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SYNTHESIS ARTICLE

Carbon accounting for negative emissions technologies

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ABSTRACT

Negative emissions technologies (NETs) are an essential part of most scenarios for achieving the Paris Agreement goal of limiting warming to below 2°C and for all scenarios that limit warming to 1.5 °C. The deployment of these technologies requires carbon accounting methods for a range of different purposes, such as determining the effectiveness of specific technologies or incentivising NETs. Although the need for carbon accounting methods is discussed within the literature on NETs, there does not appear to be a clear understanding of the range of different accounting challenges. Based on a systematic literature review this study identifies five distinct accounting issues related to NETs: 1. estimating total system-wide change in emissions/removals; 2. non-permanence; 3. non-equivalence of 'no overshoot' and 'overshoot and removal'; 4. accounting for incentives for NETs; and 5. the temporal distribution of emissions/removals. Solutions to these accounting challenges are proposed, or alternatively, areas for further research and the development of solutions are highlighted. One key recommendation is that carbon accounting methods should follow a 'reality principle' to report emissions and removals when and where they actually occur, and an important overall conclusion is that it is essential to use the correct accounting method for its appropriate purpose. For example, consequential methods that take account of total system-wide changes in emissions/removals should be used if the purpose is to inform decisions on the deployment or incentivisation of NETs. Attributional methods, however, should be used if the purpose is to construct static descriptions of possible net zero worlds.

Key policy insights:

- Negative emissions technologies (NETs) raise a number of distinct carbon accounting challenges, the importance of which varies across different NETs.
- Attributional life cycle assessment is not an appropriate method for estimating the system-wide changes caused by the deployment of NETs.
- Consequential greenhouse gas accounting methods should be used to estimate system-wide changes, and should be used as much as possible for guiding incentives for NETs.
- Greenhouse gas accounting methods should follow a 'reality principle' to report emissions and removals when and where they actually occur.

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1. Introduction

Negative emissions technologies (NETs) are an essential part of most scenarios for achieving the Paris Agreement goal of limiting warming to below 2°C (Anderson & Peters, 2016; Smith et al., 2016; van Vuuren et al., 2013), and all scenarios for limiting warming below 1.5 °C (IPCC, 2018). The deployment of these technologies will require carbon accounting methods for a range of different purposes, such as determining the effectiveness of specific technologies, or allocating responsibility and determining who will pay for NETs. Although the need for carbon accounting methods is discussed in the NETs literature (e.g. Royal Society and Royal Academy of

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Engineering (2018), hereafter 'RS-RAEng') there does not appear to be a clear understanding of the range of different accounting issues and requirements associated with NETs. This study therefore aims to identify these different accounting challenges, and to identify potential solutions or areas for further development.

A NET is a technology that achieves a net removal of greenhouse gases (GHGs) from the atmosphere, i.e. the removals achieved are greater than any positive emissions caused by the deployment of the technology (Tanzer & Ramírez, 2019). Examples include technologies or actions such as afforestation/reforestation/forest management (AR/FM), enhanced soil carbon sequestration (SCS), enhanced weathering of minerals (EW), ocean fertilization (OF), bioenergy with carbon capture and storage (BECCS), and direct air capture and carbon storage (DACCS) (Smith & Friedmann, 2017). These technologies include those that primarily enhance natural processes, e.g. AR/FM, those which rely entirely on human engineering, e.g. DACCS, and those involving some combination of natural processes and human engineering, e.g. BECCS. NETs can also be referred to as 'carbon dioxide removal' (CDR), if only CO_2 is removed, or 'greenhouse gas removal' (GGR), but for consistency the term NETs is used in this paper.

The need for accounting and accountability in relation to NETs is mentioned extensively in the academic literature. For example, McLaren (2012a) identifies 'accountability', i.e. the 'impacts of the technique should be capable of being adequately measured and accounted for' (2012a, p. 490), as one of seven criteria for assessing NETs, concluding that accountability 'raises further challenges for the deployment (and incentivisation) of most NETs' (2012a, p. 498). Lomax et al. (2015) reach a similar conclusion, stating that integrating 'GGR effectively into policy raises significant challenges relating to uncertain costs, side effects, life-cycle effectiveness and accounting' (2015, p. 125). Likewise, Fuss et al. (2016, p. 7) highlight the 'current lack of consistent emissions accounting rules for all types of NETs' (Fuss et al., 2016, p. 7). Lin (2018), writing from an environmental law perspective, also emphasizes the point that reliable 'accounting of net carbon emissions is necessary for CDR to work and for policymakers, investors, and the public to support CDR' (2018, p. 579). One of the key recommendations from the RS-RAEng's (2018) report for the development of NETs is to establish 'a framework to govern sustainability of GGR deployment. Undertake rigorous life cycle assessments and environmental monitoring of individual methods and of their use together' (2018, p. 116). Similarly, although focused specifically on BECCS, Stavrakas et al. (2018) identify carbon reporting and accounting systems under the EU Emissions Trading System (EU ETS), United Nations Framework Convention on Climate Change (UNFCCC), and Kyoto Protocol as a key area for investigation and policy development.

The above illustrates the broad acknowledgement of the importance of carbon accounting for NETs, and recognition of some specific challenges that need to be addressed, such as uncertainty and consistency. However, there appears to be neither a clear classification of the distinct accounting issues associated with NETs in the literature, nor recognition of the possibility that different accounting methods may be required for different aspects of deployment and governance (Ascui & Lovell, 2011). To address this gap, this paper undertakes a systematic literature review to identify the different carbon accounting issues associated with NETs. In many cases the identified accounting challenges are similar to those for other climate change mitigation technologies, and on this basis the paper proposes a number of potential solutions.

The remainder of the paper is structured as follows: Section 2 describes the methodology for the systematic literature review; Section 3 presents the different accounting issues identified, and proposes potential solutions; and Section 4 sets out some limitations and concluding remarks.

2. Methods

A two-stage literature review was conducted in order to identify the extant literature related to NETs and carbon accounting. The first stage used a search for key phrases in Google Scholar, combining two categories, the first relating to carbon accounting ('carbon accounting', 'GHG accounting', 'MRV' and 'accountability') and the second to NETs ('negative emissions', 'NETs', 'greenhouse gas removal', 'CDR', 'CO_2 removal' and 'carbon dioxide removal'). The titles and abstracts of the publications returned were then screened to exclude those that were in fact not related to carbon accounting and NETs. The second stage used 'snowballing' to identify further relevant publications which cited or were cited by the publications identified in the first stage in order to help address possible bias caused by the choice of key words (Camacho-Otero et al., 2018). A later iteration of the key phrase search was also undertaken with the terms 'LCA' and 'life cycle assessment', also to address possible bias caused by the initial choice of key words.

A grounded approach was used for the analysis of the literature, i.e. we did not use a pre-determined analytical framework, as the intention for the review was to identify different categories of accounting issue from the literature itself, rather than prejudge what those categories should be. The analysis followed the three forms of coding recommended by Wolfswinkel et al. (2013), with 'open coding' providing the main categories of accounting issue, 'selective coding' identifying linkages between those categories, and 'axial coding' reflecting on other cross-cutting issues. It should be noted that there is no single 'right way' to structure the categorization of accounting issues identified from the literature, and alternative categorisations are possible. In our conclusions, we note additional issues that could also be considered within the remit of accounting.

3. Results and discussion

The key phrase search returned 32 peer reviewed journal articles that explicitly discuss NETs *and* carbon accounting, and the subsequent snowballing exercise returned a further 33 articles, including letters and commentary articles. Based on these articles, the following five distinct but interrelated carbon accounting issues were identified: 1. Accounting for total system-wide change in emissions/removals; 2. Non-permanence of negative emissions; 3. Non-equivalence of 'no overshoot' and 'overshoot and removal'; 4. Accounting for incentives for NETs; and 5. Accounting for the temporal distribution of emissions/removals. These accounting issues are described below. For each issue, we identify or propose a number of potential solutions, largely based on existing accounting techniques or practices. Where we did not identify possible solutions, areas for further research are instead highlighted. We also present an initial assessment of the importance of the different accounting issues identified to specific types of NETs.

The later iteration of the key phrase search using 'LCA' or 'life cycle assessment' returned a further 51 articles. These provided further examples and instances of the accounting issues identified from the initial key phrase search and snowballing, but did not reveal additional accounting issues.

3.1. Total system-wide change in emissions/removals

A key accounting issue within the NETs literature is the quantification of the net change in emissions/removals caused by the deployment of NETs (Fajardy et al., 2019; Guest et al., 2013; National Academies of Science Engineering and Medicine, 2019; Tanzer & Ramírez, 2019; Zakkour et al., 2014).[1] One of the predominant carbon accounting methods used to quantify net removals is 'attributional' LCA, for which the system boundary is defined by the processes used in the life cycle of a technology (Brander, 2016a). For example, Zakkour et al. (2014) state that in order to calculate the life cycle emissions from BECCS, emissions from processes such as biomass harvesting and the energy used in capturing, transporting and injecting CO_2 should be included. LCA also appears to be endorsed as an appropriate method by the RS-RAEng report which recommends 'rigorous life cycle assessments' (2018, p. 116). However, it is increasingly recognized within the LCA community that 'attributional' LCA is not appropriate for informing decisions, as the system boundary does not necessarily provide information on the total system-wide change in emissions caused by the decision in question (Plevin et al., 2014).

Tanzer and Ramírez (2019) provide a useful illustration of the limitations with attributional LCA, using BECCS as an example. Attributional LCA includes all the processes directly used in the life cycle of a technology, but does not include indirect market-mediated effects, such as indirect land use change caused by increased market prices for biomass (caused by the deployment of BECCS). Similarly, if the BECCS system uses captured CO_2 for enhanced oil recovery (EOR), the resulting increase in the supply of oil may cause a marginal decrease in oil prices and thereby increase oil consumption (with associated emissions).

Although there is growing recognition of the insufficiency of attributional LCA for decision-making, and the need for methods which include all changes within the system boundary (Gough et al., 2018; Tanzer & Ramírez, 2019), it is important that this message is disseminated more widely. Often the distinction between attributional LCA and consequential LCA, or other methods that aim to estimate system-wide changes, is not explicitly recognized, as illustrated by the RS-RAEng report (2018), which does not clarify which type of LCA it is recommending.

Broadly, consequential methods are those that explicitly aim to quantity the total system-wide change caused by a specified decision or action (Brander, 2016b), and include consequential LCA, project-level accounting, and policy-level accounting. Even when it is recognized that all changes in emissions/removals need to be considered, there appear to be misunderstandings about which carbon accounting methods are appropriate for this purpose. For example, Torvanger (2019) recognizes the need for accounting methods which include all changes in emissions/removals 'including indirect market and price effects' (2019, p. 332), and recommends the establishment of a 'standardized framework for calculation of the effect of biomass crops and processing on net CO_2 emissions'. However, Torvanger (2019) suggests that such a framework could be based on methods such as the IPCC guidelines for national GHG inventories or the EU's Renewable Energy Directive (RED) sustainability reporting, which are both 'attributional' in nature, and do not include indirect market and price effects (Brander, 2016b). In addition, recognition of indirect effects is often limited to indirect land use change (van Vuuren et al., 2013), but it is important that *all* changes in emissions are considered, including other market-mediated effects such as the oil price effects from EOR, or material displacement effects (Brander, 2017; Guest et al., 2013; Kemper, 2015; National Academies of Science Engineering and Medicine, 2019). It is worth noting that attributional LCA may be useful for other purposes (other than estimating the total change in emissions/removals caused by a decision), e.g. for constructing plausible static descriptions of a net zero world. This is because attributional LCA shows the balance of emissions/removals from the processes directly or inherently used within the life cycle of a technology, and the results are, in principle, additive to estimate global totals (Brander et al., 2019). However, any decisions or policies aimed at achieving a specified scenario would still need to be assessed using a consequential method, to avoid unintended indirect consequences.

In addition to misunderstandings about which carbon accounting methods consider all emissions/removals that change, there also appear to be misunderstandings about which accounting approaches are appropriate for modelling *change*. For instance, RS-RAEng recommend developing 'international science-based standards for monitoring, reporting and verification for GGR approaches' (2018, p. 117). However, if intended as an approach to assess the change in emissions/removals caused by NETs, such an approach is not sufficient on its own, as change caused by an intervention in complex dynamic systems typically cannot be directly monitored or observed, but only estimated or modelled relative to a counterfactual baseline. A similar misconception is evident in the Ecofys (2017) report on indicators for NETs, which suggests that a monitoring system could be used to prove additionality (i.e. that net removals would not have occurred anyway, in the absence of an intervention). Demonstrating additionality involves proving that an intervention has caused a change, and also necessarily involves the use of a counterfactual baseline, which by definition cannot be directly monitored.

The necessity of a baseline is illustrated in Figure 1, which shows that even though observed/monitored carbon stocks following the implementation of a NET might be increasing over time, this does not entail that the NET has not caused an increase in emissions (or decrease in removals) relative to what would have happened in the absence of the intervention, if the baseline increase in carbon stocks would have been greater than the observed increase. This misconception (concerning the necessity of a baseline for estimating change) also appears to be prevalent in the bioenergy and forest carbon accounting literature, with studies suggesting that stable or increasing forest carbon stocks at the 'landscape' level indicate that the use of bioenergy does not have a negative impact on carbon stocks (Adams et al., 2013; Mitchell et al., 2012; Smith & Bustamante, 2014; Zanchi et al., 2012).

In summary, in order to understand the effectiveness of NETs, carbon accounting methods are needed that include all emissions and removals that change, and a counterfactual baseline is needed to estimate the change caused by the decision in question (Guest et al., 2013). An example of an accounting method with these features is the GHG Protocol *Policy and Action Standard* (WRI, 2014), which is also suitable for representing the temporal distributions of emissions/removals, discussed in Section 3.5.

3.2. Non-permanence of negative emissions

A second challenge is how to account for non-permanence, which is a potential risk for many NETs (Boucher et al., 2014; Kemper, 2015; Lomax et al., 2015; Meadowcroft, 2013; Scott et al., 2015). Whilst all NETs share the characteristic of removing GHGs from the atmosphere, they differ considerably with respect to the final destination of the

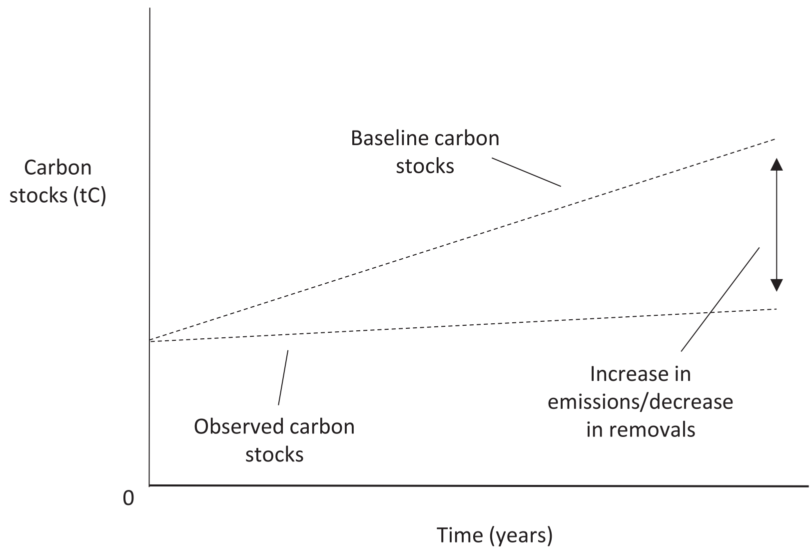

Figure 1. Illustration of baseline and monitored carbon stocks.

removed gas, with options including above and below-ground biomass (AR/FM); soil (SCS); geological formations (BECCS, DACCS) and the ocean (EW, OF). Each of these sinks has different characteristics, especially with regard to residence times and the risk of flow reversal, For example, carbon stored in forests may suffer from catastrophic release due to wildfires or disease (Galik & Jackson, 2009), or CO_2 captured from BECCS or DACCS which is stored in geological formations could suffer from leakage (Lilliestam et al., 2012), though this may be minimal (Alcalde, Flude, et al., 2018; Daggash et al., 2019). Non-permanence is highly important as temporary removals do not contribute to long-term temperature stabilization (Scott et al., 2015), unless temporary removals are replaced with further temporary removals in perpetuity. Nevertheless, temporarily removing CO_2 from the atmosphere may have some benefits in terms of reducing peak emissions overshoot or peak temperature change, thereby 'buying time' before alternative permanent NETs can be deployed. Although non-permanence is discussed in a number of places in the NETs literature (Boucher et al., 2014; Lomax et al., 2015; Meadowcroft, 2013), there does not always appear to be clear recognition that non-permanence raises a number of distinct accounting issues. Based on the literature review, the following distinct accounting issues are identified: accounting for the non-permanence of individual stores within aggregate pools of carbon; accountability/liability for non-permanence; and accounting for the uncertainty of non-permanence. Each of these is discussed in turn below.

3.2.1. Accounting for the non-permanence of individual stores within aggregate pools of carbon

Some individual stores of carbon, e.g. individual stands of trees or individual harvested wood products (HWPs), are not permanent and this raises questions about their value for achieving long-term temperature targets. However, individual temporary stores can form part of an aggregate carbon pool, which, in principle, can be maintained indefinitely. Accounting approaches do already exist for dealing with the non-permanence of individual carbon stores at the level of aggregate pools. For example, although individual HWPs may have limited half-lives (e.g. two years for paper, 35 years for sawn timber (Frieden et al., 2012)), if the aggregate stock is maintained or increased, this signifies a persisting store of carbon (Iordan et al., 2018; Johnston & Radeloff, 2019). A similar approach can be used for the permanence of forest carbon in commercial forests, i.e. although individual stands will be harvested and replanted cyclically, the aggregate stock can be used to assess the permanence of the carbon pool.

One additional issue to note with the treatment of non-permanent stores is that if the purpose of the accounting exercise is to quantify the total change in emissions caused by the deployment of the technology assessed, then it is important to account for any on-going emissions caused by maintaining the carbon pool in perpetuity. For example, the life cycle emissions from achieving on-going carbon storage in stocks of HWPs include the emissions from planting, harvesting, processing, replanting etc., repeated indefinitely. Figure 2 provides an illustrative example for HWP, and shows how repeated emissions over time will eventually exceed the amount of carbon stored, and cumulative emissions/removals will become net positive (unless the processes used to maintain the carbon stock are also decarbonized).

3.2.2. Accountability/liability for non-permanence

An accountability issue related to non-permanence is how to allocate or manage liability for reversals in stored carbon (Bode & Jung, 2006; Fuss et al., 2016). This issue is important as liability for reversals, or even uncertainty concerning liability for reversals, can undermine confidence and investment in storage technologies, as has been the case with CCS under the EU CCS Directive (Oraee-Mirzamani et al., 2013).

The main approaches that have been taken to address this issue include temporary crediting, and permanent crediting with a separate rule or mechanism to deal with the possibility of reversal (e.g. fixed liability periods, tonne-year crediting, buffers or insurance). Temporary crediting was adopted for AR projects under the Kyoto Protocol Clean Development Mechanism (CDM), with eligible projects generating credits which are only valid until a certain date, after which they must be replaced either with newly issued temporary credits, or a permanent credit from another (non-NETs) source (Galinato et al., 2011). While this approach ensures that any reversal will be compensated either with further removals or reductions in emissions elsewhere, the non-fungibility of temporary credits in international carbon markets depressed demand and ultimately investment in CDM AR projects fell far below initial expectations (Neeff & Ascui, 2009).

Permanent credits with fixed liability periods have been used in several schemes as a way of limiting liability for buyers and sellers of removals credits from individual projects, even though the country in which the project was based might still have to account for any reversal of storage in its national accounting. Tonne-year crediting was proposed as a way of awarding removals projects with permanent credits based on removals sustained over a period of years, multiplied by an equivalence factor (Fearnside et al., 2000), but credits may only accrue very slowly under this method, which can have significant negative implications for the economic viability of removal projects (Subak, 2003). Buffers and insurance are both reversal compensation mechanisms, with the main difference being that buffers hold back credits against the possibility of reversal, whereas insurance provides financial compensation, which implicitly relies on the assumed ability to purchase replacement credits from the market in order to achieve accounting integrity. Overall, permanent credits with either fixed liability periods or buffers are the two methods for allocating liability for non-permanence that have been most widely and successfully used in carbon markets to date.

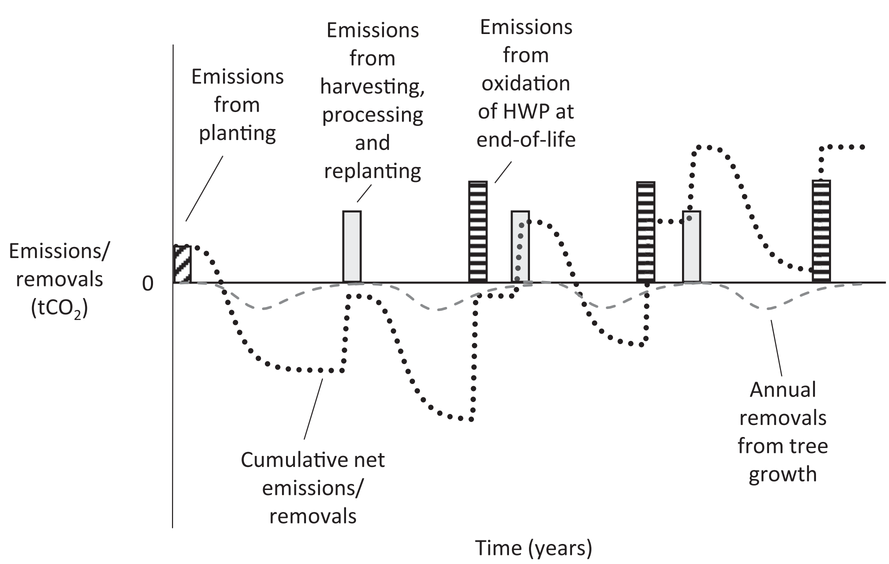

Figure 2. Illustration of cumulative net emissions/removals from non-permanent carbon stores.

3.2.3. Accounting for uncertainty and non-permanence

A third issue related to non-permanence is how to account for the uncertainty of potential reversals (Lomax et al., 2015). Although accounting for uncertainty is an issue that arises for NETs generally, rather than only in relation to non-permanence, discussion on uncertainty is included here with the intention that the points below also apply to uncertainty more broadly. Uncertainty can be categorized into two distinct types: firstly, quantifiable risk, where there are known probabilities for different outcomes, e.g. a '95% probability that the carbon stored in sawn timber will be oxidized and return to the atmosphere within *x* years'; and secondly, Knightian uncertainty, when the probabilities of different outcomes are unknown (Knight, 1933).

In the case of quantifiable risk, this can be incorporated into carbon accounting practices relatively straightforwardly, for instance, if costs per net tCO_2 removed are \$200/tCO_2, and there is a known probability of reversal of 20%, then the denominator of the metric (i.e. per tCO_2 removed) is reduced by 20%, and the risk-adjusted cost per tonne permanently removed becomes \$250/tCO_2. Known uncertainties can also be managed using risk-buffer approaches (3.2.2 above), as the size of the reserve required will be known.

However, because many factors associated with non-permanence are likely to change in the future, not least due to climate change itself (Lawrence et al., 2018), e.g. the probability of forest fire is likely to change over time due to a changing climate, the form of uncertainty associated with reversals may be more appropriately characterized as Knightian uncertainty, where the probabilities are unknown. The limited amount of experience with the deployment of NETs at scale is also likely to entail unknown probabilities. In situations of Knightian uncertainty, alternative decision-making approaches can be used, e.g. the 'minimax' principle, which states that the maximum possible loss should be minimized (Trevizan et al., 2007). The application of this principle would most likely prioritize the abatement of emissions in order to avoid reliance on NETs, which have an unknown probability of success and could result in a large emissions overshoot and substantially more damaging climate change (Larkin et al., 2018).

3.3. Non-equivalence of 'No overshoot' and 'Overshoot and removal'

An overshoot is when cumulative emissions and the resulting temperature change exceed a stated target, e.g. the 2°C target of the Paris Agreement (UNFCCC, 2015), and net negative emissions are then required to recapture emissions and bring temperature change back to below the target level (van Vuuren et al., 2013). A distinct accounting issue arises when NETs are used to recapture an overshoot in emissions (as opposed to using NETs to offset remaining emissions (Meadowcroft, 2013)) as the cooling effect of each unit of negative emissions on the downward slope of the cumulative net emissions curve may be less than the warming effect of a unit of positive emissions on the upward slope (Rickels et al., 2019; Zickfeld et al., 2016). This would contradict the common assumption that emissions and removals are equivalent across time (Goodwin et al., 2015). The accounting issue which arises is that the possible non-equivalence of warming and cooling caused by overshoot emissions and recapture removals, respectively, may warrant the use of a correction or discount factor for recapture removals (Fridahl et al., 2020; Tokarska & Zickfeld, 2015; Torvanger, 2019). This is particularly relevant when comparing the cost-effectiveness of emissions abatement (i.e. avoiding an overshoot) on the one hand, with removals for dealing with an overshoot on the other, as their effectiveness in achieving a temperature target is not equivalent on a per tonne CO_2 basis. For example, if the cost of recapture is £200/tCO_2, but the effectiveness of recapture is 80% of emissions abatement in terms of achieving a temperature target, then the corrected cost effectiveness of recapture is \$250/tCO_2. Applying a discount factor parallels a proposal for 'global cooling potentials' to deal with the non-equivalence of warming/cooling caused by emissions/removals of CH_4 and N_2O (Neubauer & Megonigal, 2015), though in this case removals are more effective at cooling than emissions are effective at warming.[2]

However, a challenge with adopting a correction approach is determining what the correction factor should be, particularly because results from different studies are inconclusive (Fridahl et al., 2020). Even if consensus can be reached on the amount of warming and cooling caused by overshoot emissions and recaptured emissions, a more fundamental accounting problem is that equivalence may be achieved for one climate impact indicator, e.g. temperature change, but this does not ensure equivalence for other impact indicators, e.g. sea level rise. This entails that there is no correction factor or overshoot-to-recapture ratio that can achieve equivalence across all climate impact indicators. It is important to note that this non-equivalence *after* an overshoot is in addition to non-equivalence of damages *during* an overshoot period caused by higher temperatures. A key conclusion for policymakers is that, once perturbed, the Earth system cannot be returned to equivalence with a no-overshoot scenario, and that NETs later in the century should not be viewed as an equivalent alternative to emissions abatement and the avoidance of an overshoot.

This difficulty with using single impact indicators underscores Cherubini et al.'s (2016) conclusion that 'the use of a single metric … cannot represent the climate system complexity for all possible research and policy contexts' (2016, p. 129), and raises broader questions about the development of more sophisticated carbon accounting metrics for policy-making and decision-support. Ideally, metrics should reflect the end-point damage that is ultimately the concern of policymakers (Kirschbaum, 2014), but there is often a trade-off between sophisticated end-point metrics and their uncertainty (Höhne & Blok, 2005; Timma & Parajuli, 2019).

3.4. Accounting and incentives for NETs

A further accounting issue within the NETs literature is how to ensure that carbon accounting rules properly incentivise NET deployment (Bird et al., 2012; Fajardy et al., 2019; Grönkvist et al., 2006; Kemper, 2015; Lomax et al., 2015; Peters & Geden, 2017; Reid et al., 2020). In essence, incentives are mediated and determined by accounting rules (Frieden et al., 2012), and if the accounting rules do not reflect a desired outcome, the outcome will not be appropriately incentivised. Moreover, if accounting for the climate benefits of NETs is uncertain, this will itself undermine confidence and investment in NETs (Creutzig et al., 2019; Nemet et al., 2018). As Torvanger puts it in relation to BECCS, 'the framework for accounting of CO_2 removal from BECCS is decisive for estimating the volume of negative emissions generated from a project, and also for rewarding the BECCS project operator(s)' (2019, p. 331). The issue of designing accounting methods that appropriately incentivise NETs clearly overlaps with other accounting issues discussed above, e.g. how to quantify the system-wide change in emissions caused by NETs (3.1), and how to account for non-permanence and uncertainty (3.2).

A prominent example of the misalignment of accounting rules, and therefore incentives, with the desired outcome (in this case GHG abatement), is national GHG accounting rules for bioenergy (Brack, 2017; Geden et al., 2018; Haberl et al., 2012; Searchinger et al., 2009). The IPCC guidance for national GHG inventories (IPCC, 2006, 2019) does not count CO_2 emissions from biomass at their point of release, but instead counts the emissions within the land use sector. A problem with this approach is that it creates an incentive to import biomass as the importing country can count the point-of-combustion emissions as zero (Bird et al., 2012), but the exporting country does not necessarily have an incentive to sustainably manage its land-based carbon stocks, e.g. if the country's Nationally Determined Contributions do not include the land use sector. Here the accounting rules create incentives which are not aligned with achieving the desired outcome, i.e. system-wide net emission reductions. A converse example of misalignment can be given for BECCS, where the existing accounting rules do not incentivise BECCs even though the technology can, in principle, achieve negative emissions (Zakkour et al., 2014).

One, at least partial, solution to this problem would be to adopt what may be termed the *reality principle*: that emissions and removals should be counted when and where they actually occur. For example, national GHG inventories should count CO_2 emissions from the combustion of biomass in the energy sector (as that is when/where the emissions occur), and if the emissions from combustion are captured and stored then there will be no emissions, and the account will correctly report emissions as zero. Similarly, the sequestration that occurs as biomass regrows should be counted in the land use sector, at the time that the regrowth occurs (which would also reflect the timing of the 'negative' component of BECCS, see Section 3.5 below). The same principle is recommended by Rabl et al. (2007) to account for CO_2 from biomass within LCA, i.e. 'that emission and removal of CO_2 be counted explicitly at each stage of the life cycle' (2007, p. 281). The reality principle would also go some way to addressing the 'fundamental error in GHG accounting' highlighted by Haberl et al. (2012), i.e. that burning biomass releases CO_2 to the atmosphere just like burning fossil fuels.

However, a remaining challenge with any type of *attributional* accounting is that it does not necessarily reflect the system-wide change in emissions caused by the deployment of the technology (as discussed in Section 3.1 above). Given that the desired outcome is the system-wide net removal of emissions from the atmosphere, it is problematic if the accounting does not align with this outcome. This can be illustrated with BECCS as an example: woody biomass is a globally traded commodity, and any increase in demand is likely to cause an increase in the market price, which in turn may cause emissions from indirect land use change if forest owners respond to the price signal and deforest their land (Harper et al., 2018). This means that the extent to which the biomass that is directly used comes from a sustainably managed source is largely irrelevant as to whether its use will achieve system-wide net removals, as demand for sustainably managed biomass can still create harmful market-mediated indirect effects on emissions. This also undermines the efficacy of sustainability certification schemes, which have been called for by some commentators (Fajardy et al., 2019). Unless there is also a universal mechanism such as a global carbon price, then attributional accounting, even with the reality principle, is not sufficient to ensure that incentives are aligned with the desired outcome.

One solution is to use consequential accounting methods (Section 3.1), which quantify the system-wide change in emissions caused by an action, and will therefore align with the desired outcome of achieving system-wide net removals. Consequential accounting could, for example, address the incentive misalignment identified by Plassmann (2012), which is that attributional product carbon footprints involving net removals appear to favour low-yield rather than high-yield production systems, since removals are expressed per unit of output. Consequential accounting would resolve this issue by taking account of induced land use change elsewhere that would be required to make up for lower yields. There appears to be some recognition of the need for consequential accounting in Torvanger (2019), with the statement that a 'sector-based approach … makes accounting of net negative emissions very difficult, so instead a project-based accounting framework [which is a form of consequential method] should be considered' (2019, p. 332). However, a significant challenge with moving to purely consequential accounting is that attributional accounting, in the form of national GHG inventories, is an embedded feature of the UNFCCC architecture and is likely to continue to underpin country-level target setting, and therefore remain a substantial component of the incentive framework for mitigation action. A solution that reflects this realpolitik would be to align national GHG inventories as much as possible with when and where emissions/removals occur (i.e. the reality principle), and separately to use consequential methods to identify and avoid actions that have unintended indirect effects (Brander et al., 2019).

3.5. Accounting for the temporal distribution of emissions/removals

Another distinct accounting issue within the NETs literature relates to the importance of, and also how to model, the temporal distribution of emissions/removals from the implementation of NETs (Bird et al., 2012; Fajardy and Mac Dowell, 2017; Gilbert & Sovacool, 2015; Goglio et al., 2020; National Academies of Science Engineering and Medicine, 2019; Reid et al., 2020; Tanzer & Ramírez, 2019). This issue is also highly policy relevant as governments require technologies that deliver net removals within target timeframes, e.g. by 2050 for the UK Government's net zero commitment (UK Parliament, 2019), and technologies that only achieve net negative emissions decades after implementation, e.g. potentially BECCS or EW, may not align with such timeframes. The timing for when technologies actually deliver negative emissions is also highly important if there is non-equivalence between overshoot emissions and recaptured removals (3.3), and the associated damages.

To illustrate the potential difference in the temporal distribution of emissions/removals for different NETs, Figure 3 compares indicative timelines for BECCS and DACCS, showing emissions and removals, cumulative net emissions, and the breakeven point at which the implementation of the technology achieves net negative emissions. For BECCS, assuming the marginal system is additional harvesting with replanting, the emission sources include those from building the facility, harvesting operations, the transportation of biomass, emissions from combustion which are not captured as expected capture efficiencies are in the region of 90% (Mantripragada et al., 2019), and emissions from CO_2 capture, compression, transportation and injection into storage. These emissions create a 'carbon debt' which is repaid over time as the forest regrows, but which may take multiple decades depending on the growth rate (Fajardy and Mac Dowell, 2017; Field et al., 2020; Jonker et al., 2014; Lamers & Junginger, 2013). In comparison, DACCS may be expected to have a relatively short carbon payback period, primarily because a high annual rate of removal is achieved as soon as the technology is deployed.

Given that information on the temporal distribution of emissions/removals, and carbon payback periods, is highly relevant to policy decision-making, carbon accounting methods are needed which provide this information.

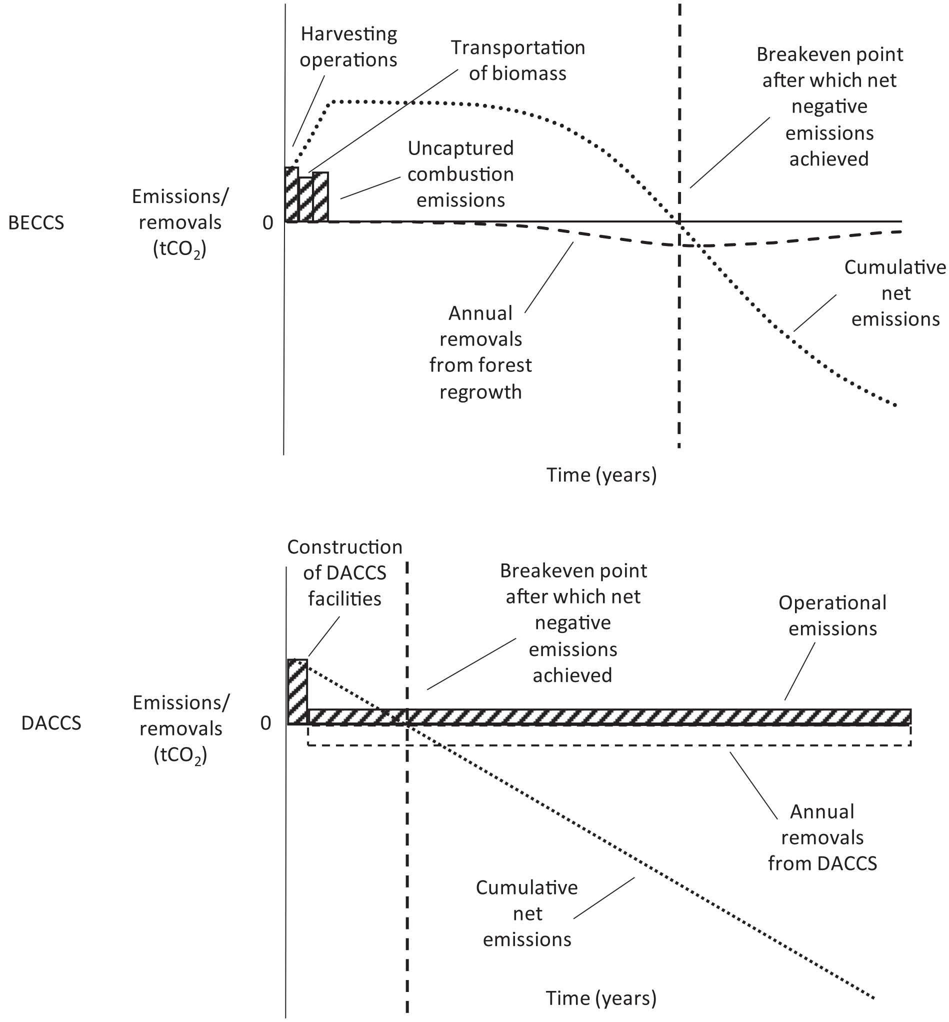

Figure 3. Illustration of temporal distribution of emissions/removals for BECCS and DACCS.[3]

LCA, both attributional and consequential, tends not to provide temporal information (Mcmanus & Taylor, 2015), although the development of dynamic LCA is intended to address this limitation (Levasseur et al., 2010). An alternative accounting solution is to use baseline-and-credit methods, such as the GHG Protocol's *Policy and Action Standard* (WRI, 2014), which can explicitly model emissions and removals as a time series (Brander, 2016b, 2017).

3.6. Summary and importance of accounting issues to different NETs

Having discussed five distinct accounting issues related to NETs in the preceding sections it is useful to summarize the key points, and to draw out how some of the issues will be relevant to different types of NETs to differing degrees. For example, accounting for market-mediated system-wide effects is likely to be highly relevant for AR as any increase in land use for this purpose may cause displacement effects and indirect land use change. In contrast, DACCS may have limited market-mediated system-wide effects as the technology has limited land use requirements, and may not interact significantly with other markets (though there may be some effects via increased demand for electricity). Table 1 provides an overall summary of the accounting challenges identified in the paper and the solutions proposed, and also provides an initial assessment of the importance of the different accounting issues to different types of NETs.

Table 1. Summary and importance of accounting issues to different NETs.

Accounting Issue	Challenges	Solutions	Type of Negative Emissions Technology: Afforestation/ reforestation	Enhanced soil carbon sequestration	Enhanced weathering of minerals	Ocean fertilization	Bioenergy with carbon capture and storage	Direct air capture and storage
1. Accounting for total system-wide change in emissions/ removals	• Deployment of NETs may indirectly cause increased emissions/ decreased removals elsewhere in the system. • Change caused by an intervention in a complex dynamic system cannot be directly observed/ monitored.	• Use consequential accounting methods, e.g. GHG Protocol *Policy and Action Standard*, that consider all changes in emissions/removals caused by deployment of NETs. • Estimate or model change relative to a counterfactual baseline.	**High**. High probability of market-mediated/ indirect effects from land use.	**High**. High probability of market-mediated/ indirect effects from land use and/or changes in productivity.	**High**. High probability of market-mediated/ indirect effects from land use and/or changes in productivity.	**Medium.** Possible market-mediated/ indirect effects if fertilization affects commercial fish stocks.	**High**. High probability of market-mediated/ indirect effects from land use.	**Low**. Low probability of market-mediated/ indirect effects as limited displacement of existing activities.
2. Non-permanence of negative emissions	• Non-permanence of individual stores within aggregate pools. • Liability for non-permanence. • Uncertainty and non-permanence.	• Use aggregate carbon pool to measure permanence. • Temporary crediting, buffers, and insurance. • Incorporate quantifiable risk into assessments of effectiveness, calculation of risk buffers etc. • Prioritize technologies that have relatively certain net GHG effects.	**High**. Non-permanence highly relevant.	**High**. Non-permanence highly relevant.	**Low.** Low risk of reversals.	**High.** Non-permanence highly relevant.	**Low**. Low risk of seepage.	**Low**. Low risk of seepage.

(*Continued*)

Table 1. Continued.

			Type of Negative Emissions Technology					
Accounting Issue	Challenges	Solutions	Afforestation/ reforestation	Enhanced soil carbon sequestration	Enhanced weathering of minerals	Ocean fertilization	Bioenergy with carbon capture and storage	Direct air capture and storage
3. Non-equivalence of 'no overshoot' and 'overshoot and removal'	• Overshoot emissions may be more effective at warming than recapture removals are effective at cooling.	• Correction factors or recapture ratios – BUT no correction factor/recapture ratio can achieve equivalence across all impact categories.	**Cross-cutting issue**					
4. Accounting for incentives for NETs	• Current national inventory guidelines do not reflect when and where emissions actually occur. • Lack of incentive to implement NETs if accounting rules do not reflect net removals.	• 'Reality principle', i.e. count emissions and removals when and where they actually occur. • However, any attributional accounting method may reward actions which do not achieve system-wide net removals – and consequential methods should be used as much as possible.	**Low**. Removals reflected in national GHG inventory accounting, and incentive mechanisms currently exist (e.g. CDM).	**Medium**. Removals reflected in national GHG inventory accounting, but limited established incentive mechanisms (e.g. voluntary offset market).	**High**. Removals not reflected in national GHG inventory accounting, and no established incentive mechanisms.	**High**. Removals not reflected in national GHG inventory accounting, and no established incentive mechanisms.	**High**. Removals not reflected in national GHG inventory accounting, and no established incentive mechanisms. Also issue of cross-border trade.	**High**. Removals not reflected in national GHG inventory accounting, and no established incentive mechanisms.

5. Accounting for the temporal distribution of emissions/ removals	• NETs may incur 'carbon debt' and have different carbon payback periods. • Non-dynamic LCA (attributional and consequential) does not provide information on timing of emissions.	• 'Reality principle', i.e. count emissions and removals when and where they occur. • Use a baseline-and-credit method, which explicitly models the temporal distribution of emissions and removals, e.g. the GHG Protocol *Policy and Action Standard*.	**High**. Removals occur over multi-decadal timescale.	**Low-High**. Timescale varies, depending on the intervention.	**High**. Removals occur over multi-decadal timescale.	**Low**? Removals occur rapidly, <1 year.	**High**. Timescale varies depending on feedstock. Removals occur over multi-decadal timescale for woody biomass.	**Low**. Removals occur rapidly, <1 year.

Note: High = issue is highly relevant to NET; Medium = medium relevance; Low = low relevance; Cross-cutting issue = equally relevant to all NETs.

4. Conclusions

Although it is widely acknowledged that carbon accounting is essential for appraising and incentivising NETs, the range of different accounting issues does not appear to be well recognized, and there does not appear to be a clear appreciation of the extent to which different accounting issues are problematic for different technologies. This paper aims to advance carbon accounting practice and policy-making related to NETs by identifying and articulating the distinct but often interconnected accounting issues in this area, and by proposing solutions to the identified challenges.

Although this paper discusses five key accounting issues in depth, it is important to note that there are a number of other issues that could also be considered within the remit of accounting, and should be explored in future research, e.g.: how to allocate responsibility for dealing with an overshoot (Bednar et al., 2019; McMullin et al., 2020); how to account for tipping points within overshoot scenarios (Lomax et al., 2015; RS-RAEng, 2018); the effect of economic discounting on policy-making for NETs (Anderson & Peters, 2016; Bednar et al., 2019; Obersteiner et al., 2018); accountability for the size of overshoot when long-term temperature change targets are used (Geden & Löschel, 2017); quantifying the scalability of NETs (Anderson & Peters, 2016; Fajardy et al., 2019; Larkin et al., 2018; Nemet et al., 2018); separating targets and markets for emission reductions and removals (McLaren et al., 2019); and broader governance, equity and accountability issues (Anderson & Peters, 2016; Carton, 2019; Colvin et al., 2020; McLaren, 2012b; Talberg et al., 2018). Parts of the discussion presented in this paper will be relevant to many of these issues, but these issues deserve their own analysis and should be considered as topics for further attention.

An overarching point from the analysis above is that, if the purpose is to inform decisions on the deployment or incentivisation of NETs, then the methods used should account for system-wide change, permanence, uncertainty, the potential non-equivalence of emissions and removals in an 'overshoot-and-recapture' scenario, and the reality of where and when emissions/removals occur. Consequential methods, especially baseline-and-credit type methods such as the GHG Protocol's *Policy and Action Standard*, are largely suited to these requirements. Attributional methods may be appropriate for other purposes, such as constructing static descriptions of possible net zero worlds, as they give the emissions/removals associated with the processes inherently used in the life cycle of a technology, and the results are additive to global totals. A key concluding point is that it is essential to use the correct accounting method for its appropriate purpose.

Notes

1. A related issue is the efficiency (or cost-effectiveness) of different NETs, i.e. \$/net tCO_2 removed (with net change in emissions/removals providing the denominator in the metric), which has also been a central topic within the literature (McLaren, 2012a; Smith *et al.*, 2016; Bhave et al., 2017; Alcalde, Smith, *et al.*, 2018). For example, McLaren (2012a) reports cost effectiveness figures of between \$8/tCO_2 and \$600/tCO_2 for different NETs, while Smith et al. (2016) report figures equivalent to between \$24tCO_2 and \$567tCO_2.
2. A further accounting issue related to non-CO_2 GHGs that is not prominent within the literature identified, but nevertheless appears to be a highly important for some types of NET, is how to compare emissions and removals of different GHGs. Neubauer and Megonigal (2015) suggest that the use of GWPs is not appropriate for ecosystem-based NETs as the emissions and removals are sustained fluxes rather than single pulses, and pulse-based GWPs may underestimate the radiative forcing of CH_4 and N_2O by as much as 40%. Cain et al. (2019) also consider how the calculation of CO_2 equivalence for CH_4 might be improved with a method equating a change in the emission rate of a short-lived climate pollutant as equivalent to a single emissions pulse of a long-lived pollutant.
3. The two illustrative charts are not completely equivalent as, for simplicity, the chart for BECCS shows a single instance of harvesting, combustion, capture, storage and regrowth (rather than overlaying on-going instances of these activities), while the chart for DACCS shows on-going removals and operational emissions over the lifetime of a DACCS facility. However, the illustrative comparison of carbon payback periods remains valid. If ongoing instances of the BECCS activities were included, the payback period would be longer (i.e. extend further to the right).

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References

Adams, P., A., Gilbert, P., J., Howard, D., Lee, R., McNamara, N., Thornley, P., C., Whitaker, J., et al. (2013). *Understanding greenhouse gas balances of bioenergy systems*. http://nora.nerc.ac.uk/503461/7/N503461CR.pdf

Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., Scott, V., Gilfillan, S. M. V., Ogaya, X., & Haszeldine, R. S. (2018). Estimating geological CO2 storage security to deliver on climate mitigation. *Nature Communications*, *9*(1), https://doi.org/10.1038/s41467-018-04423-1

Alcalde, J., Smith, P., Haszeldine, R. S., & Bond, C. E. (2018). The potential for implementation of negative emission technologies in Scotland. *International Journal of Greenhouse Gas Control*. Elsevier, *76*(June), 85–91. https://doi.org/10.1016/j.ijggc.2018.06.021

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182–183. https://doi.org/10.1126/science.aah4567

Ascui, F., & Lovell, H. (2011). As frames collide: Making sense of carbon accounting. *Accounting, Auditing & Accountability Journal*, *24*(8), 978–999. https://doi.org/10.1108/09513571111184724

Bednar, J., Obersteiner, M., & Wagner, F. (2019). On the financial viability of negative emissions. *Nature Communications*, *10*(1), 8–11. https://doi.org/10.1038/s41467-019-09782-x

Bhave, A., Taylor, R. H. S., Fennell, P., Livingston, W. R., Shah, N., Dowell, N. M., Dennis, J., Kraft, M., Pourkashanian, M., Insa, M., Jones, J., Burdett, N., Bauen, A., Beal, C., Smallbone, A., & Akroyd, J. (2017). Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO2 targets. *Applied Energy*. Elsevier Ltd, *190*, 481–489. https://doi.org/10.1016/j.apenergy.2016.12.120

Bird, D. N., Pena, N., Frieden, D., & Zanchi, G. (2012). Zero, one, or in between: Evaluation of alternative national and entity-level accounting for bioenergy. *GCB Bioenergy*, *4*(5), 576–587. https://doi.org/10.1111/j.1757-1707.2011.01137.x

Bode, S., & Jung, M. (2006). Carbon dioxide capture and storage - liability for non-permanence under the UNFCCC. *International Environmental Agreements: Politics, Law and Economics*, *6*(2), 173–186. https://doi.org/10.1007/s10784-006-9004-4

Boucher, O., Forster, P. M., Gruber, N., Ha-Duong, M., Lawrence, M. G., Lenton, T. M., Maas, A., & Vaughan, N. E. (2014). Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(1), 23–35. https://doi.org/10.1002/wcc.261

Brack, D. (2017). Woody Biomass for Power and Heat: Impacts on the Global Climate. (February). https://www.chathamhouse.org/publication/woody-biomass-power-and-heat-impacts-global-climate

Brander, M. (2016a). Conceptualising attributional LCA is necessary for resolving methodological issues such as the appropriate form of land use baseline. *International Journal of Life Cycle Assessment*, *21*(12), https://doi.org/10.1007/s11367-016-1147-0

Brander, M. (2016b). Transposing lessons between different forms of consequential greenhouse gas accounting: Lessons for consequential life cycle assessment, project-level accounting, and policy-level accounting. *Journal of Cleaner Production*. Elsevier Ltd, *112*, 4247–4256. https://doi.org/10.1016/j.jclepro.2015.05.101

Brander, M. (2017). Comparative analysis of attributional corporate greenhouse gas accounting, consequential life cycle assessment, and project/policy level accounting: A bioenergy case study. *Journal of Cleaner Production*. Elsevier Ltd, *167*, 1401–1414. https://doi.org/10.1016/j.jclepro.2017.02.097

Brander, M., Burritt, R. L., & Christ, K. L. (2019). Coupling attributional and consequential life cycle assessment: A matter of social responsibility. *Journal of Cleaner Production*. Elsevier Ltd, *215*, 514–521. https://doi.org/10.1016/j.jclepro.2019.01.066

Cain, M., Lynch, J., Allen, M. R., Fuglestvedt, J. S., Frame, D. J., & Macey, A. H. (2019). Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *NPJ Climate and Atmospheric Science*. Springer US, *2*(1), https://doi.org/10.1038/s41612-019-0086-4

Camacho-Otero, J., Boks, C., & Pettersen, I. N. (2018). Consumption in the circular economy: A literature review. *Sustainability (Switzerland)*, *10*(8), https://doi.org/10.3390/su10082758

Carton, W. (2019). "Fixing" climate change by mortgaging the future: Negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode*, *51*(3), 750–769. https://doi.org/10.1111/anti.12532

Cherubini, F., Fuglestvedt, J., Gasser, T., Reisinger, A., Cavalett, O., Huijbregts, M. A. J., Johansson, D. J. A., Jørgensen, S. V., Raugei, M., Schivley, G., Strømman, A. H., Tanaka, K., & Levasseur, A. (2016). Bridging the gap between impact assessment methods and climate science. *Environmental Science & Policy*. Elsevier Ltd, *64*, 129–140. https://doi.org/10.1016/j.envsci.2016.06.019

Colvin, R. M., Kemp, L., Talberg, A., De Castella, C., Downie, C., Friel, S., Grant, W. J., Howden, M., Jotzo, F., Markham, F., & Platow, M. J. (2020). Learning from the climate change debate to avoid polarisation on negative emissions. *Environmental Communication*, *14* (1), 23–35. https://doi.org/10.1080/17524032.2019.1630463

Creutzig, F., Breyer, C., Hilaire, J., Minx, J., Peters, G. P., & Socolow, R. (2019). The mutual dependence of negative emission technologies and energy systems. *Energy and Environmental Science*. Royal Society of Chemistry, *12*(6), 1805–1817. https://doi.org/10.1039/c8ee03682a

Daggash, H. A., Fajardy, M., & Mac Dowell, N. (2019). Negative emissions technologies. In M. Bui & N. Mac Dowell (Eds.), *Carbon capture and storage*, (pp. 447–511). Royal Society of Chemistry. https://doi.org/10.1039/9781788012744-00447.

Ecofys. (2017). CCC Indicators to Track Progress in Developing GHG Removal Options. https://www.theccc.org.uk/publication/indicators-to-track-progress-in-developing-greenhouse-gas-removal-options/

Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy and Environmental Science*. Royal Society of Chemistry, *10*(6), 1389–1426. https://doi.org/10.1039/c7ee00465f

Fajardy, M., Patrizio, P., Daggash, H. A., & Mac Dowell, N. (2019). Negative emissions: Priorities for research and policy design. *Frontiers in Climate*, *1*(October), 1–7. https://doi.org/10.3389/fclim.2019.00006

Fearnside, P. M., Lashof, D. A., & Moura-Costa, P. (2000). Accounting for time in mitigating global warming through land-use change and forestry. *Mitigation and Adaptation Strategies for Global Change*, *5*(3), 239–270. https://doi.org/10.1023/A:1009625122628

Field, J. L., Richard, T. L., Smithwick, E. A. H., Cai, H., Laser, M. S., LeBauer, D. S., Long, S. P., Paustian, K., Qin, Z., Sheehan, J. J., Smith, P., Wang, M. Q., & Lynd, L. R. (2020). Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(36), 21968–21977. https://doi.org/10.1073/pnas.1920877117

Fridahl, M., Hansson, A., & Haikola, S. (2020). Towards indicators for a negative emissions climate stabilisation index: Problems and prospects. *Climate*, *8*(6), 75–22. https://doi.org/10.3390/CLI8060075

Frieden, D., Pena, N., & Bird, D. N. (2012). Incentives for the use of forest biomass: A comparative analysis of Kyoto Protocol accounting pre- and post-2012. *Greenhouse Gas Measurement and Management*, *2*(2–3), 84–92. https://doi.org/10.1080/20430779.2012.723513

Fuss, S., Jones, C. D., Kraxner, F., Peters, G. P., Smith, P., Tavoni, M., van Vuuren, D. P., Canadell, J. G., Jackson, R. B., Milne, J., Moreira, J. R., Nakicenovic, N., Sharifi, A., & Yamagata, Y. (2016). Research priorities for negative emissions. *Environmental Research Letters*, *11* (11), 115007. https://doi.org/10.1088/1748-9326/11/11/115007

Galik, C. S., & Jackson, R. B. (2009). Risks to forest carbon offset projects in a changing climate. *Forest Ecology and Management*, *257* (11), 2209–2216. https://doi.org/10.1016/j.foreco.2009.03.017

Galinato, G. I., Olanie, A., Uchida, S., & Yoder, J. K. (2011). Long-term versus temporary certified emission reductions in forest carbon sequestration programs. *Australian Journal of Agricultural and Resource Economics*, *55*(4), 537–559. https://doi.org/10.1111/j.1467-8489.2011.00555.x

Geden, O., & Löschel, A. (2017). Define limits for temperature overshoot targets. *Nature Geoscience*, *10*(12), 881–882. https://doi.org/10.1038/s41561-017-0026-z

Geden, O., Scott, V., & Palmer, J. (2018). Integrating carbon dioxide removal into EU climate policy: Prospects for a paradigm shift. *Wiley Interdisciplinary Reviews: Climate Change*, *9*(4), e521–e510. https://doi.org/10.1002/wcc.521

Gilbert, A., & Sovacool, B. K. (2015). Emissions accounting for biomass energy with CCS. *Nature Climate Change*. Nature Publishing Group, *5*(6), 496. https://doi.org/10.1038/nclimate2634

Goglio, P., Williams, A. G., Balta-Ozkan, N., Harris, N. R. P., Williamson, P., Huisingh, D., Zhang, Z., & Tavoni, M. (2020). Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. *Journal of Cleaner Production*. Elsevier Ltd, *244*(xxxx), 118896. https://doi.org/10.1016/j.jclepro.2019.118896

Goodwin, P., Williams, R. G., & Ridgwell, A. (2015). Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake. *Nature Geoscience*, *8*(1), 29–34. https://doi.org/10.1038/ngeo2304

Gough, C., Garcia-Freites, S., Jones, C., Mander, S., Moore, B., Pereira, C., Röder, M., Vaughan, N., & Welfle, A. (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Global Sustainability*, *1*, 1–9. https://doi.org/10.1017/sus.2018.3

Grönkvist, S., Möllersten, K., & Pingoud, K. (2006). Equal opportunity for biomass in greenhouse gas accounting of CO2 capture and storage: A step towards more cost-effective climate change mitigation regimes. *Mitigation and Adaptation Strategies for Global Change*, *11*(5–6), 1083–1096. https://doi.org/10.1007/s11027-006-9034-9

Guest, G., Bright, R. M., Cherubini, F., & Strømman, A. H. (2013). Consistent quantification of climate impacts due to biogenic carbon storage across a range of bio-product systems. *Environmental Impact Assessment Review*. Elsevier B.V., *43*, 21–30. https://doi.org/10.1016/j.eiar.2013.05.002

Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O., Johnson, R. K., Kastrup, U., Laconte, P., Lange, E., Novak, P., Paavola, J., Reenberg, A., van den Hove, S., Vermeire, T., Wadhams, P., & Searchinger, T. (2012). Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy*. Elsevier, *45*(5), 18–23. https://doi.org/10.1016/j.enpol.2012.02.051

Harper, A. B., Powell, T., Cox, P. M., House, J., Huntingford, C., Lenton, T. M., Sitch, S., Burke, E., Chadburn, S. E., Collins, W. J., Comyn-Platt, E., Daioglou, V., Doelman, J. C., Hayman, G., Robertson, E., van Vuuren, D., Wiltshire, A., Webber, C. P., Bastos, A., … Shu, S.

(2018). Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications*, *9*(1), https://doi.org/10.1038/s41467-018-05340-z

Höhne, N., & Blok, K. (2005). Calculating historical contributions to climate change - Discussing the "Brazilian proposal". *Climatic Change*, *71*(1–2), 141–173. https://doi.org/10.1007/s10584-005-5929-9

Iordan, C.-M., Hu, X., Arvesen, A., Kauppi, P., & Cherubini, F. (2018). Contribution of forest wood products to negative emissions: Historical comparative analysis from 1960 to 2015 in Norway, Sweden and Finland. *Carbon Balance and Management*. Springer International Publishing, *13*(1), https://doi.org/10.1186/s13021-018-0101-9

IPCC. (2018). *IPCC special report on the impacts of global warming of 1.5°C - Summary for policy makers*. http://www.ipcc.ch/report/sr15/

IPCC. (2019). *Overivew of 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. https://www.ipcc.ch/site/assets/uploads/2018/05/Details_Selection_of_Authors.pdf

IPCC. (2006). *IPCC guidelines for national greenhouse gas inventories* (H. S. Eggleston et al., Eds). Intergovernmental Panel on Climate Change.

Johnston, C. M. T., & Radeloff, V. C. (2019). Global mitigation potential of carbon stored in harvested wood products. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(29), 14526–14531. https://doi.org/10.1073/pnas.1904231116

Jonker, J. G. G., Junginger, M., & Faaij, A. (2014). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *GCB Bioenergy*, *6*(4), 371–389. https://doi.org/10.1111/gcbb.12056

Kemper, J. (2015). Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control*, *40*, 401–430. https://doi.org/10.1016/j.ijggc.2015.06.012

Kirschbaum, M. U. F. (2014). Climate-change impact potentials as an alternative to global warming potentials. *Environmental Research Letters*, *9*(3), 034014. https://doi.org/10.1088/1748-9326/9/3/034014

Knight, F. (1933). *Risk, uncertainty, and Profit*. London School of Economics and Political Science.

Lamers, P., & Junginger, M. (2013). The "debt" is in the detail : A synthesis of recent temporal forest carbon analyses on woody biomass. 373–385. https://doi.org/10.1002/bbb.

Larkin, A., Kuriakose, J., Sharmina, M., & Anderson, K. (2018). What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Climate Policy*. Taylor & Francis, *18*(6), 690–714. https://doi.org/10.1080/14693062.2017.1346498

Lawrence, M. G., Schäfer, S., Muri, H., Scott, V., Oschlies, A., Vaughan, N. E., Boucher, O., Schmidt, H., Haywood, J., & Scheffran, J. (2018). Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals. *Nature Communications*. Springer US, *9*(1), https://doi.org/10.1038/s41467-018-05938-3

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R. (2010). Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environmental Science & Technology*, *44*(8), 3169–3174. https://doi.org/10.1021/es9030003

Lilliestam, J., Bielicki, J. M., & Patt, A. G. (2012). Comparing carbon capture and storage (CCS) with concentrating solar power (CSP): potentials, costs, risks, and barriers. *Energy Policy*. Elsevier, *47*, 447–455. https://doi.org/10.1016/j.enpol.2012.05.020

Lin, A. C. (2018). Carbon dioxide removal after Paris. *Ecology Law Quarterly*, *45*(3), 533–582. https://doi.org/10.15779/Z386M3340F

Lomax, G., Workman, M., Lenton, T., & Shah, N. (2015). Reframing the policy approach to greenhouse gas removal technologies. *Energy Policy*. Elsevier, *78*, 125–136. https://doi.org/10.1016/j.enpol.2014.10.002

Mantripragada, H. C., Zhai, H., & Rubin, E. S. (2019). Boundary Dam or Petra Nova – which is a better model for CCS energy supply? *International Journal of Greenhouse Gas Control*. Elsevier, *82*(October 2018), 59–68. https://doi.org/10.1016/j.ijggc.2019.01.004

McLaren, D. (2012a). A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection*. Institution of Chemical Engineers, *90*(6), 489–500. https://doi.org/10.1016/j.psep.2012.10.005

McLaren, D. (2012b). *Governance and equity in the development and deployment of negative emissions technologies*. http://www.earthsystemgovernance.org/lund2012/LC2012-paper237.pdf

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., & Markusson, N. O. (2019). Beyond "Net-zero": A case for separate targets for emissions Reduction and negative emissions. *Frontiers in Climate*, *1*(August), 1–5. https://doi.org/10.3389/fclim.2019.00004

Mcmanus, M. C., & Taylor, C. M. (2015). The changing nature of life cycle assessment. *Biomass and Bioenergy*. Elsevier Ltd, 13–26. https://doi.org/10.1016/j.biombioe.2015.04.024

McMullin, B., Price, P., Jones, M. B., & McGeever, A. H. (2020). Assessing negative carbon dioxide emissions from the perspective of a national "fair share" of the remaining global carbon budget. *Mitigation and Adaptation Strategies for Global Change*, https://doi.org/10.1007/s11027-019-09881-6

Meadowcroft, J. (2013). Exploring negative territory carbon dioxide removal and climate policy initiatives. *Climatic Change*, *118*(1), 137–149. https://doi.org/10.1007/s10584-012-0684-1

Mitchell, S. R., Harmon, M. E., & O'Connell, K. E. B. (2012). Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy*, *4*(6), 818–827. https://doi.org/10.1111/j.1757-1707.2012.01173.x

National Academies of Science Engineering and Medicine. (2019). *Negative emissions technologies and reliable sequestration: A research Agenda, negative emissions technologies and reliable sequestration*. The National Academies Press. https://doi.org/10.17226/25259.

Neeff, T., & Ascui, F. (2009). Lessons from carbon markets for designing an effective REDD architecture. *Climate Policy*, *9*(3), 306–315. https://doi.org/10.3763/cpol.2008.0584

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., Lamb, W. F., Minx, J. C., Rogers, S., & Smith, P. (2018). Negative emissions - part 3: Innovation and upscaling. *Environmental Research Letters*, *13*(6), https://doi.org/10.1088/1748-9326/aabff4

Neubauer, S. C., & Megonigal, J. P. (2015). Moving beyond global warming potentials to quantify the climatic role of ecosystems. *Ecosystems*. Springer US, *18*(6), 1000–1013. https://doi.org/10.1007/s10021-015-9879-4

Obersteiner, M., Bednar, J., Wagner, F., Gasser, T., Ciais, P., Forsell, N., Frank, S., Havlik, P., Valin, H., Janssens, I. A., Peñuelas, J., & Schmidt-Traub, G. (2018). How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, *8*(1), 7–10. https://doi.org/10.1038/s41558-017-0045-1

Oraee-Mirzamani, B., Cockerill, T., & Makuch, Z. (2013). Risk assessment and management associated with CCS. *Energy Procedia*. Elsevier B.V., *37*, 4757–4764. https://doi.org/10.1016/j.egypro.2013.06.385

Peters, G. P., & Geden, O. (2017). Catalysing a political shift from low to negative carbon. *Nature Climate Change*. Nature Publishing Group, *7*(9), 619–621. https://doi.org/10.1038/nclimate3369

Plassmann, K. (2012). Accounting for carbon removals. *Nature Climate Change*. Nature Publishing Group, *2*(1), 4–6. https://doi.org/10.1038/nclimate1333

Plevin, R. J., Delucchi, M. A., & Creutzig, F. (2014). Using attributional life cycle assessment to estimate climate-change mitigation benefits Misleads policy makers. *Journal of Industrial Ecology*, *18*(1), 73–83. https://doi.org/10.1111/jiec.12074

Rabl, A., Benoist, A., Dron, D., Peuportier, B., Spadaro, J. V., & Zoughaib, A. (2007). How to account for CO2 emissions from biomass in an LCA. *The International Journal of Life Cycle Assessment*, *12*(5), 281–281. https://doi.org/10.1065/lca2007.06.347

Reid, W. V., Ali, M. K., & Field, C. B. (2020). The future of bioenergy. *Global Change Biology*, *26*(1), 274–286. https://doi.org/10.1111/gcb.14883

Rickels, W., Merk, C., Reith, F., Keller, D. P., & Oschlies, A. (2019). (Mis)conceptions about modeling of negative emissions technologies. *Environmental Research Letters*. IOP Publishing, *14*(10), 104004. https://doi.org/10.1088/1748-9326/ab3ab4

RS-RAEng. (2018). *Greenhouse Gas Removal*. https://royalsociety.org/~/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

Scott, V., Haszeldine, R. S., Tett, S. F. B., & Oschlies, A. (2015). Fossil fuels in a trillion tonne world. *Nature Climate Change*. Nature Publishing Group, *5*(5), 419–423. https://doi.org/10.1038/nclimate2578

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., Likens, G. E., Lubowski, R. N., Obersteiner, M., Oppenheimer, M., Philip Robertson, G., Schlesinger, W. H., & David Tilman, G. (2009). Fixing a critical climate accounting error. *Science*, *326*(October), 527–528. https://doi.org/10.1126/science.1178797

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E., & Tubiello, F. (2014). Agriculture, Forestry and other land Use (AFOLU). In Edenhofer O., Pichs-Madruga R., Sokona Y., Farahani E., Kadner S., Seyboth K., Adler A., Baum I., Brunner S., Eickemeier P., Kriemann B, Savolainen J., Schlomer S., Von Stechow C., Zwickel T., & Minx J. (Eds.), *Climate change 2014: mitigation of climate change. Contribution of working group III to the Fifth assessment report of the intergovernmental panel on climate change* (pp. 811–922). Cambridge University Press.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., … Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*. Nature Publishing Group, a Division of Macmillan Publishers Limited. All Rights Reserved, *6*(1), 42. https://doi.org/10.1038/nclimate2870

Smith, P., & Friedmann, J. (2017). Briding the Gap - carbon dioxide removal. In Olhof A. & Christensen J. (Eds.), *The emissions Gap report* (pp. 58–66). UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/22108/EGR_2017_ch_7.pdf?isAllowed=y&sequence=1

Stavrakas, V., Spyridaki, N. A., & Flamos, A. (2018). Striving towards the deployment of bio-energy with carbon capture and storage (BECCS): A review of research priorities and assessment needs. *Sustainability (Switzerland)*, *10*(7), https://doi.org/10.3390/su10072206

Subak, S. (2003). Replacing carbon lost from forests: An assessment of insurance, reserves, and expiring credits. *Climate Policy*, *3*(2), 107–122. https://doi.org/10.3763/cpol.2003.0315

Talberg, A., Christoff, P., Thomas, S., & Karoly, D. (2018). Geoengineering governance-by-default: An earth system governance perspective. *International Environmental Agreements: Politics, Law and Economics*. Springer Netherlands, *18*(2), 229–253. https://doi.org/10.1007/s10784-017-9374-9

Tanzer, S. E., & Ramírez, A. (2019). When are negative emissions negative emissions? *Energy and Environmental Science*, *12*(4), 1210–1218. https://doi.org/10.1039/c8ee03338b

Timma, L., & Parajuli, R. (2019). Time Dynamics in Life Cycle Assessment-Exemplified By a Case Study on Biorefineries. *Http://Www.Sdewes.Org/Jsdewes/Reviewers.Php*, (May), 27–30. https://pure.au.dk/ws/files/159309859/4DO.5.2_paper_27th_2019.pdf?fbclid=IwAR3AgpP7JlixbXKrmNuj9dafSHaf0wTkFWbhMfsGmuvhfNUozeV1BwZhDvw

Tokarska, K. B., & Zickfeld, K. (2015). The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environmental Research Letters*. IOP Publishing, *10*(9), https://doi.org/10.1088/1748-9326/10/9/094013

Torvanger, A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. *Climate Policy*. Taylor & Francis, *19*(3), 329–341. https://doi.org/10.1080/14693062.2018.1509044

Trevizan, F., Cozman, F., & de Barros, L. (2007). Planning under Risk and Knightian Uncertainty. *Proceedings of the 20th International Joint Conference on Artifical Intelligence*. San Francisco, USA: Morgan Kaufmann Publishers Inc, pp. 2023–2028.

UK Parliament. (2019). *The Climate Change Act 2008 (2050 Target Amendment) Order 2019*. http://www.legislation.gov.uk/ukdsi/2019/9780111187654/pdfs/ukdsi_9780111187654_en.pdf

UNFCCC. (2015). *Paris Agreement*, *Paris Agreement*. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

van Vuuren, D. P., Deetman, S., van Vliet, J., van den Berg, M., van Ruijven, B. J., & Koelbl, B. (2013). The role of negative CO2 emissions for reaching 2 °C-insights from integrated assessment modelling. *Climatic Change*, *118*(1), 15–27. https://doi.org/10.1007/s10584-012-0680-5

Wolfswinkel, J. F., Furtmueller, E., & Wilderom, C. P. M. (2013). Using grounded theory as a method for rigorously reviewing literature. *European Journal of Information Systems*, *22*(1), 45–55. https://doi.org/10.1057/ejis.2011.51

WRI. (2014). *Greenhouse Gas Protocol: Policy and Action Standard*. World Resources Institute.

Zakkour, P., Kemper, J., & Dixon, T. (2014). Incentivising and accounting for negative emission technologies. *Energy Procedia*, *63*, 6824–6833. https://doi.org/10.1016/j.egypro.2014.11.716

Zanchi, G., Pena, N., & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, *4*(6), 761–772. https://doi.org/10.1111/j.1757-1707.2011.01149.x

Zickfeld, K., MacDougall, A. H., & Damon Matthews, H. (2016). On the proportionality between global temperature change and cumulative CO2 emissions during periods of net negative CO2 emissions. *Environmental Research Letters*. IOP Publishing, *11*(5), https://doi.org/10.1088/1748-9326/11/5/055006