technology, and will change depending on the reference scenario selected. Avoided emissions refer to the potential of adding a smaller, but still positive, amount of greenhouse gas to the atmosphere. This is in contrast to how the term negative emissions is used in the context of pathways to reach 1.5 °C mitigation targets, which refers to greenhouse gases that are physically removed from the atmosphere. Some LCAs[23,24] further conflate these terms by lumping together physical removal and assumed avoidance of greenhouse gases while other LCAs simply use the term negative emissions to refer to avoided emissions without any removal of atmospheric greenhouse gases at all.[25–27] The full list of LCAs in the review that conflate the term negative emissions with avoided emissions is available in the ESI.†

The term negative emissions is also sometimes used to refer to CCS applied to fossil fuels, particularly in papers within the field of enhanced oil recovery (EOR).[28–30] In EOR, CO_2 is used to extract otherwise unrecoverable oil from otherwise depleted oil fields. Some EOR studies label the balance of CO_2 (CO_2 trapped in the geological formation minus CO_2 released when oil is combusted) negative emissions, regardless of the origin of the CO_2, which, in most cases, is either extracted from natural formations or from the flue gas from the combustion of fossil fuels. Storage of fossil CO_2 does not involve any removal of CO_2 from the atmosphere, and therefore cannot result in any decrease in atmospheric greenhouse gases. Furthermore, even when removed atmospheric CO_2 is used and permanently stored in the process of EOR, the CO_2 emissions from the use of the recovered oil can be greater than the atmospheric CO_2 removed and stored, thus leading to a net increase in atmospheric CO_2. In at least one study,[31] the emissions from the combustion of the recovered oil—which otherwise would have remained in the ground—are excluded from the CO_2 balance, and the whole quantity of stored CO_2 is considered negative emissions.

How system boundaries selection matters for negative emissions

To illustrate the impact of system boundary selection on the estimated greenhouse gas emissions of a NET system, the following example looks at the way the emission estimate changes for a steel mill implementing BECCS based on different boundary selection. The system itself, an overview of which is shown in Fig. 1, is the same in every case; it is only our perspective of it that changes, as indicated by the different system boundary lines.

Fig. 1 provides an overview of system boundaries common in technology assessment. A ''gate-to-gate'' system considers only the processes and emissions that occur within the steel plant itself. Studies on bioenergy often use a modified gate-to-gate boundary, that additionally includes an amount CO_2 removed by biomass from the atmosphere that is assumed to be exactly equal to the CO_2 emitted from its combustion, and thus the bioenergy is considered to be ''carbon neutral''. A ''cradle-to-gate'' system includes upstream emissions and resource use, such as land use, cultivation, harvest, transportation of biomass, and the production of other inputs, but nothing downstream of the factory gate, such as product use or waste treatment. The inclusion of both upstream and downstream emissions is a ''cradle-to-grave'' system. Since bioenergy systems often involve changes in land use that many not be temporally or geographically immediate to the cultivation or harvest of biomass, a further expansion of the boundaries to encompass indirect land use change (ILUC) is also used. The below example illustrates that without a ''cradle-to-grave'' perspective, it is not possible to determine whether the use of a NET will result in an overall decrease in atmospheric greenhouse gas concentration and thereby achieve negative emissions.

This example, illustrated in Fig. 2, considers a steel mill that first implements capture and geologic storage of its CO_2

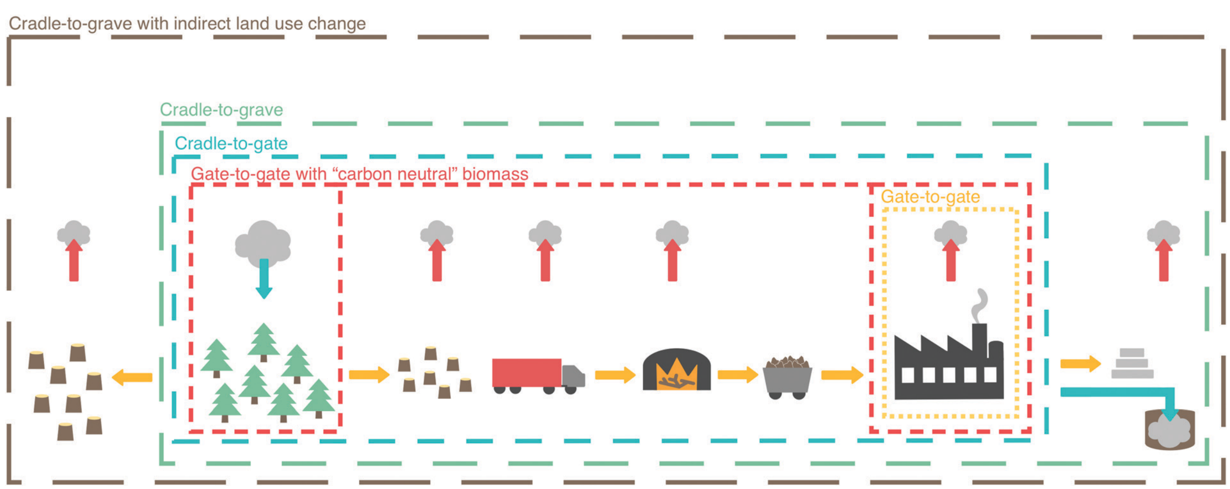

Fig. 1 Different technology assessments boundaries applied to a BECCS steel plant. A "gate-to-gate" system only considers the emission within the steel plant itself. Bioenergy assessment also often includes the uptake of atmospheric carbon by the biomass without also including the biomass processing and transport in a "cradle-to-gate" or "cradle-to-grave" system, the latter also including the impacts of product use and waste processing after they leave the steel plant. In bioenergy systems, unintended (or "indirect") land use change may also need to be included to achieve a full picture of the system impacts.

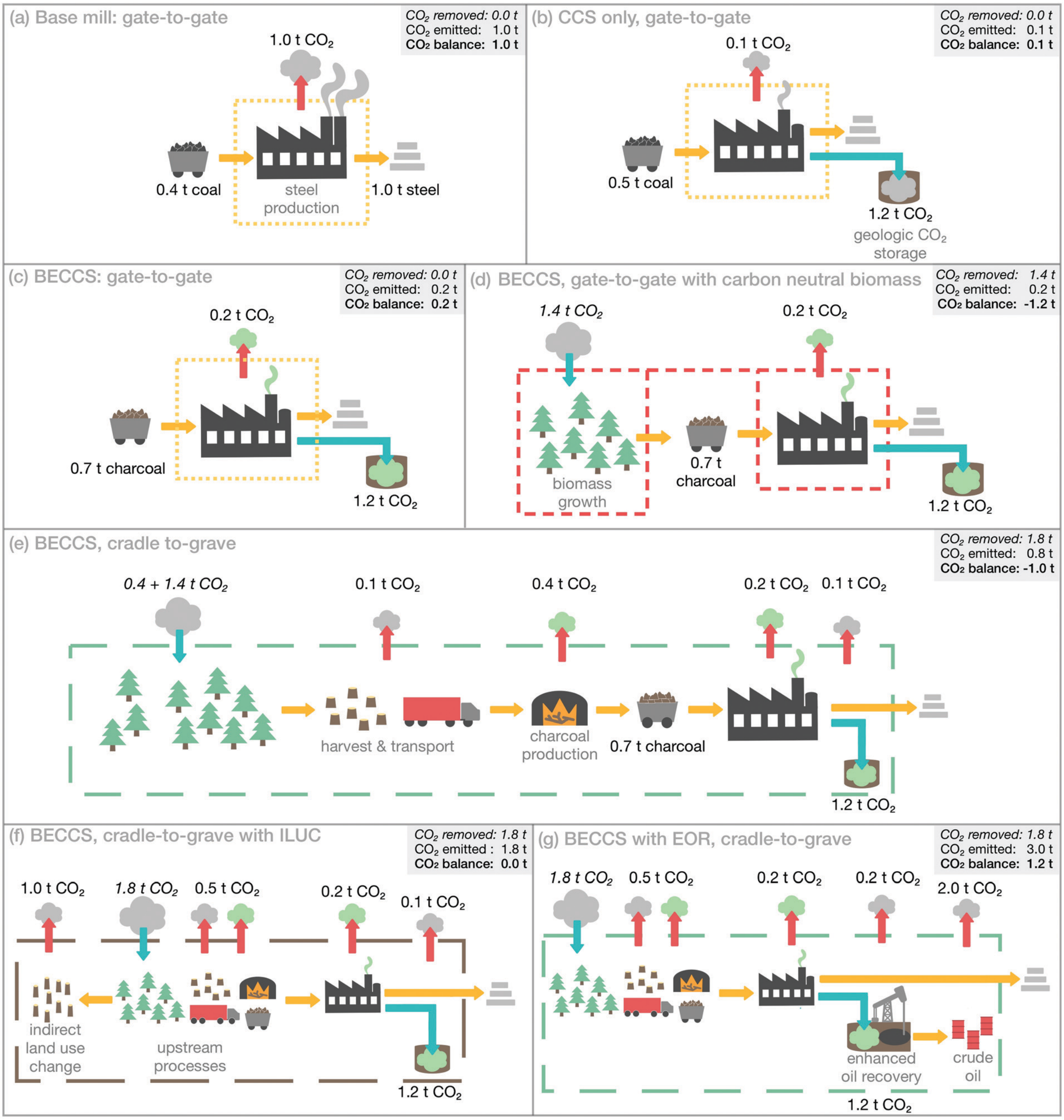

Fig. 2 Perceived CO_2 emissions of a simplified steel production system when viewed from different system boundaries. The dashed line in each subfigure represents the system boundaries used to estimate the overall CO_2 emissions in the upper right corner of each figure. The system design and numbers used are heavily simplified for illustrative purposes. (a–c) show the gate-to-gate CO_2 emissions of a steel mill, considering only the CO_2 produced at the mill itself for normal production (a), with the use of carbon capture and storage (b), and the use of bioenergy with carbon capture and storage (c). (d) expands the system boundaries to include the photosynthetic absorption of the exact amount of CO_2 released by the combustion; the assumption that the charcoal is "carbon neutral". (e) shows a simplified "cradle-to-grave" system, including in its boundaries the CO_2 absorbed by the wood that is lost in the charcoal production process, the CO_2 emissions from biomass harvest and transport, the CO_2 emissions of charcoal production, and the CO_2 emissions CO_2 storage. (f) is a variant where the production of biomass has significant emissions from indirect land use change (ILUC). (g) is a variant where the geologic storage of CO_2 leads to the production and combustion of fossil fuels whose CO_2 emissions outweigh the CO_2 stored.

emissions (CCS), and later also switches its energy source from coal to wood charcoal (BECCS). For clarity, the example assumes a heavily simplified steel mill that produces one type of steel and derives all its energy and emissions from the combustion of one type of fuel. Since the focus of this example is CO_2 emissions, the mining of iron ore and use of the steel product are excluded. The quantities used in this example are heavily simplified and intended only for illustrative purposes. This example illustrates only a single possible configuration, and many other choices of technology, production methods, and transport are available. Furthermore, a full inventory of greenhouse gas emissions from the supply chain of steel production, charcoal, and CCS would be much more extensive, but is neglected for clarity.

Fig. 2(a) and (b) show the steel mill as viewed from gate-to-gate perspective. In (a), the steel mill produces one metric tonne (t) of steel using the energy from the combustion of 0.4 t of coal, which emits 1.0 t of CO_2 to the atmosphere. In (b), the steel mill has installed CCS technology that captures 90% of the CO_2 produced at the mill. However, the energy required for carbon capture increases the mill's coal consumption to 0.5 t, thus increasing the total amount of CO_2 produced by combustion to 1.3 t. The CCS technology captures 1.2 t of this CO_2, which is then sent to for storage in a geologic formation. The uncaptured 0.1 t of CO_2 is still emitted to the atmosphere. Therefore, from a gate-to-gate perspective, the addition of CCS reduces the steel mill's atmospheric CO_2 emissions from 1.0 t to 0.1 t.

Fig. 2(c–g) assume that the steel mill with CCS that has also switched its energy source from coal, a fossil fuel, to charcoal, a biogenic fuel. Fossil fuels contain carbon that has been removed from the carbon cycle for geologic time periods, and CO_2 emissions from fossil fuels increase the level of CO_2 into the atmosphere. In contrast, CO_2 emitted *via* the combustion of biogenic fuels contains carbon that was recently removed from the atmosphere *via* photosynthesis of growing biomass. Theoretically, if the biomass harvested for combustion is replaced by an equivalent amount of new planting, the replacement biomass will eventually absorb an equivalent amount of CO_2 from the atmosphere, resulting in a net zero addition of CO_2 to the atmosphere. In a system emitting fossil CO_2, the maximum impact of CCS is that emissions can be reduced to near-zero. If a system emits biogenic CO_2, it is possible to generate a flow of CO_2 from the atmosphere to some form of permanent storage, thus potentially generating negative emissions.

In this example, the charcoal has a lower energy content than coal, therefore 0.7 t is necessary to provide the same amount of power as the 0.5 t of coal in (b). In Fig. 2(c–g), the combustion of charcoal generates 1.4 t of CO_2, of which 1.2 t are captured and stored in a geological formation, and 0.2 t are uncaptured and emitted to the atmosphere.

Fig. 2(c) looks at this BECCS steel mill from a gate-to-gate perspective, which only considers the emissions at the mill itself. The biogenic origin of the charcoal is outside the system boundaries. From this perspective, the estimated emissions from the BECCS mill are the 0.2 t of uncaptured CO_2, still 0.8 t less than the original mill, but 0.1 t more than the mill using coal and CCS.

In Fig. 2(d), the system is extended to include the assumption that the charcoal used is ''carbon neutral.'' That is, since the combustion of the charcoal resulted in generation of 1.4 t of CO_2 emissions, the charcoal is assumed to have been produced from biomass that removed exactly 1.4 t of CO_2 from the atmosphere. Therefore, from the perspective of a ''gate-to-gate with carbon neutral biomass'' system, a net 1.2 t of CO_2 is estimated to be permanently removed from the atmosphere *via* BECCS.

Fig. 2(e) takes a cradle-to-grave view of the BECCS steel mill, including the upstream emissions of biomass harvesting, charcoal production, and transport, and the downstream emissions of CO_2 transport and storage. In (d), it was assumed that biomass absorption of CO_2 was equal to the CO_2 it produces when it is combusted, neglecting any losses between photosynthesis and combustion. The emission accounting for the cradle-to-grave system includes these losses, which encompass an additional 0.4 t of CO_2 absorbed from the atmosphere that is re-emitted during charcoal production. Furthermore, biomass harvest and transport here use energy from fossil fuels, emitting 0.1 t of CO_2. For CO_2 transport and storage, 0.1 t of fossil CO_2 is emitted while providing the energy needed to transport, inject, store, and monitor the CO_2. Leakage of CO_2 from storage is assumed to be negligible. In total, the cradle-to-grave boundaries encompass 1.8 t of CO_2 removed from the atmosphere *via* photosynthesis, of which 1.2 t is captured after combustion for energy and stored in a geologic formation, and 0.6 t is emitted to the atmosphere during charcoal production and from CO_2 capture losses. Additionally, 0.2 t of fossil CO_2 is emitted to the atmosphere during the upstream processing of biomass and the downstream processing of CO_2. Overall, the cradle-to-grave perspective accounts for an additional 0.4 t of CO_2 removal and 0.6 t of CO_2 emissions than is estimated by using the gate-to-gate system boundaries of (d). Here, a net 1.0 t CO_2 is estimated to be permanently removed from the atmosphere *via* BECCS. Nothing in the system has changed, but more of the supply chain is now included in the boundaries used to estimate the emission balance.

Fig. 2(f) is an example of the possible impact of indirect land use change (ILUC). ILUC is when a change in land use triggers unintentional changes in land use elsewhere.[32,33] In this specific example, the charcoal is assumed to come from a forestry plantation that replaced a sheep pasture. The pasture owner then clears woodland elsewhere to replace the grazing space lost to timber production. The clearing releases the CO_2 stored by the woodland into the atmosphere, as well as removes the CO_2 storage capacity provided by the woodland. If this results in CO_2 emissions equivalent to 1.0 t CO_2 per tonne of steel, as in this example, the negative emissions seen in Fig. 2(e) are completely negated.

Fig. 2(g) presents a variation where the CO_2 is permanently stored into a geologic formation after being used for enhanced oil recovery. Here, 1.2 t of CO_2 allows for the recovery of 0.6 t of crude oil, a co-product of the CO_2 storage.[34] The oil extraction and associated processes emit about 0.2 t of fossil CO_2 and the combustion of the 0.6 t oil emit about 2.0 t of fossil CO_2.[34] Therefore, the total emission balance of the BECCS + EOR system is 1.2 t of CO_2 added to the atmosphere.

Fig. 2(c–g) all describe the same system of steel production with BECCS, using the same amount of bioenergy, and permanently storing the same quantity of atmospheric CO_2. However, the estimated balance of emissions varies from 1.2 t of CO_2 removed to 1.2 t of CO_2 emitted, depending on which system boundaries are used and whether the upstream or downstream system generates indirect emissions. This dramatic variation for the exact same BECCS installation underlines the importance of selecting inclusive system boundaries when estimating whether a technology or intervention will result in negative emissions.

Quantified estimates of negative emissions should take into account, as fully as possible, all greenhouse gas removals and emissions in the cradle-to-grave system, including indirect emissions when pertinent (*e.g.* from indirect land use change or the combustion of system coproducts such as EOR oil). While any emissions estimate is limited by the available data, the use of as broad a system boundary as possible minimized the possibility of inconsistent or short-sighted system boundary selection leading to emission estimates that are misleading, contradictory, and possibly very wrong.

Further consideration for biomass-based NETs

As several NETs rely on the large-scale cultivation of biomass, it is relevant to briefly highlight the limitations of the above example with regard to biomass production and use, particularly as it only describes a single possible system configuration. In the above example, the bioenergy system of cultivation, harvest, processing, and combustion, by itself (excluding CCS) resulted in a positive balance of CO_2 emitted to the atmosphere. However, depending on the method of cultivation and processing, bioenergy can be carbon positive, carbon negative, or carbon neutral.[35,36] Factors that influence the emission balance of bioenergy systems include the growth rate and harvest frequency of the biomass, the preparation of the land for biomass cultivation (direct land use change), the energy intensity and energy source for biomass harvest, transport, and processing, and the management of soil and biomass residues, among others.[36] Furthermore, while significant emissions from ILUC were included in the example for illustrative purposes, whether and how much land use change occurs, direct or indirect, is highly specific to the geographic considerations, such as existing available land and land use patterns, of each bioenergy system.[37]

Besides the physical considerations of the biomass system, the accounting method can significantly influence the estimated emissions of a bioenergy system, particularly for slow-growth biomass such as forestry. In particular, as highlighted in Daystar *et al.* (2015),[35] the geographic and temporal scale of the bioenergy system, whether CO_2 removals and emissions are assumed to be instantaneous or occur over time, and whether the time boundary begins at biomass planting or biomass harvest, can all substantially influence the emission balance. The development of emission accounting methods for bioenergy and biomass systems is an active area of research.[35,38–40]

Conclusions

The use of "negative emissions" terminology is not consistent in recent literature. Misinterpreting or miscounting negative emissions could have unintended, and possibly dangerous, consequences, such as policy incentives that reward increasing atmospheric greenhouse gas concentrations under the guise of negative emissions. While cradle-to-grave system analysis is not within the scope of all research on NETs, it is vital for researchers and decision-makers to be aware of the system boundaries they explicitly or implicitly use, and the limitations of those boundaries, particularly when estimating quantities of negative emissions. As shown in the simplified example above, emission negativity cannot be determined without accounting as fully as possible for all emissions and removals of greenhouse gases in the cradle-to-grave system. Based on the most common defining elements seen in explicit and implicit usage of the term "negative emissions", and keeping in mind the goal of negative emissions—reducing atmospheric level of greenhouse gases—four key criteria can be considered "minimum qualifications" for determining whether a technology results in negative emissions:

1. Physical greenhouse gases are removed from the atmosphere.
2. The removed gases are stored out of the atmosphere in a manner intended to be permanent.
3. Upstream and downstream greenhouse gas emissions associated with the removal and storage process, such as biomass origin, energy use, gas fate, and co-product fate, are comprehensively estimated and included in the emission balance.
4. The total quantity of atmospheric greenhouse gases removed and permanently stored is greater than the total quantity of greenhouse gases emitted to the atmosphere.

While the above criteria require a cradle-to-grave system perspective for emissions accounting, they do not endorse a specific methodology for emission accounting, as evaluating the merits and limitations of the different accounting practices is outside the scope of this paper. However, a clear distinction should always be made between physical negative emissions, as defined above, and the emission reduction potential of one technology in comparison to another (avoided emissions), which can appear as negative numbers in LCAs. The use of the term "negative emissions" for both physical removals and assumed avoidance has a particular risk for counterproductive misunderstanding in decision-making and incentive design.

Furthermore, the impact on atmospheric greenhouse gas concentrations is just one of several impacts that a negative emission technology could have that may affect global warming. Others include changes in albedo,[41] the response of natural carbon sinks,[42] or a rebound effect of increased consumption.[43] Additionally, other environmental impacts, such as biodiversity loss, acidification, and water use, also require consideration when evaluating the utility of a specific NET.[41,44] It is also important to leave space for impacts that are currently beyond our knowledge—the unknown unknowns—and to adapt analysis as understanding of the impacts of negative emissions increases.

Finally, it should be emphasised that negative emission technologies are nascent and the scale on which they could be effectively implemented is uncertain. Preventing catastrophic climate change is a race against the clock requiring unprecedented levels of global cooperation and technological development. While it is imperative to develop long-term technological options such as negative emission technologies, they do not reduce the necessity of immediate and drastic reductions in global greenhouse gas emissions.

Conflicts of interest

There are no conflicts to declare.

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