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Carbon accounting without life cycle analysis

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Life cycle analysis (LCA) is deeply embedded in carbon accounting. LCA is valuable for qualitatively understanding technologies' environmental footprints. However, ambiguities and insatiable data requirements make it ill-suited for quantitative analysis. Fortunately, accounting without LCA is possible, for example, by demanding that for every ton of carbon coming out of the ground, another ton must be sequestered. This "Carbon Takeback Obligation" (CTBO) policy would eliminate the need for tracking carbon through supply chains. With all supply chains already carbon balanced, it is sufficient to quantify the amount of carbon sequestered without subtracting upstream emissions. Our modeling shows that once full carbon neutrality is demanded, market forces alone will eliminate counterproductive sequestration technologies, approaches that release more CO_2 than they store. Complications arise during the transition where some carbon extraction is not yet balanced out by sequestration, as under some policies, counterproductive technologies could be introduced solely to game the system. We explore the economics of four transition pathways: a simple CTBO, a CTBO combined with permits required for all unbalanced carbon, a CTBO combined with a futures market, and permit-future hybrid schemes. A simple CTBO that does not add an economic burden on unmitigated carbon would incentivize low-cost, counterproductive technologies. Contrastingly, a CTBO policy that includes permits and/or futures will render such technologies uneconomical at any point in the transition. A policy with controlled futures would allow for rapid permit phaseout. Hybrid systems could lessen the initiation shock and bridge the transition time when market demand exceeds sequestration capacity.

Broader context

Achieving net zero carbon dioxide emissions through carbon sequestration will require tracking carbon. Current carbon accounting practices use Life Cycle Analysis (LCA) to trace emissions through supply chains using the scope 1, 2, and 3 emission accounting framework. The need for LCA emerges because of the hidden decision that neither the fossil carbon producer nor the end consumer should be responsible for emissions. As a result, LCA tries to decide which businesses in the supply chains are responsible. However, LCA cannot make such attributions consistently and fairly because it is a qualitative tool used for quantitative purposes. Fortunately, carbon accounting without LCA is possible, for example, by only focusing on carbon and demanding that for every ton of carbon coming out of the ground (*e.g.*, coal, oil, gas, calcinated limestone), another ton must be sequestered. Known as the "Carbon Takeback Obligation" (CTBO), such a policy eliminates the need for tracking carbon through supply chains. Market forces eliminate counterproductive sequestration technologies, approaches that release more CO_2 than they store, at full carbon neutrality. However, the transition can be gamed, so interim guardrails like permits or futures must be introduced. LCAs are insufficient; subsidies and tax credits distort the market.

Introduction

Achieving net-zero or net-negative carbon dioxide (CO_2) emissions will require keeping track of and accounting for carbon, both in terms of carbon produced and carbon sequestered. This requires universal accounting standards for carbon extraction, CO_2 removal, and sequestration that must be quantified and certified. Current best accounting practices rooted in Life Cycle Analysis (LCA) have difficulties achieving the necessary accuracy. The reliance on LCA, or carbon footprinting (CFP), for CO_2 accounting introduces all the uncertainties and ambiguities inherent in complex intertwined global supply chains.

LCA is a tool that traces material flows, emissions, and environmental damages through supply chains. It requires detailed data on vast swaths of the economy to determine the

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environmental impact, including the CO_2, of an entity, product, or service.[1] CFP is a more limited form of LCA focused on determining greenhouse gas emissions, typically reported as CO_2 equivalent (CO_2-eq) emissions. LCAs and CFPs guide product, service, and process design. However, trying to quantitatively untangle the CO_2-eq emission contributions from all supply chains ending in a particular product is notoriously difficult. This raises the question of whether LCA or CFP techniques offer the best approach to carbon accounting. In 1993, Udo de Haes feared that ''LCA may become too dominant, superseding other well-functioning policy''.[2] This fear may have been prescient, as today, LCA and CFP have surged in use as the ''best practice'' for carbon accounting, crowding out other approaches. LCA is used for greenhouse gas inventories and certifying carbon sequestration.

While LCA and CFP are powerful methods to understand a system qualitatively,[3] in this paper, we make the case that neither LCA nor CFP are adequate quantitative accounting tools for the foundation of a net-zero climate policy. Their well-known subjectivity, inaccuracy, incomparability, complexity, and incompleteness make it a challenge, if not impossible, to assign carbon liabilities accurately.[2,4–8] We further make the case that given the right regulatory setting, LCA is not necessary for carbon accounting in the certification of carbon sequestration. We propose a more reliable approach that avoids incorporating LCA techniques into accounting tools.

The current uses of LCA

Reaching net-zero

The world committed under the Paris Agreement to hold the increase in the global average temperature to below 2 °C above pre-industrial levels.[9] This commitment implies that the world has a finite carbon allowance, which the Intergovernmental Panel on Climate Change (IPCC) calls the remaining carbon budget.[10] Although this budget has uncertainties,[11,12] it has effectively drawn attention to new fossil fuel infrastructure and their financial investments.[13] The IPCC and the commitments by most nations recognize carbon dioxide (CO_2) as the fundamental source of climate change, even if other greenhouse gases, like methane and nitrous oxide, also play a role.

Under a finite budget, the rate of all CO_2 emissions must go to zero or be canceled out by activities that sequester an equivalent amount of carbon. There are only three options: (1) eliminate fossil fuels through substitution, increased efficiency, and reduced consumption, (2) prevent CO_2 from being emitted at the source through point source capture and subsequent sequestration, and (3) remove unabated and legacy carbon from the environment through carbon dioxide removal (CDR).

It is unlikely that any one of these options will dominate climate stabilization. The last 30% of emissions avoidance or substitution will be challenging due to cost and technology availability.[14] Point source capture is not an option for distributive uses of fossil carbon[14] and is also not 100% efficient.[15] Apart from entirely stopping activities that use fossil carbon or producing synthetic fuels from other carbon sources, the remaining option is neutralizing the emissions through CDR. In essence, CDR must be purchased for every emission that cannot be eliminated. This requires an inventory of the remaining CO_2 emissions and an accounting methodology that makes it possible to generate certificates of sequestration to represent the carbon sequestered.

When the amount of carbon recorded by a registry of sequestered carbon catches up with a registry of fossil fuels like the Global Registry of Fossil Fuels,[16] the world has achieved a net-zero carbon economy. This situation requires careful tracking of carbon fluxes, either emissions and removals *via* CDR or carbon injection (*i.e.*, fossil fuel extraction) and sequestration from point sources and the environment. Current discussions suggest that LCA and CFP will be deeply involved in the associated accounting.

Inventories

Emissions are tracked through greenhouse gas inventories in the form of CFP that estimates total absolute emissions minus removals. How emissions are compiled differs based on the organizational level (nation, community, or corporation). At the national level, the IPCC accounting guidelines[17,18] recommend compiling emissions based on stationary, mobile, and fugitive emissions in the energy sector; industrial processes and product use; agriculture, forestry, and other land use; and waste. At the community level, the ICLEI – Local Governments for Sustainability USA[19] recommends compiling emissions based on sources (*e.g.*, industrial stationary combustion sources) and activities (*e.g.*, use of electricity by the community) to capture the total direct and indirect emissions, and the carbon efficiency of a community, respectively. At the corporate level, The Greenhouse Gas Protocol[20] advises compiling emissions based on scope 1, 2, and 3 emissions. Scope 1 emissions are direct emissions from sources controlled or owned by an organization. Scope 2 emissions are indirect emissions associated with purchasing electricity, steam, heat, or cooling. Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organization but that the organization indirectly impacts through its value chain.

The use of scopes for the compilation is a growing practice. On one level, it is growing as more and more corporations are pledging net-zero goals and using the standards devised by The Greenhouse Gas Protocol initiative.[20] According to the Climate Disclosure Project, the Greenhouse Gas Protocol is the most widely used accounting standard.† On another level, the scopes framework is increasingly recommended for community accounting. For example, The Greenhouse Gas Protocol initiative also produced the Global Protocol for Community Scale Emissions Inventories,[21] defining scopes based on geography rather than based on control. In doing so, the geographical scopes can be aggregated nationally. Switching to geographical

† In 2016, 92% of Fortune 500 companies responding to the CDP used GHG Protocol directly or indirectly.

scopes solved one of the major pitfalls with control-based scopes that could not be aggregated from one level to another.[22]

Certifying carbon sequestration

The methods to account for project-based emission reduction and avoidance have been explored at length elsewhere.[23–28] This paper concerns carbon sequestration. Because both point source capture and CDR require sequestration into a reservoir where the carbon will be held, sequestration must be certified. Carbon accounting must quantify the amounts sequestered. At least 125 standards of carbon removal have been developed worldwide for accounting,[29] all of which rely on some form of LCA or CFP. Notably, emission reduction and avoidance credits also rely on LCA.

An example where LCA accounting could apply is direct air capture with subsequent injection of the captured CO_2 into a deep saline aquifer. A different example would measure the amount of carbon stored in an agroforestry project for carbon sequestration. In both cases, LCA accounting would have to establish the net carbon sequestered after subtracting the CO_2-eq emissions incurred in the operations and supply chains. This requires large datasets to characterize the entire supply chain.

Issues with using LCA as a quantitative tool

LCA is useful in understanding the carbon footprint of an activity qualitatively. It is far more difficult to obtain accurate carbon footprints. Nevertheless, many organizations track their emissions through such LCAs and treat them as quantitative tools. Exploring the use of LCA for quantitative carbon accounting reveals issues across LCA methods (*e.g.*, attributional, consequential, input–output, and process-based).[30] Despite best efforts, these issues have remained unresolved since the conception of the LCA because they are features of the methodology.[2] These issues include the need for detailed material flow data across the entire economy, which is impractical; high cost and labor penalties for collecting data and continuous updating of information; subjectivity in boundary setting and temporal preference; inability to reduce variance in results; incompatibility of results from different systems; the frequent need for counterfactuals; and inaccuracy in inventorying emissions. These issues of LCA affect both inventory accounting and certification of carbon sequestration.

Any accounting tool will require data. However, by demanding information about the associated supply chains, LCA relies on gathering vast amounts of data of many different types from many sources.[4,7] This imposes a penalty in terms of cost and labor for collecting quality data. Costs and quality are tradeoffs suggesting that many LCAs are hindered by low data quality. Furthermore, because of the breadth of data required, every LCA will depend on the quality and completeness of the work of others, which is difficult to verify and often involves different standards in different countries. LCA has limited control over the quality of the input data without international efforts to produce specialized, standardized, and reusable databases specific to the LCA method.[7,31] By drawing cautious conclusions, LCA practitioners compensate for poor-quality data.[32] Another challenge is frequent changes in the workings of the supply chains starting from substitutions in the energy supplies through changes in consumer behavior. Therefore, LCA data cannot be considered static and must be continuously updated.

In addition to data issues, LCA is a subjective method in various ways. Performing an LCA requires drawing boundaries, whether the analysis uses an input–output or process-based approach. Despite guidance on approaching boundary setting, what to include or exclude remains a decision.[8] These decisions depend on the researcher's motivation, data availability, and considerations of costs and labor.[33] Truncation errors, the numeric gap between the reported and actual figures, arise from boundary setting, meaning that not all emissions are accounted for.[34] For example, Crawford found that truncation errors in process analysis could amount to 87% compared to approaches that combine input–output and process-based approaches, the so-called hybrid approaches.[35]

Calls for hybrid approaches solve some boundary selection issues but introduce others. Namely, the need for even more data of good quality[36] – one of the critical issues with LCA in the first place.[35] Accounting ought to be objective and repeatable to support verification, which is untrue if LCA methodologies allow *ad hoc* choices. Even if choices are gradually standardized, they are standardized in a political environment that creates winners and losers. Someone's scope 1 is someone else's scope 2 or 3. While some of this may be unavoidable, LCA tends to exacerbate this problem.

Moreover, performing an LCA for the certification of carbon sequestration introduces a time preference for the variables used in the accounting. For example, the value of temporary sequestration is still debated.[37–39] The shorter the time preference, the higher the value of temporary sequestration.[40] For example, in their LCA of building materials, Mequignon *et al.* had to settle on a time preference to calculate the carbon footprint of building materials and how they are affected by the lifespan of the building.[41] Lack of consensus on time preference from standards or in the academic literature[5,7] is an argument against using an accounting method that requires choosing a time preference.

Furthermore, by putting different greenhouse gases on the same footing through the global warming potential (GWP), LCAs introduce more subjectivity and uncertainty. GWPs cannot be directly measured but are constructs of climate computer models and consequently change with every IPCC assessment.[42] In addition to these conceptual and methodological problems, GWPs introduce strong time preferences into these comparisons.[6,43–47]

Another issue with the verifiability of LCA is how to define a baseline which is often necessary for determining avoided emissions in sequestration and inventory accounting. The least contentious baseline in inventory accounting is the inventory at the start of accounting. However, it is generally not true that emissions would not change absent climate action. This forces the LCA practitioner to create a baseline based on a counterfactual scenario considering political, economic, technological, and social changes. As a result, setting the baseline can be challenging.[6] Estimates of net sequestration typically involve counterfactuals because the net amount of carbon sequestered depends on assumptions about what would have happened without these activities. What would have happened to the land if there had not been any agroforestry? Could the renewable electricity applied to the direct air capture system be better used to avoid the firing of a fossil fuel-powered power plant?

For example, Hawkins *et al.* performed an LCA to account for carbon sequestered in different construction materials.[48] They developed two ''what-if'' scenarios to estimate carbon sequestration in timber. One optimistically included the regrowth of the original forest, and one pessimistically did not. The authors found that the LCA resulted in net carbon sequestration in the former and a net increase in emissions in the latter. Verifiers could not determine the sign of the effect without recourse to hindsight. Over the decades, relying on counterfactual baselines has been considered impossible to verify because counterfactuals cannot be observed.[49–51] Counterfactuals get less accurate over time because they are ''alternate timelines'' instead of projections into the future that can be adjusted as the future catches up to the projection.

For LCA to get more accurate, the amount and precision of data required grows very rapidly. There are indications that improving LCA accuracy already encounters rapidly diminishing returns. For example, the debate over the carbon footprint of corn ethanol, which is like certifying avoided carbon in carbon sequestration, has not improved over decades. Systematic issues involving the subjective choice of boundaries and lack of accurate data contribute to the problem. A review of early estimates ranged from 55–125 gCO_2-eq MJ^{-1}, representing a 32% reduction to a 20% increase in emissions in using ethanol compared to gasoline.[52] Different choices of boundaries in part explain the large span. In a later review based on updated datasets and technological improvements, Liska *et al.* reported the best estimated intensity of 38–48 gCO_2-eq MJ^{-1}, representing a 48–59% reduction in emission.[53] Even though this approach settled on a particular set of boundaries, the range is still 23% of its median value and, therefore, inadequate for quantitative accounting. From 2009 onwards, the impact of land use change started to be incorporated into the LCA, raising the carbon intensity and drawing questions about which impacts should be included.[54] In a recent review, Scully *et al.* reported a range of 37.6–65.1 gCO_2-eq MJ^{-1} (a range of 54%)[55] which was then questioned by Spawn-Lee *et al.* based on their choices regarding the land use impact.[56]

There are ways of reducing uncertainties. Collecting more data with different types of equipment and careful sensitivity analysis[4] can help constrain the uncertainty range. A major challenge with LCA is that people's worldviews affect how boundaries tend to be drawn. Therefore, better data alone cannot constrain the range, and no model can produce a definitive assessment[6] – only the reconciliation of world views.[57] Estimating the net climate effects of alternative actions engender multiple perspectives and evaluation frameworks, yielding divergent outcomes that can be equally plausible.[58]

The range of values also raises the question of what results to use for the certification of carbon sequestration. Several studies have pointed out that carbon removal must remove more than it emits,[59,60] which they call the ''net negativity'' criteria. In this paper, we use the term ''counterproductive'' to indicate that a sequestration method sequesters less carbon than it causes to emit. Such counterproductive methods are net carbon positive and would exacerbate climate change. To ascertain carbon negativity, all emissions upstream and downstream of the process must be quantified,[60] including those resulting from market changes.[59] As previously discussed, tracing those emissions through the entire supply chain is a considerable challenge and fraught with ambiguity.

The subjectivity and uncertainty also call into question whether the results of an LCA on two different types of methods (*e.g.*, DACS and afforestation) are comparable. Some boundary choices like cradle-to-grave can help in cross-comparisons. Others may lend themselves to obfuscation. In a review of 36 biochar LCAs, Terlouw *et al.* found that GWP impacts could not be compared since each LCA used specific boundary conditions, different functional units, and parameters.[61] If agreement cannot be reached for different analyses within a single sequestration technology, comparisons amongst vastly different technologies are even less likely to be useful. In an LCA study of different types of materials in automotive applications, Mair-Bauernfeind *et al.* concluded they could not make recommendations on which impact categories were relevant, let alone which ones to choose.[62] They concluded that the selection choices were based on the researcher's motivations, yielding incomparable results. Gregory *et al.* compared hand drying systems and found that conclusions depended on the treatment of uncertainty.[63] Impacts will invariably be different for various types of carbon sequestration activities. To treat systems equally, all possible impacts and uncertainty would need to be included, adding complexity and uncertainty to quantitative accounting. Truncating the list of impacts opens the door to vested interests questioning the equality of the certification outcome across technologies.

Over the years, many proposals and valiant efforts have been made to standardize LCA. Significant improvements were made with the Society of Environmental Toxicology and Chemistry (SETAC) in the 1990s[2], the Global CO_2 Initiative in the 2010s[3], and what will come out of the International CCU Assessment Harmonization Group. Yet, despite the efforts, the issues of subjectivity, inaccuracy, incomparability, and incompleteness discussed above persist (and will continue to persist) because of the nature of the tool. LCA has limitations that may be acceptable when the goal is qualitative (*i.e.*, gathering information on a process) but not quantitative (*i.e.*, for certification of sequestration or inventory accounting). The tool is complex, and the complexity is increasing.[31] More data would help some issues[64] but will hit limits.

Upstream *vs.* downstream

The need for LCA is predicated on the implicit decision that neither the fossil fuel producer nor the end consumer should be held responsible for the carbon released. Consequently, responsibility must be put on businesses in the supply chains connecting fossil fuel production with end consumers. This naturally leads to a struggle to assign scope 1, 2, and 3 emissions to the various businesses that produce goods and services. With that approach, it is nearly unavoidable that LCA must become the ultimate arbiter of who is held responsible for the excess carbon flowing through the supply chains and the associated emissions of greenhouse gases. Unfortunately, LCA cannot make such attributions quantitatively, consistently, and equitably. According to Lackner and Wilson, it also leaves ''undesirable room for special interests'' to be included in control.[65]

Moving responsibility all the way upstream has many advantages.[65,66] It makes accounting much easier. Carbon coming out of the ground is mostly already well measured in national databases, as much of it is a commercial commodity subject to tax rules or other fees like royalties that necessitate quantification. It involves a much smaller number of entities than the alternative to put the responsibility on the physical emitter of greenhouse gases and could also be done without recourse to LCA. The sheer number of small emitters renders accounting at the emission point impractical. The current system, which pins the responsibility on the entities that largely pass the carbon through, poses the most accounting difficulties and requires LCA. The introduction of accounting scopes reflects these difficulties. Companies are supposed to keep track of scope 2 and 3 emissions which they have no control over. Scope 3 emissions can reach 6–90% of a sector's emissions,[67–71] which for the fossil fuel industry equals to more than 92% of the world's CO_2 emissions.[72] In our view, the simplification of upstream accounting justifies separating carbon accounting from greenhouse gas accounting.

Upstream accounting reduces the dependence on methods that are subjective, difficult to apply, costly, require vast amounts of data, and yet result in significant uncertainty. Such methods create risks for the storage operators, greenwashing from those not playing fair, and a deflection of responsibility from those who ought to be cleaning up the carbon mess. Unclear rules will make it easy for claims to be made without a straightforward way to stop fraud. These issues will limit our ability to reach net zero. Both from the perspective of the attribution of responsibility and the quantification of carbon sequestration for certification, which will then support net-zero claims. Those are some reasons for limiting LCA to qualitative planning and design roles and moving quantitative accounting upstream.

A simpler, more accurate, and more comprehensive approach

Description

A simpler approach to balancing the anthropogenic carbon budget starts by focusing on carbon, not other greenhouse gases, and demanding that for any carbon released, an equivalent amount must be permanently sequestered.[66] By carbon release, we mean all carbon extracted from the fossil pool (*e.g.*, oil, coal, natural gas, calcination of limestone) and all carbon released from sequestration, not the CO_2 emissions by the end consumer. To balance the carbon budget, all fossil carbon brought to the surface must be matched by an equivalent amount of carbon collected from the surface environment and sequestered.[65] This carbon could be taken directly from the environment (*e.g.*, CDR) or fossil carbon intercepted at a point source of consumption (*e.g.*, power plant flue stack). This is an idea gaining traction under the name ''Carbon Takeback Obligation (CTBO)''.[73–75]

The collected carbon would have to be stored in a well-delineated reservoir. The carbon addition to this reservoir must be demonstrated, documented, and its persistence monitored. This would form the basis of methodologies that account for carbon sequestration.[76,77] Ideally, sequestration would be effectively permanent; therefore, short-term sequestration would be required to be transferred to a subsequent more long-term reservoir.[66,77] Verified sequestration would generate a certificate of sequestration that could be used to cancel out carbon extraction and carbon release from sequestration, including deliberate extraction, accidental extraction (*e.g.*, methane lost from a coal mine), byproduct extraction (*e.g.*, as in the case of calcination of limestone), and losses from sequestration.

A non-permanent sequestration site would have to be a monitored reservoir, for which the storage operator agrees that any loss of carbon from the reservoir is treated like any other carbon release and thus must be matched by a new certificate of sequestration.[66,77] In a scenario that relies on short-term sequestration, carbon removal would remain an ongoing operation even after all fossil fuel extraction ceased. Certification would be an ongoing effort with checks and guarantees.

It is difficult to envision a scenario in which transfers from short-term sequestration are guaranteed for the millennia required to balance the carbon budget.[78] Therefore, all carbon should eventually transfer to permanent sequestration to avoid the cost of continuous monitoring and re-sequestration and prevent a termination shock. Such sequestration must be declared permanent immediately or after some trial period based on scientific principles, which is the only assurance one can give on timescales exceeding human civilization.[79] The advantage of allowing non-permanent monitored sequestration with an associated guarantee of re-sequestration is that it allows a more rapid approach to carbon neutrality and net negative carbon economies. The advantage of permanent sequestration is that it stops the long-term liabilities of storage operators. This move to permanent sequestration is nearly unavoidable. The practical requirement of sequestration duration, which is to be guaranteed by a certificate of sequestration, is tens of thousands of years and thus well beyond the lifetime of human institutions.

Rationale

Balancing carbon as it comes out of the ground is inherently simple. Specifically, we show later in this paper that, once fully implemented, such a system does not require LCA in its monitoring and accounting scheme. Focusing on carbon simplifies the problem in two ways.

First, we can avoid using the GWP to create equivalence between greenhouse gases. Methane and nitrous oxide are far more powerful greenhouse gases than CO_2, but the quantities are much smaller. Moreover, they act very differently. CO_2, once put out, stays in the surface environment for tens of thousands of years.[80] There is little to be gained by mitigating other greenhouse gases before CO_2 emissions have reached near zero.[81] Carbon extraction and release are concentrated in a few places making accurate accounting relatively easy. In contrast, methane and nitrous oxide emissions are highly diffuse, making accounting inherently difficult. By separating the accounting of the largest source of greenhouse gases from the rest, we can take advantage of the inherently easier accounting. By making it easier to balance the carbon budget, we increase the value of curtailing other greenhouse gases, especially methane. In a world where the CO_2 level keeps rising, worrying about the difference between CO_2 and CO_2-eq concentrations is not helpful. On the other hand, if CO_2 levels are stabilized or even reduced, avoiding climate forcing through short-lived greenhouse gases becomes extremely valuable.

Second, by focusing on carbon extraction, we can avoid the complexity of tracking many sources of CO_2 emissions. As mentioned before, it would be theoretically possible to avoid LCA if carbon sequestration came due at the actual point of CO_2 release. The challenge with this approach is the vast number of places where emissions occur. Keeping track of all emissions is not practical. It is far easier to match certification against the much smaller number of points of carbon extraction. It should also be noted that not all emissions are simple to identify. For example, a waste incinerator plant can burn a mixture of biomass and waste plastics produced from fossil carbon. Not all the CO_2 emitted from the plant would need to be canceled out, only the fraction associated with the fossil carbon component in the waste stream. Therefore, it is easier to clear all carbon as it comes out of the ground.

In our proposed approach, since an equal amount of carbon sequestration balances all fossil extraction, any CO_2 emitted downstream from the extraction is already balanced. Everyone and everyone's activities are carbon neutral. Carbon used upstream in the supply chain of generating certificates of sequestration, for example, in collecting and processing the CO_2, is also covered by a certificate of sequestration and thus is properly accounted for. The cost of balancing out carbon releases in the supply chain for generating a certificate of sequestration is added to the cost of the certificate. Suppose it turns out that generating a certificate of sequestration for a ton of CO_2 requires more than one certificate in its generation, in other words, the process is counterproductive or lacks carbon negativity. In that case, the technology is not competitive. It thus could not be used even on the margin of such a system. The cost of a new certificate must be higher than the total cost of the implicitly included certificates, meaning it has to be less than one certificate. Identifying where precisely in the supply chain these additional emissions reside and how big they are may be challenging. Still, in a world that balances carbon at the source, cheating on the life cycle carbon balance is impossible. LCA practitioners may be able to help identify the sources of the carbon losses and improve the overall carbon efficiency of the process through better design, but their services are not needed to ensure that carbon is accounted for.

A significant advantage is avoiding the need for LCA in the monitoring and accounting schemes. This does not mean that LCA is useless. Quite the contrary, the business developer selling certificates must understand the LCA of the product. Otherwise, they might end up in a situation where upstream emissions make success impossible.

Challenges

Complications may arise during the transition from today's carbon-emitting economy to a net-zero or net-negative carbon economy. Any fully developed carbon management system requires an introductory phase. It is simply impossible to create the necessary carbon sequestration capacity overnight. There are many different pathways for the transition from an economy that does not control carbon fluxes to one that fully balances all anthropogenic carbon fluxes. For many of those, economics alone may not be sufficient to discourage the introduction of counterproductive sequestration technologies. During this transition phase, not all carbon mobilized in oil and gas wells, coal mines, and cement kilns will be immediately balanced by sequestration efforts. Therefore, not all carbon emitted in the supply chains of carbon sequestration will be stopped. This allows for the possibility that more carbon is released upstream of sequestration than is stored at the end of the chain, *i.e.*, a counterproductive sequestration technology. Unless the cost of fuel incorporates the future cost of the remaining sequestration, sequestration technologies can be economically viable while being counterproductive. Therefore, it is important to carefully consider the pathway for a transition, even if the end goal is a net zero carbon economy, where every ton of carbon coming out of the ground is canceled out by the sequestration of another ton of carbon.

Transition pathways

It is impossible to sequester overnight at the current emission rate of 40 Gt CO_2 per year.[72] Therefore, there must be a transition period in which actual sequestration falls short of the necessary amount. There are two fundamentally different ways to achieve this goal. The first is to gradually phase in the obligation of sequestering carbon and increase it over time to 100% of all extracted carbon.[73–75] The second is establishing the obligation to sequester carbon immediately but allowing for some time before the carbon is sequestered (this paper).

The advantage of the first set of pathways is that the transition starts slowly, and people, institutions, and firms can gradually adjust to the necessary changes. By contrast, if responsibility for the carbon is immediately put on the carbon extractor, the cost of fossil carbon will instantly rise, creating a shock to the economy like the one seen in past and current energy crises. The disadvantage of a gradual phasing-in of liability is that it creates a "moral hazard" because it incentivizes firms to spend down their carbon resources as quickly as possible. Indeed, it might promote a run to the exits and drive-up fossil fuel consumption in the short term. It also makes it difficult to ensure that one does not encourage counterproductive sequestration technologies.

Even if one gives companies time to perform sequestration, the liability for balancing carbon could start instantly. This would result in a financial shock to the existing system. One may have to ease this shock by giving tax breaks, subsidies, or, as we will discuss, introducing permits to lower the initial cost. On the other hand, immediate liability creates a clear incentive to minimize emissions from the start. It also is not unfair and reduces the advantage given to fossil fuel producers over other energy producers. From a fairness perspective, one can argue that climate change was not understood in the past and that there is no need to punish past behavior. However, today no one can argue that carbon extraction is harmless. If CO_2 is a waste stream that needs to be cleaned up,[82] nobody should be able to avoid this requirement. Paying for it at the point of extraction may well be the easiest way to handle this problem.

Characterizing the transition

To facilitate the discussion, we introduce a coefficient α that measures the ratio of carbon sequestered from point sources and CDR to carbon released by fossil carbon extraction. In echoing the ambiguities in LCA, we need to clarify whether carbon released includes losses from sequestration. Conceptually, defining the ratio as the carbon sequestered to the amount of carbon extracted from the ground appears cleaner. In this case, the re-sequestration of carbon escaped from sequestration becomes part of the sequestration cost. For clarity, this is the choice we make.

At present, α is very small, but if the climate is to be stabilized, it will have to rise to $\alpha = 1$. If stabilization is to occur at a level lower than the peak reached (*i.e.*, if societies wish to lower the atmospheric CO_2 concentration), then α will have to be larger than one for at least some time. Any policy guiding the transition to a carbon neutral economy will result in a time trajectory $\alpha(t)$ that starts from a small value, may overshoot $\alpha = 1$, and eventually asymptotes to $\alpha = 1$. Policies could proscribe the $\alpha(t)$ trajectory, or use other levers to shape it.

The class of policies we consider rests heavily on requiring CO_2 sequestration at the point of carbon extraction. This is often called a carbon takeback obligation (CTBO) by the fossil carbon extractor.[73–75] The extractor ultimately must pay for the sequestration that balances the carbon extraction but may fall short of that initially. In other words, the initial takeback obligation is only a fraction of the carbon taken from the ground. We will refer to the ratio of carbon sequestered *via* such a takeback obligation per unit of carbon extracted as α_t. The numerical value of α_t is expected to result from regulatory policies, and we assume it to be uniform across all types of extraction. A central premise of our approach is that it is possible to sequester carbon from many different sources, including the environment, resulting in a uniform carbon sequestration price across different technologies. Therefore, it is not necessary to differentiate the takeback obligation of different extractors. Since the ratios α and α_t share the same denominator, and sequestration to cancel out concurrent fossil carbon extraction as part of a takeback scheme is a part of the overall sequestration, we find that $\alpha \geq \alpha_t$. The two ratios need not be equal. For example, voluntary or government action may drive additional carbon sequestration to cancel out past emissions. In that case, $\alpha > \alpha_t$.

A simple carbon takeback obligation

After some transition, all carbon extracted will be balanced out by sequestration, as demonstrated by certificates of sequestration. The simplest transition scenario suggests fossil carbon extractors have an increasing carbon takeback obligation that gradually rises to $\alpha_t = 1$. This is inherent in the CTBO approach.[73–75] The trajectory $\alpha_t(t)$ may be predetermined or dynamically adjusted. Absent other policies or voluntary actions, $\alpha_t(t) = \alpha(t)$. Certificates of sequestration that include the responsibility for re-sequestration in case carbon is lost from sequestration would make it possible to introduce such a policy while allowing for temporary sequestration.[77]

A permit scheme for carbon takeback

Lackner *et al.* argued that one way of handling early introduction is to differentiate between permits, which allow the extraction of carbon without actual carbon sequestration, and a certificate of sequestration that guarantees the permanent removal of carbon if necessary through re-sequestration if the carbon is lost.[66] This concept assumes a "carbon board" that issues permits, which trade at the same price as certificates of sequestration, but only the certificate guarantees carbon sequestration. Once the scheme is introduced, permits or certificates would be needed to extract carbon.

By initially oversupplying the market with permits, the transition from today's economy to a carbon-controlled economy avoids a price shock. The carbon board, in effect, controls the sequestration price by adjusting the permit supply. By limiting the supply of permits, the carbon board would indirectly control α_t. The price of permits and certificates could initially be small. It would increase as the supply of permits is gradually reduced. In this approach, permits discourage the unnecessary use of fossil carbon and provide a financial incentive for carbon sequestration. If permit prices are high enough to stimulate sequestration, their supply can be gradually reduced as the sequestration industry grows and becomes more mature. A carbon board that sets the permit price would, in effect, have introduced a tax. If it had set the supply of permits instead, it would have created a cap-and-trade system. However, the permit system is more flexible and can navigate between extremes.

The permit scheme has some of the same benefits as the new CTBO described by Jenkins *et al.*, where the stored fraction escalates predictably toward 100%.[74] In the permit scheme, the carbon board can announce the change in the number of permits and set the trajectory.

A futures market in certificates

A third option is to create an immediate liability for all future carbon to be extracted. Since it is impossible to deliver enough certificates of sequestration overnight, one would have to phase in sequestration. To this end, one may introduce well-defined and controlled futures of sequestration to be used instead of certificates. For example, one could allow a storage operator who has demonstrated the ability to store carbon to generate actual certificates of sequestration as indicative of the ability to deliver future sequestration and allow such an operator to issue a certain number of futures on certificates of sequestration. These futures could be used to balance out today's extraction. Of course, future extraction would require a separate certificate of sequestration or promise of future sequestration.‡ Closing that gap will take years. Such futures on certificates of sequestration would need to come with stringent assurance. Assurances may involve bonding or insurance or transfer of the liability to a trusted third party. Furthermore, the number of futures that could be promised in balancing today's carbon would be tightly circumscribed. The major challenge with this approach would be a severe initiation shock, as markets would have to price in the current cost of sequestration and the uncertainty of the future cost of sequestration. On the other hand, this approach would internalize all externalities instantly and make it extremely difficult to game the system. For example, it removes the incentive to sell all the oil in the ground before it is banned.

Hybrid approach

One can think of a permit approach as a variation of the simple carbon takeback approach. Its main difference is that it does insist that carbon extractors take on some responsibility for the carbon that is still exempt from sequestration. The advantage of a simple carbon takeback is that it initially could support a high price of carbon sequestration as the cost is diluted by the much larger extraction. However, since the market for sequestration is small, low-cost, small-scale options would likely dominate. Therefore, these early sequestration efforts are unlikely to drive down the cost of scalable options.

As we will show below, a simple carbon takeback obligation makes it difficult to weed out counterproductive sequestration technologies that turn out to be profitable. However, in a permit scheme, counterproductive technologies would never be profitable. Allowing such technologies to take hold encourages operators to extract money from climate mitigation policies without any intent or path toward carbon negativity.

A challenge to the permit scheme that was already noted by Lackner *et al.* is the accumulation of large revenues.[66] This problem could be fixed by asking the carbon board to gradually convert permits into certificates of sequestration or futures of certificates of sequestration. The other suggestion, to give the proceeds out as a windfall to the public may create an awkward incentive to ensure that permits are not phased out to protect a windfall that is supposed to disappear. Many have proposed carbon dividends to mitigate climate change (*e.g.*, ref. 83 and 84), but once benefits are established, they become difficult to stop (*e.g.*, governments relying on tax revenue from fossil fuel use to pay for social services). Fossil carbon must be cleaned up or phased out as quickly as possible, not supported and extended in time. The permit scheme creates the possibility of a rapid transition. It is possible to combine the permit scheme with an approach that relies on controlled futures of certificates of sequestration in lieu of actual certificates of sequestration. This hybrid approach would create significant flexibility in responding to market failures and glitches but would require a politically independent carbon board.

In the first year of introducing this hybrid scheme, the permit supply could be intentionally large to keep costs down and solely focus on phasing in an accounting scheme. Then the carbon board could rapidly reduce the number of available permits. This requires an expiration date on permits to avoid hoarding past cheap permits. The rising price would encourage the introduction of a mixture of certificates of sequestration and controlled futures of certificates of sequestration to take on a rapidly growing market fraction. After a relatively short time, five to ten years, the only role of the permits would be to assure some price stability in the face of sudden impacts on the markets.

The permit scheme differs from the simple takeback obligation by demanding payment for all carbon from the start. Specifically, it demands a permit's price equal to that of a certificate of sequestration. An alternative would be to augment the takeback obligation scheme with a carbon tax on the unmitigated fraction of the extracted carbon.[74] If that tax were equal to the price of a certificate of sequestration, it is effectively a permit scheme. In a market-driven system, storage operators would price their certificates right at the cost of the tax. When sequestration supply exceeds demand, competition among storage operators would set the price. The advantage of the permit scheme over the tax is that the carbon board can adjust the permit supply to take advantage of the decreasing sequestration cost. Once set, taxes tend to persist, creating an obvious market failure.

Lastly, not all sequestration needs to be tied to fossil carbon extraction. Indeed there is a need to remove carbon from the environment to reduce the already high CO_2 concentrations in the atmosphere. Carbon accounting and the resulting certificates of sequestration could be used to eliminate excess carbon in the environment. CDR and sequestration technologies used for this purpose are generally called negative emissions technologies (NETs). Governments, private institutions, and even individuals could purchase certificates of sequestration that are not used to cancel out concurrent fossil fuel extraction. Such voluntary efforts are outside the regulatory market. They could

‡ In effect, this situation has arisen in the voluntary market, where there is an oversubscription of investor demand towards Climeworks and other DAC companies' capacity. According to CDR.fyi, almost 4 million tons have been purchased but only 2% delivered as of 06/29/2023.

support higher prices and subsidies for technology development without distorting incentives in the regulatory market. Such a market is beginning, as evidenced by advance purchases made by Frontier Climate and Microsoft.

The economics during the transition

If the cost of carbon sequestration or the equal cost of a permit for carbon extraction is added to the cost of fossil carbon, there is a direct link between the sequestration requirement and the cost trickling through the economy. For the transition, we consider $\alpha < 1$ and try to avoid economic incentives for counterproductive technologies. We have already concluded that such technologies are not viable for $\alpha \geq 1$. At $\alpha < 1$, counterproductive sequestration technology can remain cost-effective.

This then raises the question of how a system can be stabilized in the early days against such developments when $\alpha \ll 1$. Will it require a life cycle approach, or can it move through the early stage without encouraging counterproductive technologies? The following simple model aims to shed light on this question.

Let C be the rate at which carbon is extracted, and S the rate at which it is stored. A policy results in sequestration balancing out a fraction α of all carbon extracted. Hence

$$S = \alpha C \tag{1}$$

The amount of carbon extracted includes the amount necessary to run capture and sequestration operations. We therefore introduce the concept of a baseline and refer to C_0 as the rate of carbon extraction that would be present absent of the sequestration effort. We then note that to sequester a unit of carbon, it is necessary to consume additional carbon. Therefore, we have

$$C - C_0 = \varepsilon S \tag{2}$$

The multiplier ε which we refer to as carbon intensity is hopefully small and it may change over time. Clearly, $\varepsilon < 1$ is a requirement for the system to close.

We find

$$C = C_0 + \varepsilon S = C_0 + \alpha\varepsilon C \tag{3}$$

or

$$C = \frac{C_0}{1 - \alpha\varepsilon} \tag{4}$$

Eqn (4) shows that for fixed ε the total carbon consumption goes up as the required collection fraction α increases. For the system to be stable and not hit a singularity, it is important that the $\alpha\varepsilon < 1$. Since one aims to reach $\alpha \gtrsim 1$, it is important that ε is small or drops in time fast enough to assure that the product remains small.

Based on this analysis, we can compute the net emission E, which has a baseline value E_0. Staying with the same carbon units as before, we find that

$$E_0 = C_0 \tag{5}$$

And

$$E = C - S = C(1 - \alpha) = E_0 \frac{1 - \alpha}{1 - \alpha\varepsilon} \tag{6}$$

For $\alpha > 0$, $0 < \varepsilon < 1$ and $\alpha\varepsilon < 1$, the emissions are indeed reduced from those of the baseline. They can be negative, if $\alpha > 1$.

Cost of carbon sequestration under a simple carbon takeback scenario

We now proceed to estimate the cost of carbon sequestration. To simplify the discussion, we set $\alpha_t = \alpha$. In other words, no other efforts are made to sequester. Furthermore, the only cost in carbon management is the sequestration of carbon. There are no additional carbon taxes, subsidies, or carbon fees to consider.

We assume that we can break the carbon cost into an intrinsic cost of the unit process plus the implicit costs arising from the supply chain, which we can estimate because we know how much CO_2 we will have to sequester in total.

$$k = k_0 + \alpha\varepsilon k \tag{7}$$

Here k_0 is the total direct cost, and $\alpha\varepsilon k$ breaks out the incremental cost of all other certificates that happened elsewhere in the supply chain. We also know that for any $\alpha > 0$, k_0 and ε are conceptual quantities that can be estimated but cannot be easily measured. The challenge to LCA is that it actually needs to know these numbers. Of course, in the limit that $\alpha = 0$, $k = k_0$. In terms of the direct cost, the total cost can be estimated as

$$k = \frac{k_0}{1 - \alpha\varepsilon}, \tag{8}$$

The cost becomes singular as $\alpha\varepsilon$ approaches 1. Initially, when $\alpha \ll 1$, a counterproductive technology could turn out to be the most competitive. However, the cost of a technology explodes as ε approaches

$$\varepsilon_{\max} = \frac{1}{\alpha}, \tag{9}$$

This assures that technologies which are highly counterproductive are ruled out, but until α reaches one, one cannot suppress counterproductive technologies based on cost alone.

Can counterproductive sequestration technologies enter the carbon market?

The above analysis considers one technology that is characterized by k and ε. In general, many different sequestration technologies may compete. A new technology that enters the market initially does not imprint its own characteristics on its supply chain. Here we show that nevertheless the range of allowable values of ε is the same as for the baseline technology.

There is another heuristic to explain the formula for the cost that becomes visible after expanding out the geometric sequence implied by eqn (8),

$$k = k_0 + k_0(\alpha\varepsilon) + k_0(\alpha\varepsilon)^2 + k_0(\alpha\varepsilon)^3 + \ldots \tag{10}$$

Each successive term stores the carbon released in the previous term.

With this form, we can now study what happens if someone is trying to introduce a new technology to solve the problem. The new technology differs from the old, in that it has a different value for $k_0 \rightarrow k_0'$ and for $\varepsilon \rightarrow \varepsilon'$. However, this will not affect all terms in the series, because the new technology has not yet permeated through the entire supply chain but is limited to the direct effort at the end of the chain. Therefore, we can estimate the new cost of the newly introduced technology as

$$k' = k_0' + k_0\alpha\varepsilon' + k_0\alpha\varepsilon'(\alpha\varepsilon) + k_0\alpha\varepsilon'(\alpha\varepsilon)^2 + k_0\alpha\varepsilon'(\alpha\varepsilon)^3 + \ldots \tag{11}$$

Collecting our terms back into a geometric series we note that this can be written as

$$k' = k_0' + k_0\alpha\varepsilon'\frac{1}{1-\alpha\varepsilon} = k_0' + \alpha\varepsilon' k \tag{12}$$

Thus, we can express the new costs in terms of the old cost, and the new parameters. In the limit that the prime variable equals the unprimed, we recover the old formula. If the world managed to move the system to some level of α, it could still revert to a different cheaper counterproductive technology.

Starting from the observation:

$$k' = k_0' + a\varepsilon' k \tag{13}$$

$$k = k_0 + \alpha\varepsilon k \tag{14}$$

We conclude

$$k' - k = (k_0' - k_0) + \alpha k(\varepsilon' - \varepsilon) \tag{15}$$

This we can rewrite by dividing by k and introducing differences of the form

$$\Delta x = x' - x. \tag{16}$$

We find

$$\frac{\Delta k}{k} = \frac{\Delta k_0}{k_0}(1-\alpha\varepsilon) + \alpha(\varepsilon' - \varepsilon) \tag{17}$$

As a shorthand we introduce $r = \frac{\Delta k_0}{k_0}$

$$\frac{\Delta k}{k} = r(1-\alpha\varepsilon) + \alpha(\varepsilon' - \varepsilon) = r - \alpha(r+1)\varepsilon + \alpha\varepsilon' \tag{18}$$

To be an improvement, at least one of r and $(\varepsilon' - \varepsilon)$ must be negative. However, costs can come down, even for positive values of $(\varepsilon' - \varepsilon)$. The maximum value ε' can take on without raising cost for a given choice of r is given by

$$\varepsilon'_{\max} = -\frac{r}{\alpha} + (1+r)\varepsilon \tag{19}$$

The largest value is obtained if r is as small as possible. The most extreme outcome is that the new cost is zero, in which case $r = -1$. In other words,

$$\varepsilon'_{\max} < \frac{1}{\alpha} \tag{20}$$

Therefore, an existing carbon negative sequestration technology that dominates the market cannot prevent a new technology from entering the market even if it is counterproductive. Even though the economics of a system that does not include the entire supply chain is different from one which does, the same barriers to entry remain. As long as $\alpha\varepsilon < 1$, one can introduce a new, but counterproductive sequestration technology. Specifically, this means that a system with very low direct cost, could operate at $\varepsilon \lesssim \frac{1}{\alpha}$.

Cost of carbon sequestration under a permit scheme

Again, we assume that $\alpha_t = \alpha$ and that no other efforts are made to enhance carbon sequestration and no further costs are added by taxes or subtracted by subsidies.

Indirect costs in the permit scheme are different from those in the simple carbon takeback obligation because the indirect carbon sequestration costs include the costs of the necessary permits which are by definition equal to the cost of a certificate of sequestration, *i.e.*, the indirect cost of permits is k as well.

Therefore,

$$k = k_0 + \alpha\varepsilon k + (1-\alpha)\varepsilon k \tag{21}$$

The last term captures the cost of the permits associated with the indirect emissions. The permits eliminate α from eqn (21) resulting in

$$k = k_0 + \varepsilon k \tag{22}$$

Or

$$k = \frac{k_0}{1-\varepsilon} \tag{23}$$

This cost remains finite as long as $\varepsilon < 1$. This suggests that from the start only technologies can be introduced that are truly carbon negative.

Again we can expand k into a geometric series

$$k = k_0 + k_0\varepsilon + k_0\varepsilon^2 + k_0\varepsilon^3 + \ldots \tag{24}$$

And introducing a new technology with k_0' and ε', will incur an initial cost of

$$k' = k_0' + k_0\varepsilon' + k_0\varepsilon'\varepsilon + k_0\varepsilon'\varepsilon^2 + k_0\varepsilon'\varepsilon^3 + \ldots \tag{25}$$

Or

$$k' = k_0' + \frac{k_0\varepsilon'}{1-\varepsilon} = k_0' + k\varepsilon' \tag{26}$$

The analogous transformations to that above leads to

$$\frac{\Delta k}{k} = \frac{\Delta k_0}{k_0}(1-\varepsilon) + (\varepsilon' - \varepsilon) \tag{27}$$

Or using the same notation as before, we have the requirement that

$$0 > r(1-\varepsilon) + (\varepsilon' - \varepsilon) \tag{28}$$

$$\varepsilon'_{\max} = -r + (1 + r)\varepsilon \quad (29)$$

For a fixed value of $0 < \varepsilon < 1$, $\varepsilon'_{\max}$ is maximized by the smallest possible value of r, *i.e.*, $r = -1$. In this limit

$$\varepsilon'_{\max} = 1 \quad (30)$$

In other words, counterproductive technologies cannot enter the market under a permit scheme.

The consequences of subsidies

If carbon sequestration used in satisfying takeback obligations is paid for externally through subsidies, including tax break credits, it would eliminate price signals and thus, economics would not stop a bad technological choice. A fixed reduction in cost would dampen the price signal but not eliminate it. Indeed, one can look at the above cost analysis and show that the cost will look the same as before, except that the subsidy has been deleted from the cost. In the first case, the cost is

$$k = k_0 + \alpha\varepsilon(k - s) \quad (31)$$

where s is the subsidy. By subtracting s from both k and k_0, the equation goes back to its original form. The only change is that the cost has been replaced by the cost minus the subsidy.

In the case of the permit scheme, the same argument can be made because the cost of the permit and that of the subsidized sequestration still must match. Again, the analysis can treat the subsidized cost, as if it were a real cost.

There are more complicated cases. For example, one could demand that a fraction α of the extracted carbon is matched by subsidized sequestration and that any further sequestration is not subsidized. In that case, the cost structure of the permit scheme would change and does not follow a simple geometric series anymore. A weird situation arises when the effective cost of sequestration after subsidy turns out to be negative, in that case one would in effect encourage fossil fuel extraction for the purpose of generating profits on carbon sequestration.

In the presence of subsidies, the lowest cost of a new competitor is not limited to zero anymore, it could be as low as $-s$. This means r is not bound from below at -1, it could now drop well below that, especially if k_0 is small but still positive. This in turn means that counterproductive technologies can no longer be suppressed by economic incentives alone.

We understand that subsidies can help a nascent industry to grow. However, we propose that certificates of sequestration for canceling out fossil carbon should not be subsidized because subsidies open the door to counterproductive sequestration technologies, as shown. However, introducing a subsidized industry for NETs might be of practical interest as it would allow subsidies for advancing new technologies, without biasing the carbon takeback market.

Finally, we note that in analyzing economic incentives, it does not matter whether the carbon is sequestered immediately, or whether the sequestration service that has been purchased is a promise for sequestration at a future date. The indirect costs would still accrue in a similar manner.

Reflections

Policy choices and approaches to transitioning to a net zero carbon economy depend on political will. While there are various options available, all of them require accurate carbon accounting. LCA is a useful qualitative tool, but for quantitative purposes it is well-known to be expensive, inaccurate, and open to interpretation. Therefore, LCA in the accounting process should be avoided. We showed that LCA for accounting can be avoided during and after the transition to a net zero carbon economy.

For any policy that completely balances carbon either at the point of extraction or at the point of emission, LCA accounting is unnecessary. The purpose of LCA accounting is to keep track of carbon in the supply chains between the points of extraction and emissions. If the problem is taken care of on either end, this tracking is unnecessary. We made the point that upstream balancing at the point of extraction involves a far smaller number of stakeholders and most of the accounting necessary is already performed for other purposes like calculating royalties and taxes. We therefore suggest upstream balancing at the point of extraction.

Once all of the carbon extraction must be balanced, counterproductive sequestration technologies, *i.e.*, technologies that release more carbon in the supply chains than they sequester, are economically unviable. However, during the transition some policies inadvertently could encourage counterproductive sequestration. Others would prevent it. One simple scheme that prevents counterproductive sequestration demands certificates of sequestration or permits for all carbon extracted and released from storage. By charging equally (either through a certificate or a permit), the cost of carbon sequestration must pay for all the carbon released in its supply chain and therefore counterproductive sequestration is economically unviable.

By introducing permits, the system avoids the need for LCA and is safe from being gamed by counterproductive technologies. Adding controlled futures, *i.e.*, a firm promise of future sequestration, introduces a hybrid scheme that separates the time constant for phasing in the accounting from the time constant for developing the new sequestration infrastructure. The goal of the permits is to ameliorate the initiation shock, the controlled futures are designed to bridge the transition time in which the sequestration capacity falls short of market demand. Softening the initiation shock will take a few years, building the necessary infrastructure will take decades.

Subsidies or tax credits can help in the early development of a technology. Unfortunately, they tend to distort the market and open the door to counterproductive sequestration technologies. However, they are unnecessary. The large and currently unmet demand for negative emissions, *i.e.*, the sequestration of legacy carbon, has reached a level that this becomes the natural place for governments to support new technologies and help them drive their costs down. It is likely that driving down the CO_2 concentration in the atmosphere will be paid for by public funds. If this effort starts now and is distinct from balancing the carbon for current fossil fuel consumption, it will not only jumpstart the reduction of CO_2 into the atmosphere, but it will also incubate new technologies that need help in moving from early stages to commercially viable approaches without unnecessarily creating incentives for counterproductive sequestration.

The approach outlined in this paper presents a different perspective of climate mitigation and carbon management. It focuses on inputs and outputs rather than the convoluted pathways through the economy. It is inherently simpler. To implement such a system requires regulatory frameworks. These frameworks must address the issuance of permits for fossil carbon extracted and lacking a certificate of sequestration; standards to certify sequestration and provide guarantees for its permanence; and standards for controlled sequestration futures. Testing this approach with storage operators and jurisdictions would be the next step, which would yield data for a quantitative comparison to the current approach.

Author contributions

K. Lackner and H. Azarabadi conceived of the idea and developed the model. S. Arcusa and V. Sriramprasad reviewed LCA literature. R. Page developed the idea of immediate liability. S. Arcusa and K. Lackner wrote the first draft and all authors edited the manuscript.

Conflicts of interest

K. Lackner is a co-inventor of IP owned by Arizona State University (ASU) that relates to certain implementations of direct air capture. K. Lackner also consults for companies that work on direct air capture. ASU has licensed part of its IP to Carbon Collect and owns a stake in the new company. As an employee of the University, K. Lackner is a technical advisor to the company and in recognition also received shares from the company. Carbon Collect also supports DAC research at ASU. R. Page is also a co-inventor on several capture processes, including the Carbon Collect device. Further, he consults with industrial companies and start-ups on direct air capture devices, algae capture, and battery technology. Most of his consulting work is with ASU/CNCE.

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