# DEVELOPING AND DEPLOYING NEGATIVE EMISSION TECHNOLOGIES: SYSTEM-LEVEL ASSESSMENT AND RATIONALIZATION

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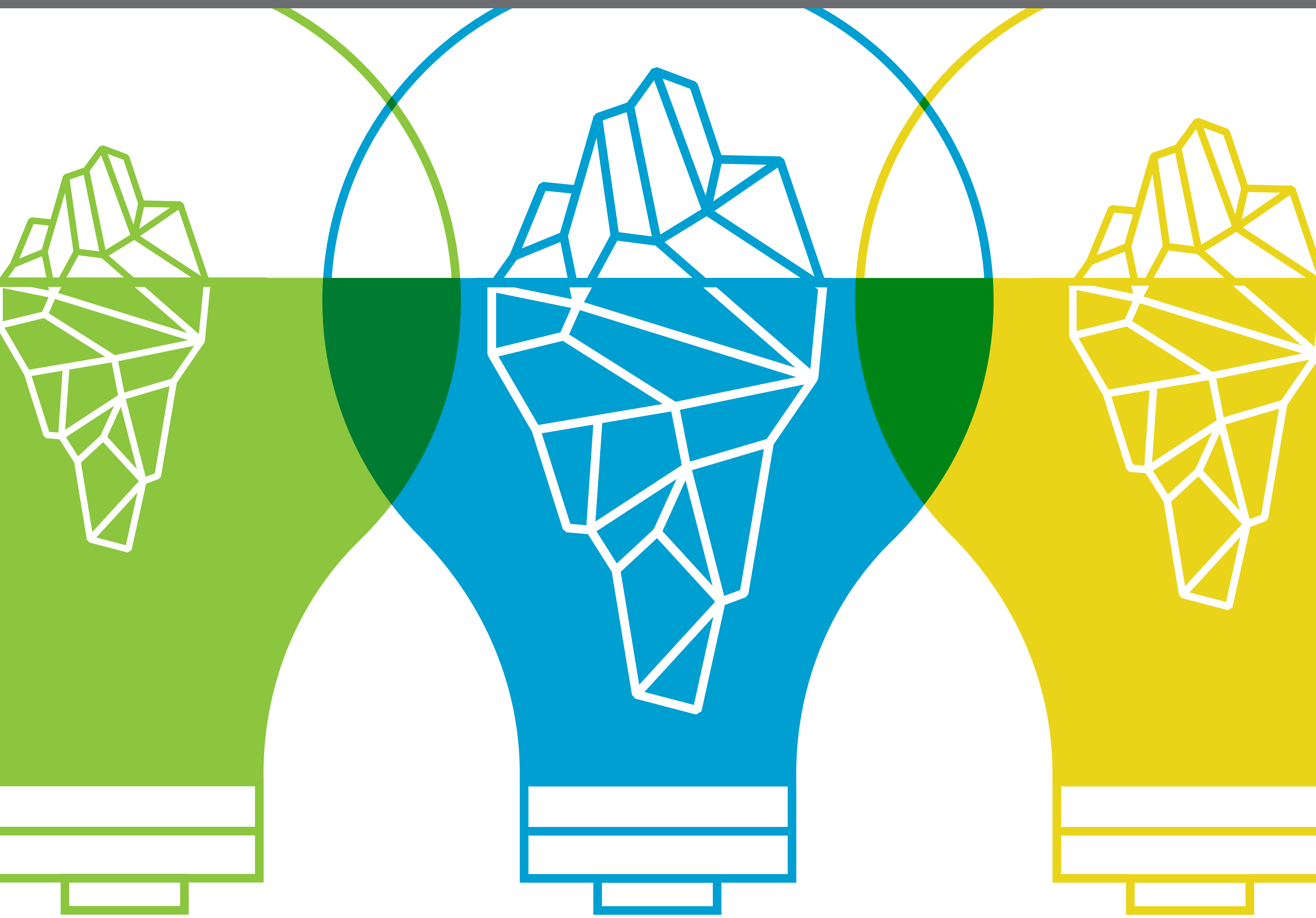

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# DEVELOPING AND DEPLOYING NEGATIVE EMISSION TECHNOLOGIES: SYSTEM-LEVEL ASSESSMENT AND RATIONALIZATION

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EDITORIAL
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# Editorial: Developing and Deploying Negative Emission Technologies: System-Level Assessment and Rationalization

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**Editorial on the Research Topic**

**Developing and Deploying Negative Emission Technologies: System-Level Assessment and Rationalization**

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Climate change, induced by the excessive amount of greenhouse gas (GHG) emissions from anthropogenic activities, is one of the greatest global challenges of our times. To address this challenge, a range of important measures are being developed or have already been adopted, including switching from fossil fuels to renewable energy resources, reducing emissions through improving efficiencies and demand management, and capturing $CO_2$ at point sources with subsequent storage to avoid their release to the atmosphere. In addition to measures curbing new emissions, intentional atmospheric carbon dioxide removal (CDR) by negative emissions technologies (NETs) is increasingly considered as necessary for compliance with ambitious temperature targets. According to the Intergovernmental Panel on Climate Change (2018), all climate pathways that limit global warming to 1.5°C with controlled (or no) overshoot project the use of CDR in the order of 100–1,000 $GtCO_2$ over the twenty first century. The deployment of NETs, removing $CO_2$ from the atmosphere and storing it on land, underground, or in the oceans, could become one of the most significant undertakings in industrial development, with profound impacts on the future of our society.

NETs include a diverse range of options, such as bioenergy with carbon capture and storage (BECCS), direct air capture (DAC) and subsequent sequestration (DACCS) or use in products with long lifetimes, such a construction material, enhanced weathering and increasing ocean alkalinity, afforestation, and other land/soil management solutions (Royal Society and Royal Academy of Engineering, 2018; National Academy of Sciences Engineering Medicine, 2019). These options differ widely in their approach to capturing atmospheric carbon (such as biological vs. abiotic) and to storing the captured carbon (such as above ground, in soil, below the subsurface, or in the sea; and with or without chemical conversion).

Complementary to the technical research and development of these schemes through experimental and pilot explorations, there is emerging research on important system aspects, such as the overall technoeconomic, environmental and social viability of individual NETs, policy requirements, potential synergies and conflicts with other climate actions (such as emission reduction), strategies for deploying NETs (where and when), and the integration of NETs and the associated industries with the wider economy.

Focusing on these systems issues, this Research Topic aimed to promote research and discussion on systematic approaches to the future deployment of NETs. At present, such approaches are particularly relevant for assessing their feasibility at the national level. Through examining the long-term low GHG emission development strategies from 16 countries plus one from the EU, Thoni et al. report the broad recognition of the role of NETs. However, their work show that existing feasibility assessments have mostly focused on technical and biophysical perspectives and lack social and cultural considerations. The authors highlight the need for further assessing pathways involving NETs to reflect upon challenges beyond climate mitigation, including socioeconomic goals. They argue that the outcome of more holistic feasibility assessments would be highly desirable to underpin the viability of NETs, especially when they are included in integrated assessment models (IAMs) and related trajectories for long-term climate mitigation and adaptation scenarios.

Focusing on UK land use and agriculture, Reay echoes the importance of carefully considering and taking actions along multiple perspectives, such as governance, finance, skills and society, in addition to research and development, in order to avoid pitfalls of NETs and other net zero initiatives caused by the lack of concerted and inclusive measures. Field also addresses bio-based systems and revisits the notion of "additional carbon," calling for increased attention to the difference between alternative carbon abatement systems with respect to carbon additionality, with more reliable accounting of ecosystem—atmosphere exchanges to complement existing approaches, such as LCA and supply-chain assessment.

Addressing the interplay between NETs and power generation, the work by Lehtveer and Emanuelsson on comparing BECCS and DACCS shows that, although DACCS has a higher levelized cost for carbon capture, its greater flexibility may lead to a lower total system (carbon removal + power generation) cost if NETs were to integrate with a power sector dominated by variable and intermittent renewables which would favor flexible demand. This study offers a concrete example illustrating the importance of integrative thinking between the deployment of NETs and other sectors.

Despite their potential importance, technology-readiness levels of some and total deployment levels of all NETs are still low, with a gradual deployment process yet to unfold along with other technological and socioeconomic transitions. Therefore, understanding the possible trajectories of co-evaluation with other sectors may provide important insights about the future of NETs. In this respect, the LCA study by Rosental et al. on carbon capture (including DAC) and utilization (CCU) shows that the reduction of negative environmental impacts of producing large-volume organic chemicals from captured carbon to a large extent depends on the progression in the sustainability of resource extraction, processing and recycling of materials (e.g., steel, aluminum and concrete) that form the technical infrastructure for CCU. In a separate discussion, Hastings and Smith argue that achieving net zero emissions would benefit significantly from the knowledge, skills, and assets of the oil and gas industry, and that seeking to play an active role in the deployment of NETs could in turn contribute to transforming the sector, which itself is facing an enormous challenge of transitioning to a sustainable future (Wilkinson et al., 2021).

In summary, the articles in this Research Topic are offering a valuable starting point for advocating and developing systematic approaches to the future progression of NETs. This is deemed to be part of a greater societal transition, where interactions between different perspectives and sectors will increasingly require robust system-level assessment and rationalization. We envisage that contributions will be particularly valued from future work focusing on the assessment of spatial and temporal deployment strategies, understanding of synergies and trade-offs, development of tools to support inclusive decisions, and regional case studies that harness interdisciplinary strengths. Furthermore, research in these areas needs to be facilitated by the progress in LCA and technoeconomic assessment tools and standards to enable sound choices of boundary conditions and data, as these are essential for achieving rigorous, consistent and transparent results when assessing various NET or CDR schemes (Sick et al., 2020; Wilcox et al., 2021).

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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# Land Use and Agriculture: Pitfalls and Precautions on the Road to Net Zero

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Land use is a crucial sector in delivering enhanced carbon sequestration globally. At the same time food production is a major source of global greenhouse gas emissions. As pressure mounts for all nations to increase their levels of ambition under the Paris Climate Agreement, so the pressure to radically reduce emissions from the agriculture sector and enhance carbon sequestration in the land use sector also ramps up. This trend is most clearly evident in the drive for "net zero" where unavoidable emissions, such as those from food production, are balanced by more sequestration via land use change. Here we examine some of the major risks, applicable safeguards, and potential pathways for agriculture and land use in realizing net zero. Using the UK as an example we highlight the importance of governance, finance, skills, research and technology, and society in this transition. We conclude that successful land use policy for net zero will require extremely demanding levels of integration and spatial resolution, and that the research community has a vital role to play in providing a robust evidence base for this. We also invoke the Cancun safeguards as a basis on which a more sustainable and just transition to net zero might be based. Finally, we warn of unintended distortions to policy and markets if the drive for net zero is too blinkered.

**Keywords: afforestation, peatlands, soil carbon (C) sequestration, carbon sequestration, rural policy design**

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## INTRODUCTION

Our global food system is now responsible for around one-quarter of anthropogenic greenhouse gas emissions, with agricultural production the dominant source of these emissions (Vermeulen et al., 2012). As human population expands and diets become more meat and dairy intensive, so emissions will rise further unless substantial changes in food production and supply are realized (Tilman and Clark, 2014). The Paris Climate Agreement aims to limit global average temperature increase to well below 2°C above the pre-industrial baseline and pursue efforts to keep warming within 1.5°C. Achieving this goal will require net global $CO_2$ emissions to reduce to zero by the middle of the century (Rogelj et al., 2018). Some developed nations, such as the UK, have now committed to a target of "net zero" for all greenhouse gases (GHGs) by 2050—whereby unavoidable emissions are balanced by increased domestic sequestration. Without major reductions in emissions from agriculture alongside substantial increases in sequestration such national targets become near impossible. As such, our agriculture and land use sectors face a fiendishly difficult balancing act of ensuring sufficient quantity and quality of food, lower emissions, increased sequestration, protection of natural ecosystems, soil, water, and air quality, and all in the context of a climate that is already changing (Seddon et al., 2020). The prize for humanity of achieving this balance is huge, but the potential pitfalls of "carbon blinkered" rural policy to deliver net zero are enormous. Here we discuss some of the key issues that must be addressed, safeguards that should be put in place, and some of the mechanisms that can deliver a sustainable net zero future for land use. We include examination of "conventional" carbon sequestration strategies, such as on-farm woodland and managed soil C enhancement, as well as emerging approaches such as BECCS (Biomass Energy with Carbon Capture and Storage), biochar and enhanced weathering. All have high relevance to the agriculture and land use sectors, but also significant risks in terms unintended consequences.

We focus on the UK as a developed nation with a legally-binding target of net zero GHG emissions by 2050 and where development of new farming policy to support "public goods" like climate change mitigation is already a focus due to exit from the EU's Common Agricultural Policy (Bateman and Balmford, 2018). Here, the transition to net zero is set to rely heavily on changes in domestic land use and agriculture, potentially delivering greenhouse gas emissions savings of over 40 Mt $CO_2$e per year by 2050 (compared to today) and including forestry (∼14 Mt), low carbon farming practices (∼10 MT), dietary change and food waste (∼7 Mt), agroforestry (∼6 Mt), peatlands (∼5 Mt) and energy crops (∼2 Mt) (CCC, 2020).

## LAND USE AND NET ZERO IN THE UK

The UK's net zero by 2050 target requires an estimated 20% of current agricultural land be repurposed to increase forest cover, bioenergy production, peatland restoration and overall land use diversification (CCC, 2019). The prime strategy put forward to allow such a large release of existing agricultural land is that of increased efficiency of food production—enhanced productivity in some areas allowing land sparing and the use of these other land areas for climate change mitigation (Lamb et al., 2016).

To incentivise such release of land to meet non-food aims (rather than simply to try and enhance production in all areas), the opportunity costs of a change to non-food land use must be met (Bustamante et al., 2014)—often referred to as "income foregone" (Barnes et al., 2011). In principle this mechanism allows governments to manage levels of domestic food self-sufficiency while also allowing enhanced action on their key non-food objectives, such as climate change mitigation. In reality, setting an effective "income foregone" price point that avoids unintended consequences, like falls in domestic food security and increased reliance on imports, can be very difficult. Even where land sparing occurs, it does not inevitably mean greater public goods are then delivered. The spared land might not end up in the aimed-for alternative use, or the desired performance of the spared land in delivering public goods may not be met (Balmford et al., 2019).

Fundamental to successful delivery of such complex transformations will be a well-integrated decision support system for rural policy that takes account of potential for food production alongside greenhouse gas (GHG) mitigation, C sequestration, biodiversity protection, livelihoods, water and air quality, climate resilience and the host of other demands placed on our land (Helm et al., 2020). Clearly, for any nation aiming to achieve net zero there are multiple trade-offs to be made within a limited land area, and big risks if local socioeconomic contexts are not well-integrated with national science-based targets (Dooley and Kartha, 2018).

## NET ZERO PITFALLS

The planned transition in UK land use to achieve net zero is both rapid and far-reaching, making the risk of unintended consequences policy outcomes especially high. A "just transition," whereby the sustainability of land use change, livelihoods and support mechanisms is ensured, is crucial to avoiding pitfalls ranging from clashes with other national and international frameworks, through erosion of rural communities and cultures, to complete reversal of C sequestration and off-shoring of emissions.

Firstly, future rural policy for net zero at a national level would need to complement or be consistent with overlapping national programmes and relevant international agreements. On the latter, "net zero GHG by 2050" for developed economies is deemed consistent with the Paris Climate Goals (CCC, 2019), but any land use actions to deliver it would also need to consider synergies and antagonisms with international agreements such as the UN Convention on Biodiversity (CBD) and the UN Sustainable Development Goals (SDGs) (Smith R. et al., 2019).

Governance of a net zero transition must likewise take full account of national and sub-national legislation and powers. For example, land use change in Scotland is likely to deliver a significant proportion of the C sequestration required for the whole of the UK by 2050 (Alcalde et al., 2018; CCC, 2019). The risk here is that misaligned constitutional competencies lead to sub-national mitigation being hindered, with aggregate national targets then being missed.

### Permanence

Ultimately the success of a net zero transition is measured by its sustainability and the negative impacts of climate change that it prevents. Where changes in land use to enhance C sequestration are only short-term (a few years or decades) and are then reversed, the benefits in terms of reduced climate change impacts may be negligible (Kirschbaum, 2006). This "permanence" issue should therefore be a fundamental consideration in future support systems. Current financial support for such agricultural land use change in the UK is commonly for 5–10 years, with a requirement that new woodland remains in place for 20 years (Commission, 2019). Likewise, though soil C this can be enhanced in some areas through changed farming practices (e.g., minimum tillage) or changed land use (e.g., woodland creation) any particular enhancement is both limited and reversible. For highly degraded soils the gains in soil C through changed land use may initially be very rapid, but in all systems an equilibrium level will eventually be reached and subsequent return to cultivation can then mean rapid loss of stored C to the atmosphere.

Any enhanced C sequestration achieved may therefore be short-lived as land is converted back to its original use once funding and contractual obligations have expired. While the design of future land use support systems could help mitigate such permanence risks, there are aligned policy approaches that may provide even more sequestration security. Direct linkage of enhanced timber production with building construction could, for instance, greatly extend the magnitude and average lifetime of sequestered C—high use of timber in urban building construction could store up to 0.68 GTC $y^{-1}$ globally (Churkina et al., 2020).

Soil amendments, such as biochar or the use of basic and ultrabasic minerals for enhanced weathering, also have the potential to provide much longer lifetimes for C sequestration in the land use sector, though with significant barriers to large scale implementation in sourcing of sustainable feedstocks, costs, and land availability (Alcalde et al., 2018).

Finally, combustion of biomass for energy and capture and geological storage of the associated $CO_2$ (Biomass Energy with Carbon Capture and Storage, BECCS), promises very long term (multi-millennial) C storage and so could play a very large role in future land use strategies to achieve net zero (Azar et al., 2010). Again, unsustainable feedstock sources, high costs, and limited land availability represent significant barriers to successful implementation (Fajardy and Mac Dowell, 2017; Harper et al., 2018).

## Leakage

Like permanence, the issue of "leakage" is one that has already challenged many land use change policies designed to help mitigate climate change (Schwarze et al., 2002). Here, emissions reductions or enhanced sequestration in one place are partly or wholly offset by increased emissions elsewhere—forest protection one area leading to increased deforestation in another for instance. At national scales such leakage results in effective offshoring of a nation's reported emissions as these are reported to the UNFCCC on a production (rather than consumption) basis.

Were new land use and agriculture support policies to align with net zero ambitions in a way that reduced national food self-sufficiency, and so raised food imports, then such offshoring of emissions would be highly likely. One illustration of these risks for the UK is in the expansion of commercial forestry. As described previously, expansion of forestry combined with increased use of timber for construction offers a way to address some of the permanence issues inherent in land-based climate mitigation policies. For the UK such a transition could mitigate over 2 tons $CO_2e$ $ha^{-1}$ over a 100 year time horizon. However, the effective mitigation per hectare of forest could be halved if this forest expansion resulted in displacement of UK beef production to Brazil (Forster et al., 2019).

Another recently highlighted example of such risks is that of a 100% conversion to organic food production in England and Wales. Under such a scenario, domestic food production and production-based emissions estimates would fall, but overseas emissions (including those due to land use change) could rise to an extent that would more than offset any of the emission reductions seen in England and Wales (Smith L. G. et al., 2019).

Leakage is therefore of major importance for agriculture and land use in the context of global net zero ambitions as it can entirely undermine the global efficacy of national actions to tackle climate change (de Ruiter et al., 2016).

# REALIZING NET ZERO

## Governance

For the UK, indeed for all nations, important lessons can be learned from existing international frameworks relating to land use. The UN's REDD (Reduced Emissions from Deforestation and Degradation) programme and in particular its "Cancun Safeguards" (Chhatre et al., 2012) provide an exemplar of efforts to balance multiple competing needs within a finite land area. Though developed with forestry in mind, these safeguards—such as transparent and effective governance—could usefully align with wider rural policy development as nations like the UK strive to deliver net zero alongside a multitude of other goals.

Transparent and effective land use governance for net zero could not only help avoid unintended consequences of policy changes, they would also help to ensure that aggregate change remains compatible with targets. To give alignment with international and national commitments, the balancing of natural ecosystem and biodiversity protection with net zero and food production goals must be overtly integrated within rural policy development, support and MRV (Monitoring, Reporting, and Verification). Past on-farm mitigation or woodland planting schemes, for instance, may well have provided multiple "public goods," but the evidence base for these is badly lacking (Burton et al., 2018).

Independent advice on emission reduction targets and pathways is a central plank of any sustainable strategy to deliver net zero. In this, the UK's Committee on Climate Change already serves a vital role in advising government and monitoring progress at a UK-wide level and at a devolved administration level (McGregor et al., 2012). This has allowed integration of national and sub-national targets along with a consistent use of the evidence base. However, the co-dependency of UK and devolved administration climate targets means policy development and implementation must be well-integrated too. To avoid a cross-border blame game of shortfalls and delays, governance and delivery of the UK's regionally-biased demands on land use for net zero will therefore need to tread a careful line to ensure transparency is maintained and that the competencies and circumstances of the devolved administrations are respected.

## Finance

Effective financial support systems will be fundamental to realizing net zero via land use change. These could be adaptations of existing systems (like revised CAP payments) (Matthews, 2013), newly developed ones directly targeted at public goods (e.g., the UK's Agriculture Bill and its ELM scheme; Rayment, 2019; Rodgers, 2019), or more market-led climate change-specific approaches such as carbon pricing and offsets (Crossman et al., 2011). Each has its strengths and weaknesses.

For revision of the EU's Common Agricultural Policy (CAP), a strength could be its proposed "Eco-scheme" which would allow member states more latitude to align subsidies with net zero objectives and so drive more rapid change. The potential weakness here is that that same latitude is used to water down climate change action in the agriculture sector for nations where short-term political pressures or climate-skeptic ideologies prevail (Dupraz and Guyomard, 2019).

For the "Environmental Land Management" (ELM) scheme proposed as part of post-CAP support in England, there are significant strengths in the overt linkage of climate change mitigation and resilience to future support—allowing government to much more directly incentivise both emissions reductions and C sequestration in the agriculture and land use sectors. Key potential weaknesses again include the danger that political pressures distort incentive levels and focus. There also remain major questions around how such an ELM support scheme would reliably calculate the correct price points for specific actions, and indeed whether it is actions that should rewarded or the outcomes of these actions (Rayment, 2019).

On carbon pricing and offsets, such market-based mechanisms to incentivise land use that aligns with net zero have the significant advantage that they rely less (or not at all) on public funds and can in theory deliver the most cost effective land-based mitigation or C sequestration for any particular area or land owner. However, as evidenced by existing carbon markets, too low a carbon price can stymie activity (Wood and Jotzo, 2011) and so a carbon price floor or guarantee (as currently offered for woodland planting schemes in England for example; Government, 2019) may then be required. This price intervention then inevitably poses the risks of unintended market distortions and a greater reliance on public funds.

All of the above could also exacerbate leakage issues due to financial incentives that overvalue, say, tree planting at the expense of food production or "permanence" issues due to incentives having short lifetimes or weak assurance mechanisms for upkeep of the change in land use. Unintended market distortions such as offshoring of emissions could be limited through modeling of consumption-based emissions effects and tailoring of incentive type, magnitude and timing to better forecast and align changes in domestic food production with changes in domestic demand and global markets.

Clearly, well-directed financial incentives can simultaneously provide substantial emission reductions, C sequestration and climate resilience in the land use sector. A crucial aspect of such incentives in helping to deliver net zero aims will be creating a support system that is nuanced enough to lead to the best land management changes within local contexts while still being attuned to transboundary (e.g., leakage) and temporal (e.g., permanence) safeguarding.

## Skills

Financial support for achieving net zero is only useful if it is accessible. Land managers will need support in aligning practices with any new suite of mitigation and sequestration options available for their circumstances. They will also need assistance with how to meet any mandatory compliance checks and MRV requirements. For many, training in new skills (e.g., silviculture and agroforestry practices) will be required, while others may need assistance with best application of new technologies and practices (e.g., drone technology, farm nutrient budgeting and animal health improvements) (Feliciano et al., 2014).

Net zero capacity-building in the agriculture sector could be supported by a more comprehensive version of existing extension services, perhaps aligned to improved digital learning resources (Feliciano et al., 2017). It is also likely to require new service providers to either advise on, or provide directly, specific elements of net zero-aligned rural support. Commercial companies already provide a swathe of agricultural testing, equipment and advisory services. As specific elements of new rural support regimes become clear, so the private sector can be expected to respond to changing needs and demands. For instance, field-scale soil carbon testing may well become a requirement for farms wishing to access new subsidy payments. A certain level of such testing might be covered by publicly-funded extension services, but commercial testing, modeling and on-farm soil C estimation tools (Malone et al., 2017) are likely to play a major role in allowing all farmers to meet future MRV requirements (Smith et al., 2020).

Crucially, farm-level decision support tools would also need to be further developed to support new practices at locally-relevant scales across the UK. There is already a plethora of such tools, but engagement rates are generally low (Rose et al., 2016). Direct integration with new rural support systems, combined with greater usability, is therefore required.

Existing or emerging extension service providers would themselves need significant new training and resources in order to deliver to such emerging decision support and MRV needs. More widely there is a need for formal educational providers, such as Further and Higher Education Institutions, to align their provision with economy-wide net zero goals (Allan et al., 2020), including those relating to land use and agriculture. Part of this alignment could arise from a deliberate refocus of state-funding for courses and student places, while much could be driven by student demand and the rapid expansion in land use sector job opportunities and skills needs that a sustainable net zero transition represents.

## Research and Development

A robust evidence base for changes in rural policy is a further prerequisite for net zero. However, this research base is far from complete. New technologies, along with improved data availability and fast-changing energy systems, can certainly become powerful facilitators of a net zero pathway for land use and agriculture. Precision agriculture, for example (including drone technology, machine guidance, and field-based sensors), has developed apace and is already commercially viable for many of the larger arable farms in the developed world (Balafoutis et al., 2017). However there remain issues of accessibility to these and other technologies that could improve productivity for many farms and so enhance overall land sparing for sequestration (Long et al., 2016).

For large scale land-use dependent mitigation strategies, such as BECCS, there are significant research questions still to answer in terms of sustainable feedstock types and sources, land suitability and availability, risks to biodiversity and supporting infrastructure requirements (Donnison et al., 2020). Likewise for many of the proposed on-farm mitigation strategies that could contribute to net zero targets (Lampkin et al., 2019), such as slurry storage and application (Amon et al., 2006; Misselbrook et al., 2016), livestock breeding and feed additives (Wall et al., 2010; Gerber et al., 2013), soil and fertilizer amendments (Cayuela et al., 2014), and altered land management (Powlson et al., 2014; Garnett et al., 2017), there are uncertainties in terms of efficacy under different site conditions and potential negative side effects of implementation. For example, nitrification inhibitors offer significant potential to reduce $N_2O$ emissions from nitrogen fertilizer application, yet they may also increase $NH_3$ emissions (Soares et al., 2012) and so swap a climate change penalty for an air quality and biodiversity one.

Aligned to the need for a robust evidence base for land-based mitigation decisions at local scales is that of risk and resilience assessments (Sample et al., 2016). These, such as to account for changing climate, invasive species, and pest and disease risks, also require a degree of spatial and temporal resolution that is meaningful at farm scales. In the UK, the UKCP09 and UKCP18 climate projection products provide a good basis for this (Brown et al., 2011), but translation, downscaling and integration of such information into an effective decision support system for land users still requires a significant effort from research providers and advisors.

Crucially, extensive social, ecological, and economic research is needed to complement and challenge assessments of technical feasibility. The kinds of rapid and large scale changes in land use that are required to help to deliver net zero will not happen in a vacuum. For instance, livelihoods and community cohesion may be put at risk as financial support is refocused on different land use practices and outcomes (Mills, 2012), while changing diets and import-export tariffs may radically alter demand and market prices in ways national governments cannot fully control (Hubbard et al., 2019; Willett et al., 2019).

Indeed, even addressing the physical issues of "leakage" in national emissions discussed earlier could have profound negative social impacts internationally. A more self-sufficient UK food system would, for example, mean reduced imports of food and fiber. This transition could certainly help to avoid the offshoring of emissions, but it may simultaneously undermine livelihoods overseas and so could hinder overseas development (Larch and Wanner, 2017; Böhringer et al., 2018).

## Society

Achieving a just transition to net zero is arguably the most important aspect of all. Reductions in the land area used for agriculture are likely to be focussed on lower grade land, and so any negative impacts on livelihoods and communities may be magnified even further by the limited access to markets and infrastructure common to these areas (Ruben and Pender, 2004). As already highlighted, these local contexts and risks must be integrated into the design of any new support system, identifying the optimal change both from a physical basis and from a social basis (Feliciano et al., 2013).

High levels of engagement with and support from rural communities are required (Miller et al., 2009), again taking account of national circumstances and devolved powers. Regional land use strategies—as proposed in Scotland's Land Use Strategy (ScotGov., 2011)—could be a good starting point to address the inevitable synergies and antagonisms that arise from multiple land use objectives. They would need to be supported by improved data availability and an integrated decision support system that combines the physical and social realities at a locally relevant scale (Midgley et al., 2005). Such a system (drawing on an agent-based modeling or scenarios approach for instance; Brown and Castellazzi, 2014; Verburg et al., 2019) could be used to better identify risks and opportunities of differing support schemes and approaches. Flexibility within regional land use strategies would then help ensure that social and community priorities are better respected and could provide a dynamic structure through which national targets are kept on track.

Examinations of regional-scale approaches in Scotland have highlighted the importance of community engagement and acknowledgment of local contexts (Sutherland et al., 2011; Slee et al., 2014). This can be easier said than done of course—ideally there are existing community groups and structures that would facilitate such engagement (Rouillard et al., 2014), but this will vary from region to region and there is an inevitable trade-off between the benefits of fine scale applicability and the overheads of coordination and support required for this.

A governance system that allows effective flows of engagement and support from, say, individual landowner level, through community level, and up to local authority and regional scales would be required. Here, "regional boards" have been suggested whereby a diversity of stakeholders are represented from across the region and their representatives (or "trusted intermediaries" as they have been described for integrated catchment management; Rouillard and Spray, 2017) then provide a direct connection back to community and individual land owner levels.

Given the central role of local government in planning policy, individual (if very large) or multiple (if aligned to particular catchments for instance) local authorities might then have a formalized role in coordination of regional land use partnerships and in the design, implementation and reporting requirements of the regional frameworks that would underpin them. Such formal accountability is likely to be required to ensure sustainability of a land use strategy that must evolve in line with economy wide goals like net zero emissions. One risk is that such regional devolution of land use strategy would result in overall national divergence from a net zero pathway, so a dynamic feedback system for central government (e.g., modeled envelopes of land use change options and resulting emissions reductions for each region) would be required. Another major barrier is likely to be that of capacity within local authorities to effectively deliver this coordination and reporting role (Hislop et al., 2019). Addressing these issues will likely need both substantial capacity building within local government and additional financial support from central government.

# CONCLUSIONS

More overt alignment of the agriculture and land use sectors with delivery of the Paris Climate Goals is inevitable. Whether the huge transitions required will be sustainable, just, and timely enough is far more questionable. An inherent risk is that emissions reduction objectives exert disproportionate pressures through food production systems, leading to unintended distortion of policies and markets, and ultimately to highly damaging failures.

The levels of integration required across governance, finance, skills, research and development, and social systems are daunting. The research community now has a vital role to play in supporting policy makers, farmers and all those involved in the land use sector to attain these high levels of integration.

Developed nations like the UK have a real opportunity to simultaneously deliver net zero emissions, secure the future of rural employment and enhance the myriad other "public goods" our land provides. Yes, realizing an effective system that can fully optimize agricultural support and land use decision-making across a whole nation is a huge undertaking, yet the potential pitfalls and missed opportunities of a "carbon blinkered" pathway to net zero are bigger still.

## AUTHOR CONTRIBUTIONS

DR devised and wrote the manuscript.

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frontiers in Climate

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# Life Cycle Assessment of Carbon Capture and Utilization for the Production of Large Volume Organic Chemicals

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The combination of carbon capture and utilization (CCU) and water electrolysis technologies can be used for the production of basic chemicals from carbon dioxide ($CO_2$) and hydrogen. Here, we present a life cycle assessment (LCA) on a cradle-to-gate basis for the production of the following large volume organic chemicals: methanol, ethylene, propylene, benzene, toluene, and mixed xylenes. Investigated process chains comprise the following technologies: $CO_2$ capture from an industrial point-source or from the atmosphere through direct air capture (DAC); alkaline water electrolysis for hydrogen production; methanol synthesis; methanol-to-olefins and methanol-to-aromatics synthesis including aromatics separation. Electricity is supplied by offshore wind turbines. The system boundary includes all relevant processes from cradle to gate. A scenario was set up by exchanging the background processes for the production of important infrastructure materials like aluminum, copper, steel, and concrete with future processes that are less resource intensive, less carbon intensive and include higher recycling rates (e.g., electric arc furnaces for steel production). LCA results show that the synthesis of the investigated chemicals from CCU processes will reduce greenhouse gas (GHG) emissions by 88–97%, compared to fossil-based production routes, when electricity from offshore wind turbines is used. At the same time, other environmental impacts like eutrophication and ozone depletion will increase. The main contributors to the environmental impacts are the energy supply for water electrolysis and direct air capture. Replacement of all plants for the production of the investigated products in Germany with CCU processes would lead to a 2–7% higher total primary energy demand for the whole country. At the same time, an overall reduction of the German GHG emissions by 6% is achieved, when using offshore wind power for these processes only. The future scenario using improved background technologies leads to a further small reduction of GHG emissions and largely reduces other environmental impacts. We therefore identify the reduction of emissions through improved base material production processes and recycling of aluminum, copper, steel and concrete as main objectives to reduce negative impacts for the production of basic chemicals from CCU technologies.

**Keywords: life cycle assesment, carbon capture and utilization (CCU), carbon dioxide, organic chemicals, cradle-to-gate**

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## INTRODUCTION

The intense use of fossil resources leads to growing carbon dioxide ($CO_2$) concentrations in the atmosphere and significant global warming, caused by the anthropogenic greenhouse effect (IPCC, 2018). In order to reduce greenhouse gas (GHG) emissions and to access alternative carbon sources in the chemical industry, new approaches through carbon capture and utilization (CCU) are discussed in science and industry (Mikkelsen et al., 2010; Kuckshinrichs and Hake, 2015; Otto et al., 2015; Sanz-Pérez et al., 2016; DECHEMA, 2017; Artz et al., 2018; Kätelhön et al., 2019). While most of the latest publications focus on the production of power-to-gas or power-to-liquid fuels (Merano and Ciferno, 2001; Jaramillo et al., 2008; Zhang et al., 2015; Sternberg and Bardow, 2016; UBA, 2016; Schmidt et al., 2018; Alhyari et al., 2019; Koj et al., 2019), only few consider the application of CCU for the production of chemicals (Kaiser et al., 2013; Kim et al., 2014; Otto et al., 2015). A discussion about the effect of substituting bulk chemicals such as methanol or ethylene through CCU products was started by Kätelhön et al. (2019). By substituting the feedstock of these bulk chemicals—replacing fossil resources by renewables—the production processes and amounts of downstream products like plastics or pharmaceuticals could remain unchanged. This would allow the chemical industry to use established process chains without major transformation challenges in the near future.

The development of alternative processes for the production of chemicals was often caused by scarcities of particular resources, e.g., the oil embargo in Germany during the Second World War, leading to the development of the Fischer-Tropsch-synthesis of hydrocarbons (Henrici-Olivé and Olivé, 1976), or the abundance of resources like coal leading to a majority of coal-based chemicals in China (Xu et al., 2017). The growing amount of $CO_2$ in the atmosphere—around 3,200 Gt $CO_2$ up to now (Le Quéré et al., 2018)—has a large global warming potential but may function as a possible resource. New strategies are developed to reduce this amount through sequestration or to use $CO_2$ as a feedstock chemical (Hasan et al., 2015). While carbon capture and sequestration (CCS) would lead to permanent removal of $CO_2$ from the atmosphere, the climate change mitigation potential of CCU is controversially discussed, because $CO_2$ in products is only stored temporarily. When $CO_2$ from fossil sources is used, CCU products only post-pone $CO_2$ emissions. Mac Dowell et al. (2017) state, that CCU may only account for 4–8% of the total mitigation challenge and hence, may prove to be a "costly distraction [...] from the real task" of mitigating climate change.

There are several LCA studies that were published in the last years, highlighting the GHG effects of CCU on chemical production, such as polyols and polyurethane (Von Der Assen and Bardow, 2014), $C_1$ chemicals in general, formic acid, methane, methanol, dimethyl ether and derived polymers (Matzen and Demirel, 2016; Sternberg et al., 2017; Hoppe et al., 2018; Aldaco et al., 2019) and various other chemicals (Thonemann and Pizzol, 2019). As upcoming CCU technologies may help to reduce $CO_2$ emissions, impacts in other categories are often neglected. Focusing on climate change mitigation only, might neglect undesired environmental effects (Hoppe et al., 2018; Rosental, 2020), hence, a holistic approach is necessary to assess a broad selection of potential environmental risks: Life cycle assessment (LCA) is a suitable method to evaluate such environmental impacts. Including the whole life cycle of the products prevents the shift of environmental risks beyond the observed system. The following LCA study will provide a detailed examination of all relevant processes necessary to obtain $CO_2$ and produce hydrogen on a renewable basis, used for the production of basic chemicals and furthermore an assessment in multiple environmental impact categories, which is lacking up to date.

## GOAL AND SCOPE OF THE LCA

The objective of this LCA study is to quantify the global warming impact (GWI) and other environmental impacts of CCU technologies and to identify key elements to reduce environmental impacts. Therefore, we investigate the environmental impacts of large volume basic chemicals produced from CCU with offshore wind energy compared to the present fossil-based production. Results of the "RESCUE" study (Resource-Efficient Pathways to Greenhouse-Gas-Neutrality) of the German Environment Agency (UBA, 2019b) will be used to model pathways of a base materials supply in 2050. This will be compared to the present base materials production. Based on this model, we identify significant key parameters to reduce overall emissions that result from renewable CCU chemical production. Including other impact categories besides global warming will assure a holistic approach of the LCA, quantifying environmental impacts for the production of basic chemicals from renewable sources.

### Product System and System Boundaries

The product system is shown schematically in **Figure 1**. The foreground system (FGS) consists of a $CO_2$ capturing module (DAC or amine scrubbing), an electrolysis module and a synthesis process. $CO_2$ and hydrogen are reacted in a chemical plant to synthesize the desired product, which is processed for further purification of single compounds. The product system also includes electricity and heat generation, infrastructure and auxiliary material provisions as background system (BGS). Following a 100:0 allocation approach, the $CO_2$ point-source is excluded from the system, leaving all expenses and burdens for producing $CO_2$ and main products (e.g., clinker or energy) on the emitting system. Reference systems comprise state of the art production of methanol from syngas, olefins from steam cracking and aromatics from catalytic reforming of naphtha. We decide not to use the system expansion approach as this

**Abbreviations:** AE, alkaline electrolysis; AP, acidification potential; BTX, benzene, toluene, xylene; CCU, carbon capture and utilization; CED, cumulated energy demand; C2G, cradle-to-gate; DAC, direct air capture; EoL, end-of-life; EP, eutrophication potential; GHG, greenhouse gas; GWI, global warming impact; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; LHV, lower heating value; MEA, monoethanolamine; MTA, methanol-to-aromatics; MTO, methanol-to-olefins; ODP, ozone depletion potential; $PM_{2.5}$, particulate matter with a diameter <2.5 µm; PS, point-source; $\Delta H_R^0$, standard reaction enthalpy.

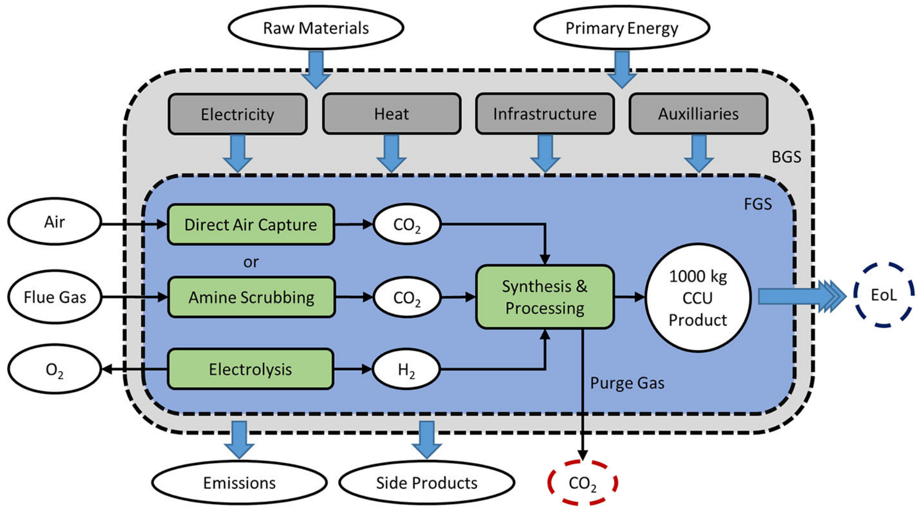


**FIGURE 1 |** Product system containing fore- and background systems (FGS = blue, BGS = gray). $CO_2$ can be extracted from air by DAC, or from a point-source using amine scrubbing. Hydrogen is provided by alkaline electrolysis. CCU products are synthesized and processed for purification. The functional unit (FU) is defined as 1,000 kg of a CCU product. EoL = end-of-life, side products = butene, alkylated aromatics, etc. (compare **Table 2**).

would change the scope and functional unit of this study, focussing on chemical products only. Applying system expansion would lead to several by-products needed to be taken into account, followed by comparability issues due to different possible functional units for several $CO_2$ point-sources (Von Der Assen et al., 2013). System boundaries for chemical products are cradle-to-gate, so further phases of processing, distribution, use, and recycling or disposal until end-of-life (EoL) are not considered.

## Functional Unit and Allocation Method

The functional unit (FU) is defined as one metric ton (1,000 kg) of one of the desired products, respectively: methanol, ethylene, propylene, benzene, toluene, mixed xylenes. Physical allocation by mass is applied by default. In chemical synthesis and processing, feedstock is allocated to all products; energy input and other expenses and emissions (including direct $CO_2$ emissions from purge gas combustion) are allocated by mass to the intended products only (see **Table 2**). All other by-products carry the burdens of the respective feedstock and are not investigated further, following existing methodological recommendations of the European Commission and PlasticsEurope (European Commission, 2003, 2019; PlasticsEurope, 2017). As a result, target products from the same process have identical environmental impacts per kg of product. In the Results section (chapter 4) products will be presented in three groups: methanol, olefins (ethylene and propylene) and BTX (benzene, toluene, xylenes). Oxygen from water electrolysis is considered an unintended by-product which receives no burdens, leaving all burdens on the main product hydrogen, following a conservative approach. Lost $CO_2$ from purge gas combustion is taken into account for captured $CO_2$, which will not be incorporated in the CCU product. The additional expenses, energy and resource requirements are assigned to the main products, the corresponding direct $CO_2$ emissions are reported separately. Excess thermal energy receives no burdens.

## Accounting Method for $CO_2$

As a consequence of the 100:0 allocation approach, the uptake of $CO_2$ is treated as negative emissions (−1 kg/kg) and the release at all life cycle stages, including $CO_2$ at end-of-life (EoL), as positive emissions (+1 kg/kg), balancing each other in absolute terms. Emissions during further processing, distribution, use and recycling or disposal are not taken into account. Only the stoichiometrically calculated emission of $CO_2$ at EoL from complete combustion of the product is considered and reported separately, because long-time storage of $CO_2$ cannot be guaranteed. Therefore, system boundaries are expanded to cradle-to-gate + end-of-life (C2G + EoL) for global warming impacts. Accounting for the release of temporarily stored carbon[1] avoids reporting net-negative $CO_2$ emission results, which otherwise would be calculated using the cradle-to-gate approach in the 100:0 allocation method. Additionally, exemplary results for the 0:100 allocation approach are calculated for $CO_2$ point-sources to demonstrate the pitfalls that can lead to omitted accounting of fossil $CO_2$ emissions.

## Impact Categories

For the life cycle impact assessment (LCIA) six relevant impact categories are considered (**Table 1**). These categories (GWI, CED, AP, EP, ODP, $PM_{2.5}$) represent commonly affected environmental impacts, where conflicts of interest could occur

[1] Carbon incorporated in the products, expressed in $CO_2$-eq. (conversion factor 3.66 kg $CO_2$/kg C): 1,375 kg $CO_2$t methanol; 3,143 kg $CO_2$t ethylene/propylene; 3,385 kg $CO_2$t benzene; 3,348 kg $CO_2$t toluene; 3,321 kg $CO_2$t xylene.

**TABLE 1** | Impact categories used for the LCIA, relevant indicators, and underlying method.

| Impact Category | Indicator | Unit | Method and Source |
|---|---|---|---|
| Global Warming Impact (GWI) | Potential global warming in a 100 year time horizon due to emissions of greenhouse gases to air which increase radiative forcing | kg $CO_2$-eq | IPCC, 2013 |
| Cumulated Energy Demand (CED) | Total energy content of all fossil, nuclear and renewable energies consumed | GJ | VDI, 2012 |
| Acidification Potential (AP) | Potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulfur oxides | kg $SO_2$-eq | Hauschild and Wenzel, 1998; CML, 2015 |
| Eutrophication Potential (EP) | Enrichment of the aquatic and terrestrial ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds | kg $PO_4$-eq | Hauschild and Wenzel, 1998; David et al., 2019 |
| Ozone Depletion Potential (ODP) | Emissions of halogenated hydrocarbons to air that cause destruction of the stratospheric ozone layer | g CFC-11-eq | WMO, 2014 |
| Particulate Matter Formation ($PM_{2.5}$) | Particulate matter emissions to air that cause damage to human health | g $PM_{2.5}$-eq | De Leeuw, 2002; SAEFL, 2003 |

in terms of environmental protection goals (UBA, 2017). Other relevant impact categories such as freshwater consumption or land use were excluded due to the lack of primary data for CCU plants in the foreground system or missing reference values in the ecoinvent and PlasticsEurope datasets for feasible comparability.

## General Assumptions and Limitations

Model parameters can be modified in many possible ways, therefore, a general set of comprehensive (background system) assumptions is applied:

1. Electricity is provided by offshore wind turbines in general; energy storage is not considered. The emission factor of offshore wind energy is 5.4 g $kWh^{-1}$ in 2010 and 2.4 g $kWh^{-1}$ in 2050 (UBA, 2020).
2. Heat energy is provided by electric heating with energy from offshore wind turbines.
3. Excess heat energy from chemical reactions is used for $CO_2$ capture thermal energy demand with 100% efficiency.
4. Manufacturing of aluminum, copper, steel, and concrete is adjusted to an optimized resource extraction and recycling, projected for the year 2050 according to the "RESCUE" study (Resource-Efficient Pathways to Greenhouse-Gas-Neutrality) of the German Environment Agency (UBA, 2019b); comparison with the current situation (year 2010) is shown.
5. $CO_2$ capture, water electrolysis and chemical synthesis are conducted "on-site," therefore infrastructure for compression, transportation and distribution is neglected.
6. Production infrastructure is included, as the relative impacts of fossil-based infrastructure becomes relevant when energy from non-fossil energy sources is used for the foreground processes.
7. Production plants are operated at full capacity (8,700 h $a^{-1}$); the production capacity of ecoinvent modules (chemical factory, organics) with 50 kt $a^{-1}$ and 50 years lifetime is scaled according to the product output and infrastructure specifications shown in **Table 3**.
8. It is assumed that chemical synthesis is carried out with a 2% purge gas combustion to prevent reactors from accumulating inert gases. Complete conversion of the purge gas to $CO_2$ and water is assumed.

Limitations for these assumptions include (a) heat integration with 100% energy efficiency assumed and without separating temperature levels; (b) purge gas combustion neglecting the formation of other organic and inorganic compounds, therefore only accounting for GWI as impact category; (c) EoL impacts of the products covering stoichiometrically calculated $CO_2$ emissions only. These assumptions frame a "best case" scenario with utilization of renewable low-carbon energy, minimal transport distances, maximum energy efficiency, and optimized resource pathways in which CCU production of chemicals could take place.

The fossil reference system is not affected by those assumptions, especially energy and construction material supply and therefore, was not prospectively assessed. Feedstock and main operation processes will remain unchanged, e.g., steam cracking, as these processes are defined as reference. While energy supply does not play a significant role for these fossil processes, construction materials are neglectable for a large scale chemical production (PlasticsEurope, 2012, 2013).

# INVESTIGATED PROCESSES AND INVENTORY

Here, the chemical processes necessary for operating CCU technologies to produce chemicals are described shortly. Input and output metrics of the synthesis and processing life cycle inventory (LCI) are given in **Table 2**, detailed technological parameters are shown in **Table 3**. Direct air capture, amine scrubbing, electrolysis, background system and energy models

**TABLE 2 |** Input and output metrics of chemical synthesis modules producing 1,000 kg of the respective product.

| CCU-Product | Input | Amount | Unit | Output | Amount | Unit |
|---|---|---|---|---|---|---|
| **Methanol** | $CO_2$ | 1,441 | kg | **Methanol** | 1,000 | kg |
| | $H_2$ | 203 | kg | Water | 578 | kg |
| | Electricity | 1,188,000 | kJ | $CO_2$ | 66 | kg |
| | Infrastructure | 2.35E-07 | units | Heat | 1,400,000 | Kj |
| | $Al_2O_3$ | 0.183 | kg | | | |
| | CuO | 1.172 | kg | | | |
| | MgO | 0.037 | kg | | | |
| | ZnO | 0.439 | kg | | | |
| **Olefins (MTO)** | Methanol | 5,437 | kg | **Ethylene** | 1,000 | kg |
| | Electricity | 5,436,735 | kJ | **Propylene** | 800 | kg |
| | Infrastructure | 6.21E-07 | units | Butene | 230 | kg |
| | Zeolite | 1.396 | kg | Aliphatics | 230 | kg |
| | | | | $CO_2$ | 145 | kg |
| | | | | Water | 3,033 | kg |
| | | | | Heat | 4,461,384 | kJ |
| **Aromatics (MTA)** | Methanol | 130,989 | kg | **Benzene** | 1,000 | kg |
| | Electricity | 24,091,588 | kJ | Aliphatics $C_5+$ | 6,418 | kg |
| | Infrastructure | 1.50E-05 | units | **Ethylbenzene** | 463 | kg |
| | Zeolite | 33.645 | kg | **Ethyltoluene** | 1,171 | kg |
| | | | | **Isopropylbenzene** | 49 | kg |
| | | | | **Olefines $C_2$-$C_4$** | 25,674 | kg |
| | | | | **Tetramethylbenzene** | 1,049 | kg |
| | | | | **Trimethylbenzene** | 3,439 | kg |
| | | | | ***m*-Xylene** | 5,561 | kg |
| | | | | ***o*-Xylene** | 2,195 | kg |
| | | | | ***p*-Xylene** | 2,439 | kg |
| | | | | **Toluene** | 6,244 | kg |
| | | | | $CO_2$ | 1,500 | kg |
| | | | | Water | 73,787 | kg |
| | | | | Heat | 182,911,274 | kJ |
| **BTX Separation** | MTA Production Mix | 55,702 | kg | **Benzene** | 1,000 | Kg |
| | Electricity | 79,506,982 | kJ | **Toluene** | 6,244 | kg |
| | Process Water | 14,482 | kg | **Xylenes** | 10,658 | kg |
| | | | | Other | 37,800 | kg |

*Products considered "intended" (receiving expenses and burdens) are shown in bold letters, other products are process burden free.*

were adapted according to the SYSEET study, detailed building parameters are given in the annex[2] of this study (UBA, 2020).

## Direct Air Capture

In the DAC unit, air is filtered through an amine functionalized adsorbent capturing $CO_2$. After reaching full capacity, the unit is evacuated and heated to release purified $CO_2$. Pilot plants are operated by Climeworks, providing technological data for the overall process (Climeworks, 2018a). The unit is operated between 80°C and 120°C with a thermal energy demand of 5.76–7.92 GJ $t^{-1}$ $CO_2$ and an electricity demand of 1.44–2.52 GJ $t^{-1}$ $CO_2$. The yearly production rate is 1,800 t $CO_2$ $a^{-1}$ with a unit lifetime of 12 years (Climeworks, 2018b). Detailed reviews of current DAC technologies, as well as economic considerations are given by Sanz-Pérez et al. (2016) and Fasihi et al. (2019).

[2]Available at: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/syseet_eingangsdaten_oekobilanzrechnungen.xlsx (German only).

## Amine Scrubbing

Capturing $CO_2$ from point-source flue gases can be achieved through amine scrubbing with aqueous amine solutions, e.g., with monoethanolamine (MEA) (Knudsen et al., 2009; Rochelle, 2009; Luis, 2016). MEA is synthesized by oxidation of ethylene to ethylene oxide and further conversion by reacting it with ammonia. MEA absorbs $CO_2$ by reacting to the carbamate in alkaline solution and heating the $CO_2$ rich solution will regenerate MEA and release pure $CO_2$. Typical amine solutions consist of 20–30 wt% MEA and reach an absorbance of 90% $CO_2$. The production capacity of the capture unit is 1.88 Mt $a^{-1}$

**TABLE 3** | Technological parameters of alkaline electrolysis, $CO_2$ capture, and CCU synthesis modules.

| Alkaline Electrolysis | | $CO_2$ Capture | | |
|---|---|---|---|---|
| | | | **DAC** | **Point-Source** |
| Product | $H_2$ | Product | $CO_2$ | $CO_2$ |
| Capacity (t/a) | 233 | Capacity (t/a) | 1,800 | 1,880,000 |
| Lifetime (a) | 20 | Lifetime (a) | 12 | 50 |
| Electrolysis Power (kW) | 6,000 | $CO_2$ Concentration (%) | 0.04 | 20 |
| Efficiency* (%) | 67/80 | MEA Loss (kg/t) | - | 2.00 |
| El. Energy (kJ/kg) | 177,433/150,000 | El. Energy (kJ/kg) | 2,520/1,440 | 54 |
| Heat (kJ/kg) | −58,069 | Heat (kJ/kg) | 7,920/5,760 | 3,134 |

| CCU Synthesis | | | |
|---|---|---|---|
| | **Methanol Synthesis** | **MTO** | **MTA** |
| Product | Methanol | Ethylene/Propylene | Benzene/Toluene/Xylene |
| Capacity (t/a) | 626,908 | 2,007,500** | 2,007,500** |
| Lifetime (a) | 50 | 50 | 50 |
| Catalyst | $CuO/ZnO/MgO/Al_2O_3$ | SAPO-34 | HZSM-5 |
| Catalyst load (t/a) | 156 | 45 | 45 |
| El. Energy (kJ/kg) | 1,188 | 1,000** | 1,000** |
| Heat (kJ/kg) | −1,400 | −820** | −820** |

*Negative values in CCU synthesis imply energy export to heat integration, duplicated values represent year 2010/2050 system parameters. *lower heating value (LHV) **related to kg methanol input.*

with a lifetime of 50 years. Thermal energy demand for a flue gas containing 20% $CO_2$ is around 3.13 GJ $t^{-1}$ $CO_2$ and the electricity demand is 54 MJ $t^{-1}$ $CO_2$ (Husebye et al., 2012). The degradation of MEA amounts to 2 kg $t^{-1}$ captured $CO_2$. Mechanisms for the degradation of amine solutions have been studied intensively (Goff and Rochelle, 2004; Bello and Idem, 2005), while the monitoring of pilot plants operated in Mongstad, Norway gives detailed emission results from $CO_2$ capture with MEA (Morken et al., 2014, 2017).

## Alkaline Water Electrolysis

Alkaline electrolysis (AE) is achieved in solutions of 20–30 wt% NaOH or KOH with nickel electrodes, separated by a diaphragm. Hydrogen is produced at the cathode, while oxygen is produced at the anode (Equation 1). Typical specifications are operating temperatures of 60–80°C, cell pressures <30 bar, current densities <0.45 A $cm^{-2}$, cell voltages of 1.8–2.4 V and electrical efficiencies ranging from 62 to 82% (lower heating value, LHV) (David et al., 2019). In this study an efficiency of 67% is used.

$$2H_2O \rightarrow 2H_2 + O_2 \qquad \Delta H_R^0 = +285\text{kJ/mol} \tag{1}$$

## Methanol Synthesis

Methanol can be synthesized from $CO_2$ by reduction with hydrogen over copper/zinc oxide catalysts on alumina at 250°C and 80 bar pressure (Equation 2) (Amenomiya, 1987; Chinchen et al., 1987). A commercial plant is operated by Carbon Recycling International in Iceland since 2011, with a total production volume of 4,000 t $a^{-1}$ methanol (Olah, 2013).

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \qquad \Delta H_R^0 = -50\text{kJ/mol} \tag{2}$$

Methanol synthesis requires 1.2 MJ electric energy per kg methanol produced and releases 1.4 MJ thermal energy, which is utilized for $CO_2$ capture energy demand. The production capacity is given with 627 Mt $a^{-1}$, considering a lifetime of 50 years and 156 t of catalyst load per unit and year. Data from process simulations, performed by Meunier et al. (2020), are considered for the life cycle inventory (LCI). To produce 1,000 kg methanol, 1,441 kg $CO_2$, and 203 kg $H_2$ are needed, including an increased input feed through purge gas combustion, hence a total methanol yield of 93.4%.

## Methanol-To-Olefins (MTO)

Ethylene and propylene can be synthesized from methanol in the MTO reaction over zeolite catalysts at 495°C (Equations 3–5) (Chang and Silvestri, 1977). A commercial MTO plant is operated in China, which produces 0.6 Mt of polyethylene and polypropylene from methanol, consuming 2.96 t methanol per ton of ethylene/propylene (Tian et al., 2015). The production capacity is around 2 Mt $a^{-1}$ with a lifetime of 50 years and a catalyst load of 45 t per year. Estimated electric energy demand is 1 MJ $t^{-1}$ methanol input, while 820 kJ $t^{-1}$ methanol excess thermal energy is provided for $CO_2$ capture.

$$2CH_3OH \rightleftharpoons CH_3OCH_3 + H_2O \qquad \Delta H_R^0 = -39\text{kJ/mol} \tag{3}$$

$$CH_3OCH_3 \rightleftharpoons C_2H_4 + H_2O \qquad \Delta H_R^0 = -93\text{kJ/mol} \tag{4}$$

$$CH_3OCH_3 + CH_3OH \rightleftharpoons C_3H_6 + 2H_2O \qquad \Delta H_R^0 = -129\text{kJ/mol} \tag{5}$$

## Methanol-To-Aromatics (MTA)

Aromatics like benzene, toluene, xylene (BTX) and many more can be synthesized from methanol at 400°C, analogous to the MTO reaction. Using modified, more acidic zeolite catalysts ensures a conversion to mainly aromatic compounds (Adebajo and Long, 2003). Technological parameters are identical to those used in the MTO process. The aromatic compounds are refined and purified to isolate benzene, toluene, xylenes, and higher aromatic compounds from the BTX mixture, requiring ~1.4 MJ $kg^{-1}$ electric energy. In current fossil-based processes, xylenes are extracted from raffinate or pygas as a mixture of *o*-xylene (25%), *m*-xylene (40%), *p*-xylene (18%), and ethylbenzene (17%) (PlasticsEurope, 2013). The composition of xylenes in the MTA process differs from the fossil product mixture. However, due to the mass allocation in the MTA process module (compare chapter 2) there is no difference in the environmental impacts of various xylene mixtures[3] and these can be compared equally.

## Background System Optimization

As part of the transformation to a largely greenhouse gas neutral economic system, which is aimed for by the German government by 2050, the environmental impacts of the processes under consideration are changing. Studies funded by the German Environment Agency (UBA) investigated the impacts on resource use and environmental impacts of this transition (UBA, 2014, 2019a,b). In these studies, it was assumed that until 2050 electricity generation will be successively switched to renewable sources, recycling rates in the production of iron, steel and other metals will increase, fossil raw materials and fuels in industry and transport will be replaced by those with a smaller carbon footprint. In order to estimate how the changes in this background system will affect the environmental impacts of the manufacture of the products under consideration, numerous processes in the models of life cycle assessment (LCA) and life cycle impact assessment (LCIA) have been taken into account for the calculations for the support year 2050. Data for the changes on the transformation path were taken from the study "Resource-Efficient Pathways to Greenhouse-Gas-Neutrality" (RESCUE). This process is described in detail in the SYSEET study (UBA, 2020). In particular, the following processes were adapted:

- Electricity generation with 100% renewable energies (incl. PtG (power-to-gas) with conversion into electricity),
- Steel production (increasing recycling rates, conversion to hydrogen as a reducing agent in the DRI (direct reduced iron) process),
- Cement production (firing with methane from PtG production, reduction of the clinker factor, novel binders)
- Aluminum and copper production (increasing recycling rates, conversion to inert anodes).

The adapted processes were placed inside the model, where aggregated datasets (e.g., organic factory construction or the construction parameters for an electrolysis cell-stack) were subdivided in their respective construction material components and replaced with the optimized construction materials. The LCI datasets for the respective construction materials can be found in the **Supplementary Material**.

# LCIA RESULTS AND DISCUSSION

For every process, electricity from offshore wind turbines and hydrogen from alkaline electrolysis is used, while $CO_2$ is provided either by DAC or by amine scrubbing from a concentrated point-source (PS). Hydrogen and $CO_2$ are then converted to the respective chemicals: methanol, ethylene and propylene (olefins), benzene, toluene and mixed xylenes (BTX). Two scenarios are provided for the production of aluminum, copper, steel and concrete as building materials today (2010) and projected for the year 2050. The products from both, CCU synthesis in 2010 and 2050, are compared to the respective fossil-based reference products with today's technology level; detailed results for environmental impacts of the reference systems are given in **Table 4** (ecoinvent, 2007; PlasticsEurope, 2012, 2013).

## Reading Example

An example on how to understand GWI results is provided in **Figure 2**. Comprising a larger amount of single values, the following contributions can be found: Uptake (Up) of $CO_2$ entering the system, which is accounted as "negative" emissions due to the 100:0 allocation approach; process emissions (Em) within the system, subdivided in single process steps; stoichiometrically calculated end-of-life (EoL) emissions after combustion of the product and release of stored $CO_2$; summarized value (Sum) of all contributions representing a C2G + EoL system. Because the values for the "Uptake," "$CO_2$ Loss," and "EoL" emission always add up to zero, these values are excluded from following result figures. For simplification and better readability, only process emissions (Em) and summarized values (Sum) will be shown and discussed in the following chapter. For other impact categories, only process emission contributions are shown, as uptake and EoL are not considered.

Furthermore, figure keys showing process emissions (Em) comprise the following processes:

- Auxiliaries: Auxiliary material production (e.g., carbon black, ethylene glycol), including required energy consumption and energy infrastructure with upstream processes.
- CCU Electricity: Production of electric energy for organic chemical synthesis and electric heat generation, including energy infrastructure and upstream processes.
- CCU Infrastructure: Organic chemical plant infrastructure and upstream processes for all building materials.
- $CO_2$ Electricity: Production of electric energy for $CO_2$ separation processes and electric heat generation, including energy infrastructure and upstream processes.

[3] Mass allocation means, that a functional unit (1 kg) of respective products receive the same environmental burdens. Therefore, there is no difference in the environmental impact of a product mixture of e.g., *meta*- and *para*-xylene consisting of either 1:3 or 3:1 parts of the respective single products.

**TABLE 4 |** Environmental impacts of 1,000 kg fossil reference products.

| Impact Category | Methanol | Olefins | Benzene | Toluene | Xylene | BTX (mean) | Unit/FU |
|---|---|---|---|---|---|---|---|
| GWI | 627 | 1,448 | 1,868 | 1,225 | 796 | 1,296 | kg $CO_2$-eq |
| GWI + EoL | 2,002 | 4,591 | 5,253 | 4,573 | 4,117 | 4,648 | kg $CO_2$-eq |
| CED | 31 | 67 | 74 | 61 | 54 | 63 | GJ |
| AP | 1.97 | 3.52 | 6.12 | 4.75 | 3.23 | 4.70 | kg $SO_2$-eq |
| EP | 0.52 | 1.08 | 1.26 | 1.06 | 0.91 | 1.08 | kg $PO_4$-eq |
| ODP | 0.40 | 0.31 | 0.57 | 0.45 | 0.30 | 0.44 | g CFC-11-eq |
| $PM_{2.5}$ | 1,639 | 3,324 | 5,098 | 3,988 | 2,848 | 3,978 | g $PM_{2.5}$-eq |

*Methanol is produced from syngas, olefins from steam cracking and BTX from catalytic reforming of naphtha. For BTX (mean) the arithmetic mean value of benzene, toluene and xylene in a 1:1:1 ratio is used.*

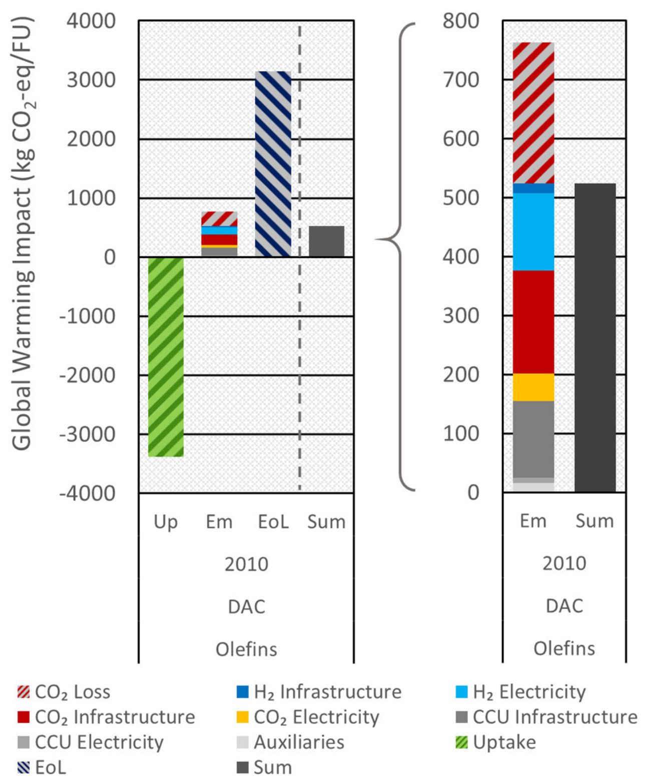


**FIGURE 2 |** Reading example of GWI results. GWI values comprise the following contributions: Uptake (Up) of $CO_2$ entering the system ("negative" emission) due to the 100:0 allocation; process emissions (Em) within the system; stoichiometrically calculated end-of-life (EoL) $CO_2$ emissions after combustion of the product; summarized value (Sum) of all contributions, representing C2G + EoL. For simplification, only process emissions (Em) and summarized values (Sum) will be shown, as "Uptake," "$CO_2$ Loss," and "EoL" always add up to zero.

- $CO_2$ Infrastructure: DAC plant infrastructure or amine scrubbing facilities and auxiliary materials, including upstream processes for all building materials.
- $H_2$ Electricity: Production of electric energy for $H_2$ production processes, including energy infrastructure and upstream processes.
- $H_2$ Infrastructure: Alkaline electrolysis infrastructure and upstream processes for all building materials.
- $CO_2$ Loss: Direct $CO_2$ emissions from purge-gas combustion in organic chemical synthesis.
- Reference: Reference value of the respective fossil process, according to **Table 4**.

## Global Warming Impact (GWI)

Producing large volume organic chemicals from CCU processes will result in lower $CO_2$ emissions compared to fossil reference processes (**Figure 3**). The GWI value is 50–540 kg $CO_2$-eq/FU, compared to the respective fossil reference with 2002–4648 kg $CO_2$-eq/FU. Therefore, GWI for chemical production can be decreased by 88–97% for products from CCU synthesis. Emissions in DAC scenarios mainly result from DAC plant construction, infrastructure for offshore wind electricity production for water electrolysis and the construction of chemical plants, while emissions in PS scenarios are lower, because of lower energy demand from amine scrubbing facilities. In the future scenario (2050), the overall GWI is more than 50% lower compared to the current production (2010). These optimized processes account for a great GHG reduction potential in applying CCU technologies. Nevertheless, direct $CO_2$ emissions from purge gas combustion would account for a considerable part of the process emissions, which should be considered in a holistic approach. The share of direct $CO_2$ emissions is in the range of 26–68% of the total emissions, however, does not account for the summarized GWI value due to the allocation method and previous uptake of $CO_2$ (see chapter 2).

Considering the 0:100 allocation approach for $CO_2$ point-sources, the system receives no credit for the uptake of $CO_2$. Therefore, emissions at EoL and emissions from purge gas combustion are not amortized and need to be allocated to the product. This results in lower GWI reduction as shown in **Figure 4**. The GHG reduction potential of chemicals produced with $CO_2$ from PS in the optimized system (2050) is only 21–26% compared to 88–97% in the 100:0 allocation system. The largest contribution is caused by EoL emissions, accounting for more than 90% of the total process emissions, while $CO_2$ from purge gas combustion will account for 4–7% of the emissions.

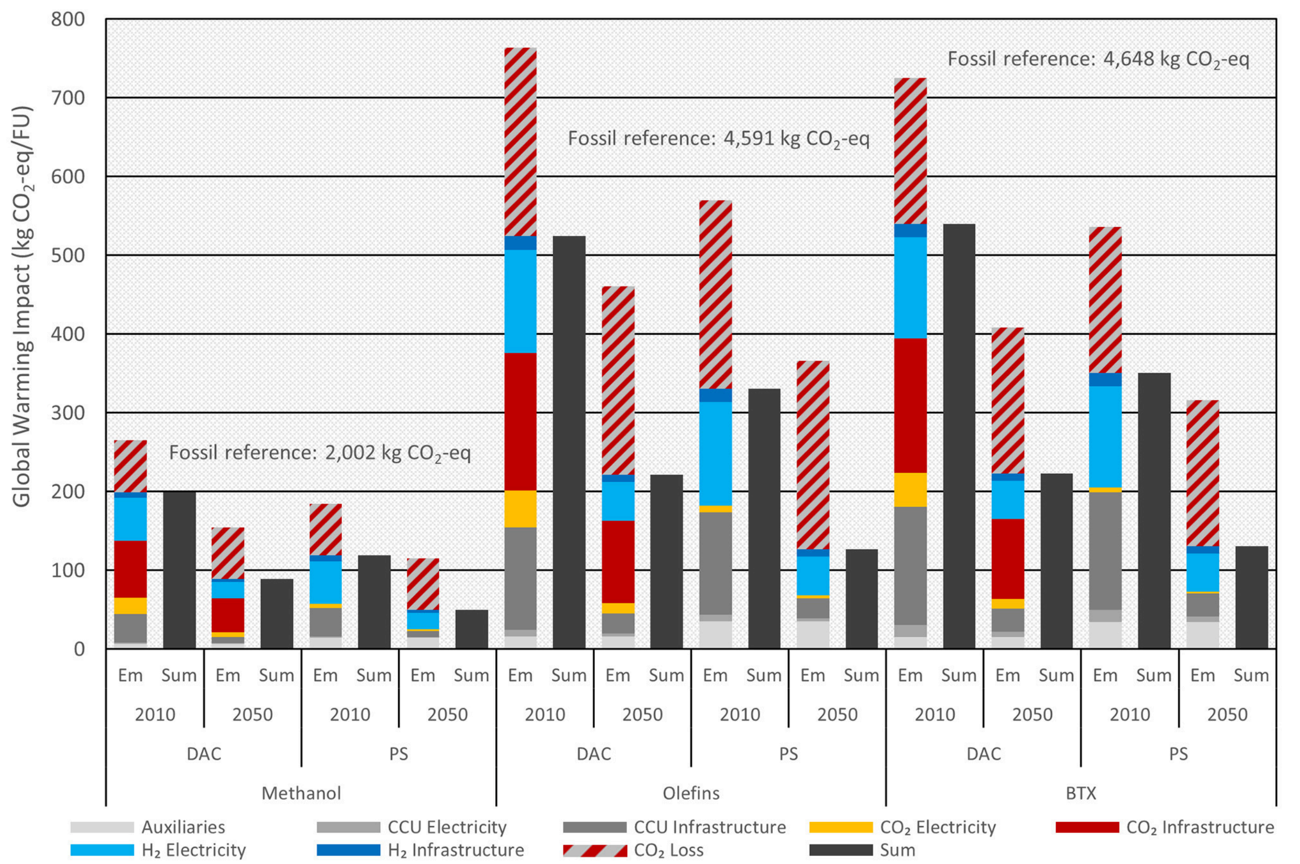


**FIGURE 3 |** 100:0 allocation approach. GWI for the production of methanol, olefins, and BTX from CCU technologies. Results are subdivided into direct air capture (DAC) and point-source (PS) scenarios with the current resource fabrication (2010) and an optimized, projected resource fabrication for the year 2050. Fossil reference values are out of scale and added separately, showing the large GHG reduction potential.

## Cumulated Energy Demand (CED)

The production of basic chemicals from CCU processes will lead to an increased CED, compared to fossil-based products (**Figure 5A**). CED values are ranging from 39 to 140 GJ/FU, this is an increase by 22–110%. The main energy demand results from electricity production for water electrolysis and heat supply for DAC. Integration of reaction heat can provide 12–25% (DAC) and 31–62% (PS) of the required heat demand for separating $CO_2$ for CCU chemical production.

## Acidification Potential (AP)

Impacts in the AP are caused by chemical plant and DAC infrastructure production, water electrolysis, and electricity production. While CCU products in DAC scenarios with today's base material production show higher AP values than reference products, DAC and PS scenarios for the year 2050 lie below the reference values. Emissions from methanol production can be decreased by 27–36%, olefins by 12% and BTX by 2 or 36% for $CO_2$ from PS and DAC, respectively (see **Supplementary Material**).

## Eutrophication Potential (EP)

Eutrophication would increase through higher resource demand and emissions of nitrogen-based flue gases, mainly caused by chemical plant production and catalyst production. These emissions can be cut in half using optimized production routes of aluminum, copper, steel, and concrete. But even then, EP values of methanol, olefins and BTX from CCU production will remain on the same level as fossil reference emissions in the year 2050 scenario (**Figure 5B**).

## Ozone Depletion Potential (ODP)

ODP would mainly be caused by the construction of DAC plants. A contribution analysis showed that the impact results from the production of anionic resin for ion exchange, used as a proxy for $CO_2$ adsorbent materials, which causes high amounts of atmospheric tetrachloromethane (R-10) emissions. The emission of R-10, however, results from the production of trichloromethane (chloroform), which is used as a solvent to produce anionic resins. For the production of chloroform, a 0.1% emission of R-10 is assumed in the ecoinvent dataset, leading to high emissions and high ODP impacts (ecoinvent, 2007).

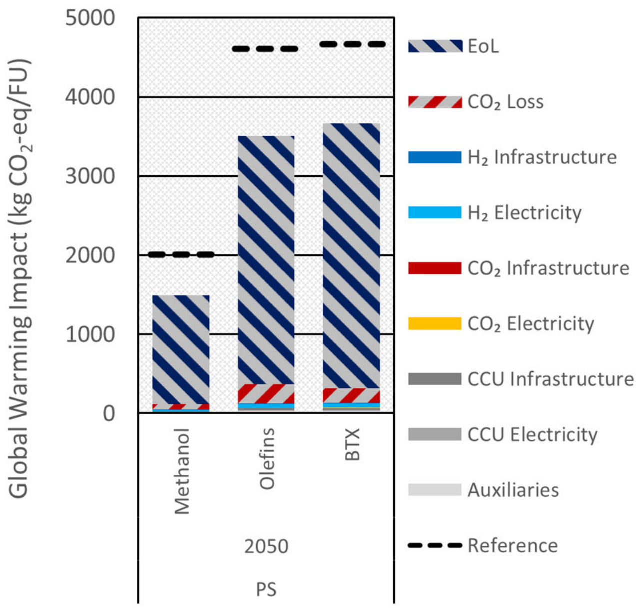


**FIGURE 4 |** 0:100 allocation approach for $CO_2$ point-sources. Contributions of process emissions and end-of-life (EoL) to the GWI for chemical production with $CO_2$ from point-sources (PS) in the optimized system (2050). GWI reduction is much smaller, when $CO_2$ from PS is allocated to the products.

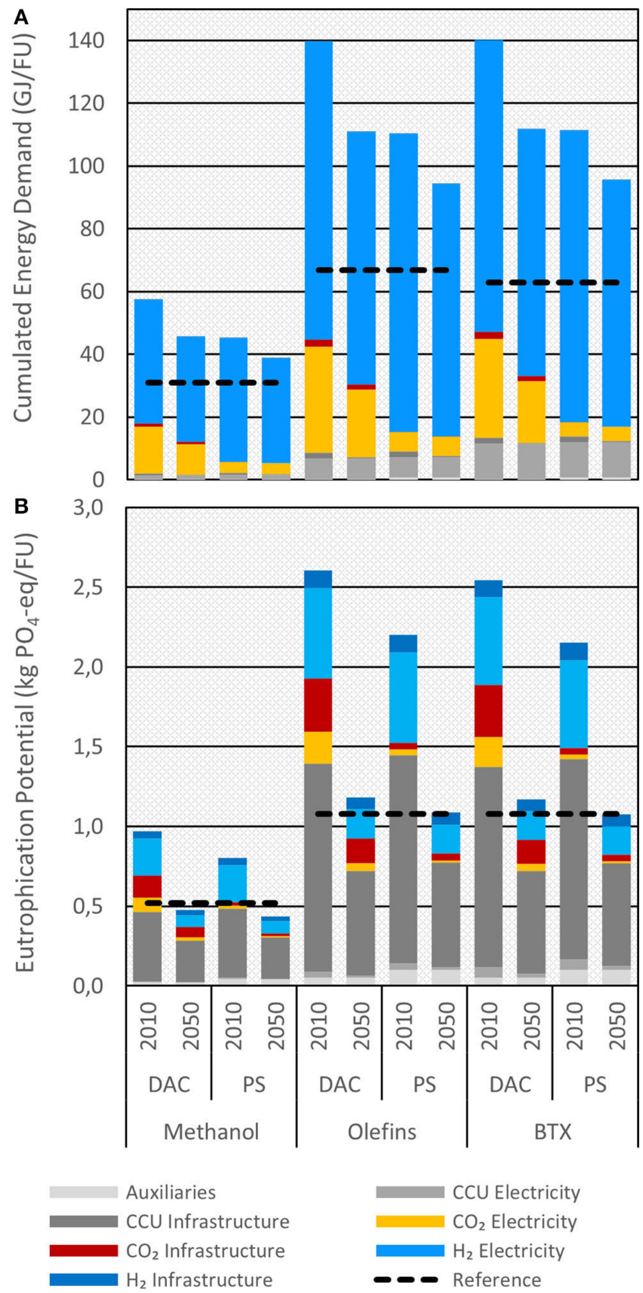


**FIGURE 5 |** Cumulated energy demand **(A)** and eutrophication potential **(B)** for methanol, olefins and BTX from CCU production compared to the respective fossil references. Results for AP, ODP, and $PM_{2.5}$ can be found in the SI.

Therefore, the ODP value increases by 158–732% compared to the fossil references (see **Supplementary Material**). However, the uncertainty of these values seems high, as we cannot verify the R-10 content in chloroform or the airborne emissions resulting from their application in solvent use and disposal. An uncertainty analysis using other module proxies was not performed.

## Particulate Matter Formation ($PM_{2.5}$)

The distribution of particulate matter emission sources is similar to these of acidic compounds. While CCU products produced with $CO_2$ from PS amine scrubbing generally show lower values than reference products, DAC gains an advantage in the year 2050 system. Emissions reduction is 39–51% for methanol, 25–40% for olefins, and 38–51% for BTX products in 2050 (see **Supplementary Material**).

## SENSITIVITY ANALYSIS

A sensitivity analysis was performed by changing several foreground system parameters and investigating their impacts on LCIA results. Therefore, two scenarios were created varying parameters of the previously identified processes which contribute to the environmental impacts in the DAC production pathways. These parameters are the energy and heat demand for water electrolysis and direct air capture as well as the lifetime of the production units (**Table 5**). While the lifetime of the production units was increased or decreased by 5 years for the highly developed and low developed system, respectively, heat and energy demand for the year 2010 and 2050 systems were interchanged to model intermediate system development. Sensitivities for energy supply and allocation including oxygen from AEL have been demonstrated in Rosental (2020).

Results for the sensitivity analysis for GWI are shown in **Figure 6**, detailed results for other impact categories can be found in the **Supplementary Material**. The variation of the GWI values is 13–25% for methanol, 8–20% for olefins, and 11–25% for BTX for the 2010 and 2050 system, respectively. The increased and decreased lifetime for $CO_2$ infrastructure is contributing to the biggest changes, while variation of

**TABLE 5 |** System parameters for the sensitivity analysis.

| Parameter | | 2010 Low | 2010 High | 2050 Low | 2050 High |
|---|---|---|---|---|---|
| **DAC** | El. Energy (kJ/kg $CO_2$) | 2,520 | 1,440 | 2,520 | 1,440 |
| | Heat (kJ/kg $CO_2$) | 7,920 | 5,760 | 7,920 | 5,760 |
| | Lifetime (a) | 12 | 17 | 7 | 12 |
| **AEL** | El. Energy (kJ/kg $H_2$) | 177,433 | 150,000 | 177,433 | 150,000 |
| | Lifetime (a) | 20 | 25 | 15 | 20 |

*Base case scenarios with the low developed 2010 system and highly developed 2050 system were not changed, intermediate scenarios with a highly developed 2010 system and low developed 2050 system were added.*

**TABLE 6 |** Total environmental impacts in Germany in 2016 (left) and production volumes of basic chemicals in 2016 (right) (UBA, 2018; VCI, 2018).

| Impact Category | Amount | Unit | Chemical | Production Volume (t) |
|---|---|---|---|---|
| GWI | 909,394,000 | t | Methanol | 1,043,776 |
| CED | 13,425,000 | TJ | Ethylene | 5,155,731 |
| AP | 2,653,440 | t | Propylene | 4,010,354 |
| EP | 702,708 | t | Benzene | 1,887,665 |
| ODP | 2,691 | t | Toluene | 593,775 |
| $PM_{2.5}$ | 1,903,524 | t | Xylene | 526,394 |

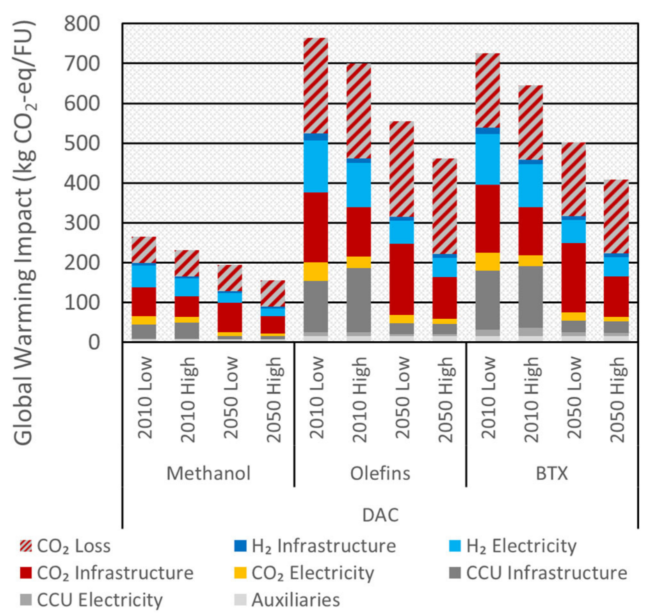


**FIGURE 6 |** Sensitivity analysis for GWI. Variation of the GWI values is 13–25% for methanol, 8–20% for olefins, and 11–25% for BTX for the 2010 low vs. high and 2050 low vs. high system, respectively. Changes in the background system remain for major GWI reduction potential.

heat and energy demand is only causing minor changes. The adaption of background changes in the 2010 and 2050 systems remains for the most important emission reduction potential. Similar results are obtained for every impact category besides the cumulated energy demand. For CED, the variation of foreground parameters results in almost identical CED values as the background system construction material adaption. This is indicating, that the decreasing energy demand for $CO_2$ and $H_2$ production is main driver of a lower CED. While the influence on GWI in the sensitivity analysis is low because of the application of low carbon energy from offshore wind turbines to the system, the impact on the CED is not affected by this choice.

## NORMALIZATION

Different supply paths lead to increasing or decreasing impacts in respective impact categories compared to the fossil reference. In order to contextualize the potential environmental impacts of CCU based basic chemical production, results of the LCIA are normalized. The additional burdens and reliefs in the respective impact categories (the difference between CCU and fossil production) is set in relation to the current environmental impacts in Germany (**Table 6**). For this purpose, we assume the entire production of these chemicals in Germany would be changed from fossil to CCU processes; in this way the hypothetical burdens and reliefs compared to the current reference year 2016 can be calculated (**Figure 7**).

Changing chemical production to CCU based feedstock, would contribute to an overall GWI reduction for Germany of 5.8–6.2% for $CO_2$ from DAC and 6.0–6.3% for $CO_2$ from point-sources. These reductions of GHG emissions are linked to an increase in the cumulated energy demand (CED) of 4.2–6.9% for DAC. The CED increase by using $CO_2$ from existing point-sources would account for 2.6–4.1% of the current energy demand and is mainly caused by the additional energy requirement for water electrolysis. Reductions in the acidification potential (AP) of 0.2–0.4% could be achieved in the year 2050 scenario, while emissions would increase by 0.3–0.7% with today's production system. An increase in the eutrophication potential (EP) from 1.9 to 2.7% in the current system (2010) could also be compensated through an optimized base materials production. As the production of adsorbent resin for DAC causes high emissions of tetrachloromethane (R-10), the production of CCU chemicals from DAC $CO_2$ would lead to a 1% increase of the ODP[4], while $CO_2$ from PS would achieve a minimal benefit. Emissions of particulate matters ($PM_{2.5}$) could be decreased by 0.8% (DAC) and 1.1% (PS) in 2050.

## CONCLUSION

Implementing the investigated CCU technologies in Germany, would reduce GHG emissions by 5.8–6.3%, replacing chemical products from fossil sources like oil, gas, and coal. While further benefits could be achieved in impact categories like acidification potential (AP) and particulate matter ($PM_{2.5}$) emissions, negative effects are possible by eutrophicating substances (EP) and ozone depleting compounds (ODP) in direct air capture (DAC) scenarios. An increase in the cumulated energy demand (CED) by 2–7% is the consequence of higher energy requirements

[4]Note that this value is uncertain due to the module proxy for the adsorbent (compare chapter 4, ODP).

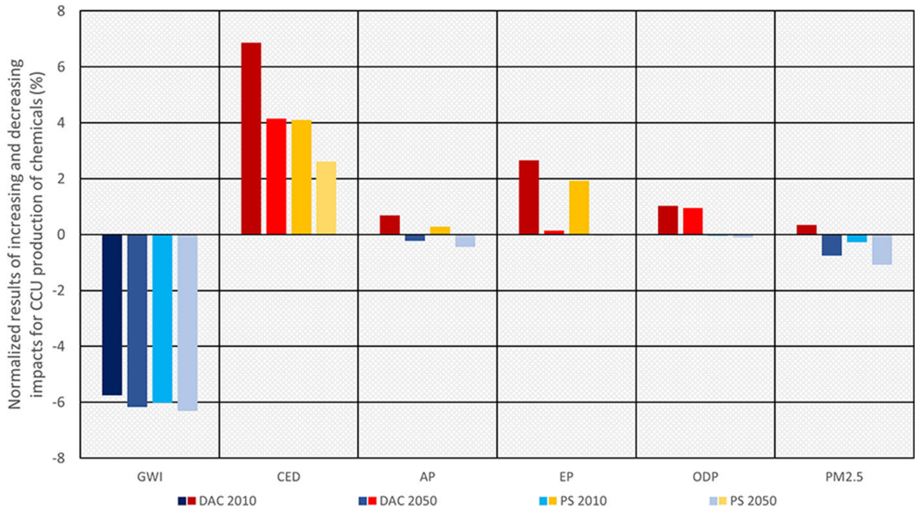


**FIGURE 7 |** Normalized results for emission reductions (negative, blue) and increases (positive, red) in different impact categories from substitution of fossil products through CCU chemicals in the Federal Republic of Germany in 2016.

for water electrolysis and supply of heat for the desorption of captured $CO_2$. We identify the optimization of resource extraction, production and recycling of aluminum, copper, steel and concrete according to the UBA "RESCUE" study as main objective to reduce emissions in all impact categories besides CED. Reduction of CED can be achieved by minimizing overall energy and heat demand for $CO_2$ and $H_2$ production. CCU technologies require low carbon energy, e.g., offshore wind energy, to avoid indirect $CO_2$ emissions. CCU will only provide a short-term storage of carbon in chemical products, $CO_2$ from DAC and non-fossil PS is required for chemical synthesis. Using $CO_2$ from fossil industrial point-sources, as shown in the 0:100 allocation approach, will only account for a 21–26% reduction of GWI, compared to the respective fossil process. Furthermore, direct emissions from purge gas combustion of CCU synthesis will remain and account for 26–68% of the total GHG emissions of CCU processes. Additional energy efforts and material requirements have to be considered to capture $CO_2$ which will not remain in the final product. The production of methanol, ethylene, propylene, benzene, toluene, and xylene from renewable resources is possible with present technologies, but should be applied only when the necessary conditions are fulfilled. This means broad access to low-carbon energy, electric heating and heat integration, highly optimized resource extraction and recycling, as well as using existing infrastructure and on-site capacities to minimize transport distances for $CO_2$ and hydrogen. In a long-term scenario, CCU technologies may be considered for a fossil free chemical industry, based on renewable resources and energies.

## DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because parts of these data are subject to NDAs. All other data will be provided by the authors. Requests to access the datasets should be directed to marian.rosental@ifeu.de.

## AUTHOR CONTRIBUTIONS

MR carried out modeling of chemical processes and performed the life cycle assessment, and impact analysis. TF and AL were responsible for modeling electrolysis, carbon capture, electricity, and background units. MR wrote and all authors revised and improved the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2020.586199/full#supplementary-material

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# Deployment of Negative Emissions Technologies at the National Level: A Need for Holistic Feasibility Assessments

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The 2015 Paris Agreement aims to strengthen the global response to climate change, and to maintain an average global temperature well below 2°C, with aspirations toward 1.5°C, by means of balancing sources and sinks of greenhouse gas emissions. Following this, the importance of carbon dioxide removal in global emission pathways has been further emphasized, and Negative Emissions Technologies (NETs) that capture carbon from the atmosphere and remove it from the system have been put in the spotlight. NETs range from innovative, engineered technologies, to well-known approaches like afforestation/reforestation. These technologies essentially compensate for a shrinking carbon budget coupled with hard-to-abate future emissions, and a historical lack of action. However, none has been deployed at scales close to what is envisioned in emission pathways in line with the Paris Agreement goals. To understand the potential contribution of NETs to meet global emission goals, we need to better understand opportunities and constraints for deploying NETs on a national level. We examine 17 Long-Term Low Greenhouse Gas Emission Development Strategies (LT-LEDS), and discuss them in the context of available NETs feasibility assessments. Our mapping shows that most countries include NETs in their long-term strategies, and that enhancement of natural sinks is the most dominating type of NET in these strategies. In line with many feasibility assessments, LT-LEDS focus on technical and biophysical considerations, and neglect socio-cultural dimensions. We suggest that feasibility assessments at the national level need to be more holistic; context-specific and comprehensive in terms of aspects assessed.

**Keywords: Negative Emissions Technology (NET), net-zero, UNFCCC (United Nations Framework Convention on Climate Change), Long-Term Low Greenhouse Gas Emission Development Strategies (LT-LEDS), feasibility assessment, integrated assessment modeling (IAM), pathway, IPCC SR15**

## INTRODUCTION

The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) aims to strengthen the global response to climate change, limiting the increase in global temperature to "well below" 2°C, with aspirations toward 1.5°C (United Nations, 2015). Importantly, the agreement specifies that the long-term temperature goal should be achieved by means of balancing sources and sinks of greenhouse gas emissions. To understand options and emission pathways compatible with this objective, the Intergovernmental Panel on Climate Change (IPCC) produced the Special Report on 1.5°C global warming (SR15) (IPCC, 2018; Livingston and Rummukainen, 2020). SR15 shows that all emission pathways consistent with a 1.5°C warming limit require near-term carbon dioxide removal at large scale in addition to reduced emissions (also Fuhrman et al., 2019; Gough and Mander, 2019).

Negative Emissions Technologies (NETs) capture and remove carbon from the system (see **Table 1** for a comprehensive list). Their rationale is: the more emissions that can be removed, the more room for maneuver in terms of (a) residual hard-to-abate emissions in the future and/or (b) closing the ambition gap, i.e., compensating for lack of action in the past (Renforth and Wilcox, 2019; Forster et al., 2020; Markusson et al., 2020). In this paper, we explore how the feasibility of NETs deployment is operationalized in assessments and analyze NETs coverage in national Long-Term Low Greenhouse Gas Emission Development Strategies (LT-LEDS), with an emphasis on how feasibility of NETs is understood, and argue that holistic assessments of NETs deployment at the national level are urgently needed.

## FEASIBILITY OPERATIONALIZED IN NETs ASSESSMENTS

Within the last 10–15 years research into NETs and their feasibility has increased and multiple new ideas on how to remove carbon dioxide from the atmosphere have emerged. Emission pathways from Integrated Assessment Models (IAMs) most prominently feature Bioenergy with Carbon Capture and Storage (BECCS) and afforestation/reforestation (IPCC, 2018). While some approaches, such as afforestation/reforestation, have a long history in climate mitigation, the envisioned deployment scale in these pathways exceeds anything that has been deployed before (Fajardy et al., 2019; Carton et al., 2020). As NETs have not yet been scaled up, assessing the feasibility of deploying such technologies at a larger scale inevitably involves uncertainties about their implementation, effectiveness, and side effects (IPCC, 2018). These are so far mostly addressed by modeling studies, which bring about their own uncertainties (see section Feasibility Discussions, Oschlies and Klepper, 2017; Minx et al., 2018; Mengis et al., 2019).

Assessing the feasibility of NETs can be described as a process, with different assessments of feasibility carried out at different moments in time. These range from specific assessments like technology- or dimension-focused (e.g., Fuss et al., 2018; Nemet et al., 2018; Roe et al., 2019; Robb et al., 2020), reviews or syntheses of multiple dimensions or comparison of NETs (Oschlies and Klepper, 2017; Minx et al., 2018; Waller et al., 2020), and combined feasibility assessments (IPCC, 2018). These assessments accordingly differ in scope and how feasibility is operationalized.

The emergence of a new technology requires a scientific and technical evaluation. Technical assessments are conducted at all innovation stages to ensure solutions to emerging problems. Most attention in the scholarly literature has been given to research and development activities (R&D), whereas demonstration and upscaling have received less attention (Nemet et al., 2018). Technical assessments may focus on parameters related to technology efficiency and/or availability, and are important tools for assessing technological feasibility. Often technological feasibility is expressed as the maturity level of a certain technology, known as the Technology Readiness Level (TRL) (DOE, 2011). The TRL is composed of nine stages that progress sequentially from the conceptual stage (TRL 1), to commercial scale deployment (TRL 9)—a process that for complex technologies can take up to 30 years (Haszeldine et al., 2018). Progression to a higher TRL requires further research, financial investment and policy support (Bui et al., 2018). Currently, proposed NETs are at different maturity levels, but most have not advanced past the demonstration stage (TRL 6) (Lomax et al., 2015). In addition, separate components of individual NETs can range in TRL (Hepburn et al., 2019).

In contrast to technology-focused (focus on specific NET) or dimension-specific studies (e.g., focusing on technological, ecological, or economic aspects), reviews of NETs often compare multiple feasibility dimensions and/or NETs. Here, feasibility is often defined by carbon sequestration potential and efficiency, deployment costs and timeline, which correspond to the TRL and risks (Oschlies and Klepper, 2017). Combining multiple dimensions in the assessment can highlight temporal, spatial, and technological aspects enabling or hindering the scale-up potential of a technology (Minx et al., 2018; Forster et al., 2020). Assessments of NETs have been criticized for being too narrow in their evaluation of what enabling conditions need to be met, with most focusing on geophysical, technological, and economic aspects (Oschlies et al., 2017; Mengis et al., 2019; Kreuter et al., 2020; Waller et al., 2020).

Finally, a comprehensive assessment of a range of NETs across multiple feasibility dimensions has been carried out by the IPCC (see SR15). Here, feasibility is broken down into several dimensions, ranging from economic, technological, institutional, socio-cultural, ecological, and geophysical, operationalized with accompanying indicators (de Coninck et al., 2018a). Feasibility is assessed based on the barriers that exist for a specific NET. Enabling conditions, such as financial support, institutional capacity and innovation, are seen as affecting the feasibility of options (technologies, actions, and measures), and can accelerate and scale up systemic transitions. SR15 also identified where there was no or limited evidence for feasibility and underlined existing research gaps, the most obvious ones being the lack of evidence for institutional and socio-cultural feasibility for many NETs. Moreover, in order to enable an assessment of these

**TABLE 1 |** Overview of 15 Long-Term Low Greenhouse Gas Emission Development Strategies (LT-LEDS) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) as of July 2020.

**Canada**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | ✓ | ✓ | ✓ | | (✓) |
| Biochar | (✓) | (✓) | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wetland | | | | | | |
| Blue Carbon | | | | | | |
| Weathering | | | | | | |
| BECCS | (✓) | (✓) | | (✓) | | |
| DACCS | | | | | | |
| Other CCUS | ✓ | ✓ | | ✓ | ✓ | |

**Costa Rica**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | | | | | | |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Wetland | (✓) | ✓ | | ✓ | ✓ | |
| Blue Carbon | (✓) | ✓ | (✓) | ✓ | ✓ | |
| Weathering | | | | | | |
| BECCS | | | | | | |
| DACCS | | | | | | |
| Other CCUS | | | | | | |

**Czech Republic**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | | | | ✓ | |
| Biochar | | | | | | |
| Forestry | ✓ | | | | ✓ | |
| Wetland | | | | | | |
| Blue Carbon | | | | | | |
| Weathering | | | | | | |
| BECCS | | | | | | |
| DACCS | | | | | | |
| Other CCUS | | ✓ | | | | |

**EU**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Biochar | | (✓) | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wetland | | ✓ | | | | |
| Blue Carbon | | | | | | |
| Weathering | | (✓) | | | | |
| BECCS | ✓ | ✓ | ✓ | ✓ | | ✓ |
| DACCS | ✓ | ✓ | | ✓ | | ✓ |
| Other CCUS | ✓ | ✓ | | ✓ | ✓ | ✓ |

**Fiji**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wetland | | | | | | |
| Blue Carbon | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Weathering | | | | | | |
| BECCS | | | | | | |
| DACCS | | | | | | |
| Other CCUS | | | | | | |

**France**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wetland | (✓) | (✓) | (✓) | | | |
| Blue Carbon | | | | | | |
| Weathering | | | | | | |
| BECCS | | | | | | |
| DACCS | | | | | | |
| Other CCUS | (✓) | (✓) | | (✓) | | |

**Germany**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | (✓) | (✓) | (✓) | (✓) | (✓) | (✓) |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wetland | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Blue Carbon | | | | | | |
| Weathering | | | | | | |
| BECCS | | | | | | |
| DACCS | | | | | | |
| Other CCUS | (✓) | (✓) | | | | (✓) |

**Japan**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | | | | | |
| Biochar | ✓ | | | | | |
| Forestry | ✓ | ✓ | ✓ | | | |
| Wetland | ✓ | | | | | |
| Blue Carbon | (✓) | | | | | |
| Weathering | (✓) | | | | | |
| BECCS | | | | | | |
| DACCS | (✓) | | | | | |
| Other CCUS | ✓ | ✓ | | ✓ | | ✓ |

**Mexico**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wetland | | | | | | |
| Blue Carbon | | | | | | |
| Weathering | | | | | | |
| BECCS | | | | (✓) | | |
| DACCS | | | | | | |
| Other CCUS | | ✓ | | | | |

**Portugal**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | | ✓ | ✓ | ✓ | |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Wetland | (✓) | | | | | |
| Blue Carbon | | | | | | |
| Weathering | | | | | | |
| BECCS | | | | | | (✓) |
| DACCS | | | | | | |
| Other CCUS | | | | (✓) | | |

**Singapore**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | | | | | | |
| Biochar | | | | | | |
| Forestry | | | | | | |
| Wetland | | | | | | |
| Blue Carbon | | | ✓ | | | |
| Weathering | | | | | | |
| BECCS | | | | | | |
| DACCS | | | | | | |
| Other CCUS | ✓ | | (✓) | ✓ | ✓ | |

**Slovakia**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Wetland | (✓) | | | | | |
| Blue Carbon | | | | | | |
| Weathering | | | | | | |
| BECCS | | | | | | |
| DACCS | | | | | | |
| Other CCUS | (✓) | | | | | |

**Ukraine**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | ✓ | ✓ | | ✓ | |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | (✓) | ✓ | (✓) |
| Wetland | (✓) | | | | | |
| Blue Carbon | | | | | | |
| Weathering | | | | | | |
| BECCS | | | | | | |
| DACCS | | | | | | |
| Other CCUS | | (✓) | | (✓) | ✓ | |

**UK**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | (✓) | ✓ | | | | |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wetland | ✓ | | | | | |
| Blue Carbon | | | | | | |
| Weathering | (✓) | | | | | |
| BECCS | (✓) | | ✓ | | | |
| DACCS | (✓) | | | | | |
| Other CCUS | ✓ | ✓ | ✓ | ✓ | ✓ | |

**US**

| | Bio-geophysical | Technological | Ecological | Economic | Institutional | Socio-cultural |
|---|---|---|---|---|---|---|
| Soil carbon | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Biochar | | | | | | |
| Forestry | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wetland | ✓ | ✓ | ✓ | | | |
| Blue Carbon | | | | | | |
| Weathering | (✓) | | | | | |
| BECCS | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| DACCS | (✓) | | | | | |
| Other CCUS | ✓ | ✓ | | ✓ | | |

*Strategies were analyzed with respect to covered Negative Emissions Technologies (NETs) and feasibility dimensions. Only information related to NETs specifically is displayed with the addition of Carbon Capture Use and Storage (CCUS), but not general information about climate mitigation. Bénin and the Marshall Islands had also submitted LT-LEDS but were excluded from this table because Bénin addresses only a timeframe until 2025 (not 2050, like the other nations) and the Marshall Islands do not mention NETs. We have not considered supporting documentation other than for the EU as their supporting document was clearly highlighted in the brief UNFCCC submission. Information was coded to all relevant categories. Dimensions: Bio-geophysical, e.g., removal potential, permanence, geological storage. Technological, e.g., technology availability and efficiency, resources, management practice. Ecological, e.g., biodiversity, ecological impact, non $CO_2$-emissions. Economic, e.g., investment, costs, economic production. Institutional, e.g., policies or legal frameworks, political acceptance, institutional capacity. Socio-cultural: public acceptance, social co-benefits, participation. NETs: Soil carbon sequestration (SCS), Agricultural practices to enhance organic carbon sequestration in soils; Biochar, application of very stable organic carbon from pyrolysis on agricultural soils; Forestry, afforestation, reforestation, Improved Forest Management (IFM), and storage of carbon in harvested forest products; Wetland, rewetting and restoring terrestrial wetlands including peatlands; Blue Carbon, restoration or plantation of seagrasses, salt marshes or mangroves; Weathering, enhanced weathering in terrestrial ecosystems; BECCS, Bioenergy with Carbon Capture and Storage; DACCS, Direct Air Capture (with Carbon Storage). Other CCUS (e.g., fossil-based CCS, Enhanced Oil Recovery (EOR), or industrial CCS) generally do not generate negative emissions, and are not implemented with this purpose. Deployment of CCUS and NETs are, however, interlinked in different ways e.g., development stages, research, and political motivations and risks. Ocean NETs like fertilization and alkalinity were excluded from the analysis because these approaches could be seen as outside the scope of the UNFCCC with its focus on national territory including the coastal zone but not international waters. Ocean NETs are discussed under other international conventions, including the Law of the Sea, and the London Convention and Protocol.*
*✓, included in LT-LEDS (intention, plan, project, and/or in some way further developed); (✓), mentioned as an option/possibility for the future but not further developed.*

dimensions, for this global scale assessment to be applicable at the national level, it must be adapted accordingly.

## NETs AT THE NATIONAL LEVEL: INSIGHTS FROM 17 LT-LEDS

The Paris Agreement requests countries to submit Nationally Determined Contributions (NDCs), and invites them to submit LT-LEDS to the UNFCCC. Here, we focus on the LT-LEDS, as NETs are more likely to be addressed in long-term considerations. As of September 2020, 16 countries plus the European Union (EU) had submitted their LT-LEDS (**Table 1**, **Supplementary Material**)[1].

NETs are highlighted as important for achieving the Paris Agreement's goal (e.g., Canada, EU, Japan, Slovakia, and UK), and in particular enhancements of natural sinks feature most heavily in the LT-LEDS examined in the present study (**Table 1**). It is important to note, however, that the land-use sector is often treated as a whole, without clearly separating negative emissions (cf. Dooley and Gupta, 2017; Minx et al., 2018). There is a degree of flexibility in the LT-LEDS with several countries including pathways where enhancement of natural sinks is essential for compensating for residual emissions, while BECCS feature in some pathways providing more time to transform society; without BECCS, emissions need to be reduced faster (e.g., EU, UK, and US). The notions of feasibility of NETs deployment vary in scope, level of detail and focus (see **Table 1**). For instance, Canada, the UK and the US consider a broad range of NETs, whereas Fiji focuses on enhancement of natural sinks including a comprehensive strategy for Blue Carbon and Germany focuses on forests, wetlands and peatlands.

The LT-LEDS feature examples of specific pilot studies, research, and deployment initiatives for NETs [e.g., dedicated research program (UK), funding for soil carbon potential and BECCS-pilot (US), and mangrove restoration projects (Singapore)]. However, the general level of detail on how NETs would be deployed is low. Such knowledge will be needed to scale up NETs deployment on a national level and it could also be instrumental in bridging the gap between global IAM assessments and action on the ground.

In terms of feasibility dimensions, national LT-LEDS generally incorporate a narrow view, i.e., focusing mostly on bio-geophysical and technological dimensions (**Table 1**). In addition, for NETs that focus on the enhancement of natural sinks, environmental dimensions are considered to a larger extent, while these dimensions are less pronounced for more technology-heavy NETs. For all NETs, socio-cultural feasibility is underrepresented. In summary, the LT-LEDS indicate which NETs are considered within the political reality of a country (indicating political feasibility), but they often do not provide a detailed assessment of the current status of research and implementation of specific NETs within a country (e.g., technical scalability or social acceptance).

Most strategies use a conditional understanding of NETs feasibility, identifying enabling conditions/barriers to deployment such as costs or knowledge gaps (e.g., Canada, Portugal, and US in the context of BECCS). However, countries differ in how they operationalize these conditions. For instance, Portugal currently excludes BECCS due to high costs, mentioning it only as a possible option for the future, while for instance the US and the UK explore different pathways with and without BECCS. In our mapping, we have also included Carbon Capture Usage and Storage (**Table 1**, "other CCUS") without bioenergy even though they do not generate negative emissions because they are relevant for the development of BECCS and may impact their social acceptance (cf. Lock et al., 2014; Thomas et al., 2018).

## FEASIBILITY DISCUSSIONS

The feasibility assessments and national LT-LEDS discussed herein foreground two different albeit interrelated discussions regarding feasibility that are relevant in the context of NETs deployment. The first discussion starts with a given policy goal and asks what is needed to reach this goal. This question is typically investigated using modeling, and the answer is typically that NETs are needed at a large scale to complement other mitigation approaches (e.g., IPCC, 2018). Examples include IAMs that look for pathways to limit temperature rise at a given level, and national strategies on how to reach net-zero emissions.

The second discussion instead starts with the NETs and asks questions regarding necessary enabling conditions or barriers to deploy NETs. This discussion can be narrow; focusing on a specific technology or dimension, or it can be broad comparing NETs and dimensions. As shown herein, both feasibility assessments and LT-LEDS tend to focus on bio-geophysical, technical, and to some extent economic dimensions, neglecting socio-cultural dimensions.

SR15 is perhaps the most prominent example of featuring both discussions. The report relies strongly on results from IAMs to identify feasible emission pathways to limit the increase of the average global temperature to 1.5°C, in turn feeding into the broader IPCC assessment of mitigation options (Low and Schäfer, 2020). It also, however, highlights a range of NETs and includes a comprehensive set of feasibility dimensions with indicators. That said, only some dimensions are comprehensively assessed in the context of NETs—most prominently geophysical, technological and economic dimensions (de Coninck et al., 2018b). Socio-cultural, institutional and to some extent ecological dimensions are not comprehensively assessed due to the lack of underlying research, instead highlighted as important uncertainties (de Coninck et al., 2018a,b).

Feasibility in the IAM-context equals model solvability, which in turn depends on model assumptions (Low and Schäfer, 2020). IAMs focus on a techno-economic context, excluding a range of other dimensions that could hinder or enable actual deployment (Fuss et al., 2014; Forster et al., 2020). If not revised carefully, such an approach may facilitate even highly improbable

[1] At the moment of writing, it is unclear how many more LT-LEDS are to be expected, as they are not mandatory. Once/if more LT-LEDS are made available, a more comprehensive analysis would be possible. The current paper should thus be seen as a contribution to a rapidly unfolding debate, not a comprehensive and final overview.

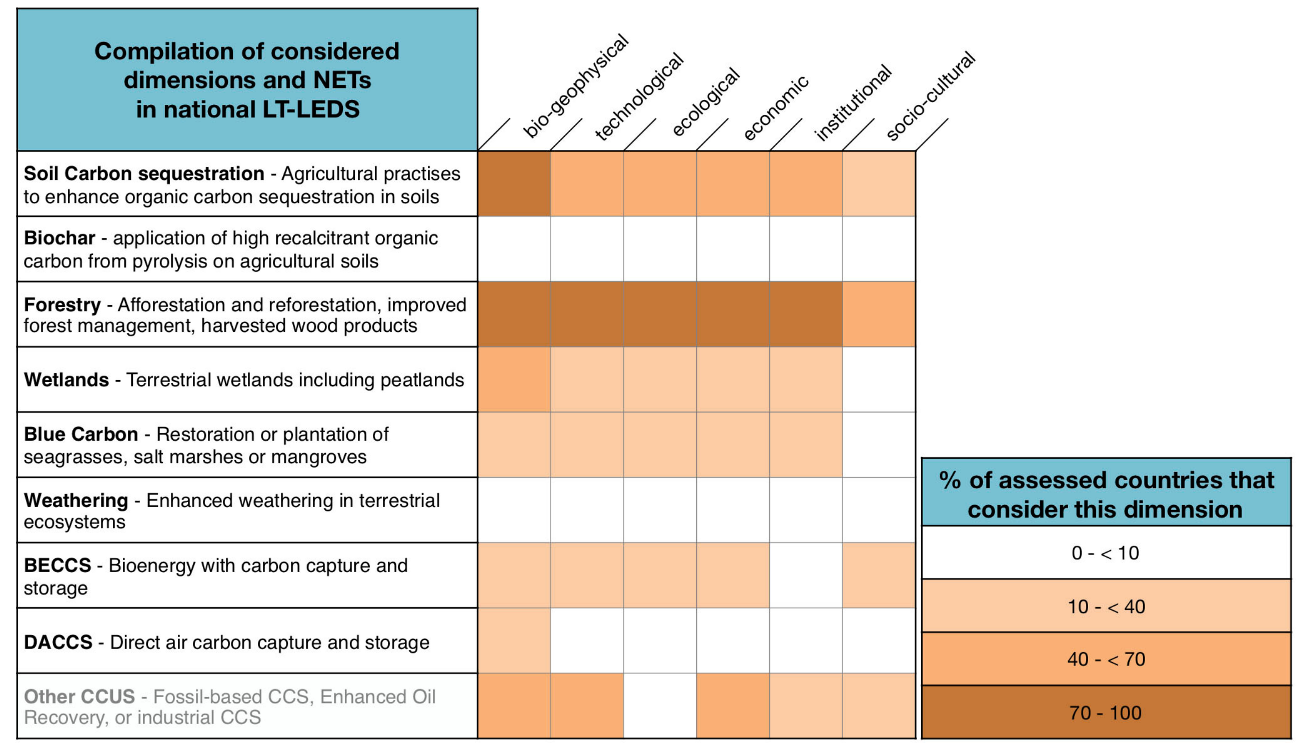


**FIGURE 1 |** Percentage of Long-Term Low Greenhouse Gas Emissions Development Strategies (LT-LEDS) that cover a given NET, considering one of six feasibility dimensions. This is a compilation of the analysis from **Table 1**, the percentage is calculated as the number of LT-LEDS that include (=1) or mention (=0.5) a NET and feasibility dimension, relative to the total number of considered LT-LEDS, excluding Benin and the Marshall Islands ($N = 15$). The category "other CCUS" in gray refers to CCUS techniques without bioenergy. These do not produce negative emissions, but are included as reference based on their interlinkage with BECCS (see also section NETs at the National Level: Insights From 17 LT-LEDS).

pathways to appear feasible. For example, when coupled with discounted future costs for action on climate change, a narrow understanding of NETs feasibility can fabricate a high reliance on future NETs and justify delayed action (Köberle, 2019; Rogelj et al., 2019). A recent study found that assumptions built into IAMs about NETs deployment could amount to an additional temperature rise of 1.4°C if these technologies do not deliver as assumed (McLaren, 2020).

In terms of the diversity of NETs considered in IAMs, BECCS, and afforestation/reforestation dominate. This can partly be understood based on traditions in IAM climate modeling focusing on the energy sector and emissions, rather than suggesting that these approaches are more feasible or more desirable than others (Fuhrman et al., 2019). This predominance, however, introduces a bias in the assessments toward a higher perceived feasibility for these technologies.

The LT-LEDS are developed following the Paris Agreement, "mindful of" its long-term temperature goal (Articles 4 and 2 of the Paris Agreement). Consequently, they feed into and relate to a feasibility-of-the-goal discussion. As illustrated in **Table 1**, NETs have a role to play in most LT-LEDS communicated thus far. While some countries communicate that the deployment of NETs is important to fulfill the Paris Agreement, they also highlight a number of hindering conditions that need to be addressed, including costs and knowledge-gaps (e.g., Canada, EU, and US). When feasibility of NETs deployment is addressed, this is typically narrowly framed, excluding most prominently socio-cultural dimensions (**Figure 1**). This leaves many important questions unanswered and thereby limits the credibility of the underlying assumptions made in the LT-LEDS.

A narrow understanding of feasibility generated by, for example, considering the potential of NETs in isolation from one another rather than as a portfolio, or not considering socio-cultural or institutional dimensions, risks creating unrealistic expectations regarding the potential of NETs deployment (Fajardy et al., 2019; Low and Schäfer, 2020). This is problematic, because it has been shown that for example social acceptance can be an important barrier to the deployment of new technologies (Lock et al., 2014; Dowd et al., 2015). A narrow feasibility discussion focusing on what can be done (technically), risks losing sight of the normative foundation of climate policy discussions, namely the future we want. While there is a growing social science and humanities literature on NETs, it is important that these disciplines are properly integrated into research projects and policy assessments, complementing or challenging dominating narratives (Markusson et al., 2020, Waller et al., 2020). This would provide breadth to consider the risk that NETs might not be feasible at large scale, as well as adequately exploring alternative futures (Buck, 2016; Beck and Mahony, 2018; McLaren et al., 2019; Low and Buck, 2020). Asking critical questions about feasibility is a first step to opening up the debate regarding the way forward, rather than taking it for granted. Moreover, to better understand socio-cultural dimensions of NETs, such as participation and acceptance, a broader range of actors included in the knowledge-making process could help us better understand local realities of NETs deployment [e.g., Markusson et al. (2020)].

## MOVING FORWARD: HOLISTIC FEASIBILITY ASSESSMENTS AT THE NATIONAL LEVEL

Because many NETs are still at an early stage of development, uncertainties remain regarding the feasibility and implications of their large-scale deployment (Fuss et al., 2014, 2018; Low and Schäfer, 2020). Thus far, the debate on NETs has predominantly been held at a global level, and it has previously been suggested that we need to better understand feasibility of NETs deployment at the national level (de Coninck et al., 2018a; Fajardy et al., 2019). In this paper, we have seen that many national strategies include NETs in their long-term mitigation portfolio to meet their national goals and contribute to the fulfillment of the Paris Agreement. However, when it comes to feasibility, focus is given to some dimensions (bio-geophysical, technological), while others, primarily socio-cultural, are neglected (**Table 1**, **Figure 1**). Turning to feasibility assessments, we found that these range in scope from focusing on specific components of technologies, to broad, global, assessments. Regardless of the type of assessment, these too tend to provide little information on socio-cultural as well as institutional dimensions. Going forward, new tools are needed to inform and catalyze a discussion with and for national policy that are: (1) scaled down and context-specific and (2) comprehensive in terms of dimensions covered.

The LT-LEDS analyzed for this paper generally specify a goal and a pathway, but lack the comprehensive assessment that would help to improve our understanding about concrete challenges and trade-offs at the national level, and the realistic potential of NETs at the global level. In theory, a holistic feasibility assessment could cover an almost endless number of enabling and/or hindering conditions. Holistic feasibility assessments therefore need to reflect their specific purpose, and be tailored to the national context (Oschlies and Klepper, 2017; Fajardy et al., 2019). NETs vary in nature, and not all will be suitable for all countries, as the LT-LEDS also indicate. For instance, some countries are geologically not suitable for $CO_2$-storage (e.g., Singapore's LT-LEDS), while others face social or institutional barriers for certain NETs (Fridahl and Lehtveer, 2018; Geden et al., 2018). Moreover, NETs are neither static nor singular and can be broken down into components or procedural steps (e.g., TRLs as described in section Feasibility Operationalized in NETs Assessments). In addition, they need to be understood in relation to other societal goals such as energy security and sustainable development at the national level, as well as trade-offs resulting from the maximization of one ecosystem-service (carbon sequestration) before others (Dooley and Kartha, 2018; Fajardy and Mac Dowell, 2018; Carton et al., 2020). Moreover, socio-cultural dimensions are not only potential barriers to deployment, but can also be potential drivers (Beck and Mahony, 2018; Fajardy et al., 2019; Waller et al., 2020) and thus holistic assessments need to embrace this dynamism.

Finally, it is important to recognize that the discussion on feasibility of NETs deployment is bound up with discussions regarding the feasibility of reaching specific policy goals in the future. NETs are commonly described as a necessary means to reaching these goals, supported by emission pathways generated by IAMs. However, IAMs assume NETs can be deployed at a large scale. Looking at the technology development rate of NETs, it is uncertain if NETs can be timely scaled-up in line with model assumptions (Nemet et al., 2018). It is therefore important that assumptions made about future deployments of NETs are complemented with holistic feasibility assessments. With new NDCs due in 2020 and the submission of LT-LEDS further encouraged, now is the time to holistically assess NETs deployment, so that in the future these strategies are more firmly anchored to the national context.

## DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

## AUTHOR CONTRIBUTIONS

SB, MB, JF, TT, and DT conceived of and designed the study. JF, KG, AH, AS, and TT analyzed the national strategies. JF and TT designed **Table 1**. NM conceived of and created **Figure 1**. SB, MB, NM, DT, and TT reviewed feasibility assessments. TT led the drafting of the paper, with contributions from all co-authors. AS edited the text. All authors contributed to the article and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

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# Achieving Net Zero Emissions Requires the Knowledge and Skills of the Oil and Gas Industry

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The challenge facing society in the 21st century is to improve the quality of life for all citizens in an egalitarian way, providing sufficient food, shelter, energy, and other resources for a healthy meaningful life, while at the same time decarbonizing anthropogenic activity to provide a safe global climate, limiting temperature rise to well-below 2°C with the aim of limiting the temperature increase to no more than 1.5°C. To do this, the world must achieve net zero greenhouse gas (GHG) emissions by 2050. Currently spreading wealth and health across the globe is dependent on growing the GDP of all countries, driven by the use of energy, which until recently has mostly been derived from fossil fuel. Recently, some countries have decoupled their GDP growth and greenhouse gas emissions through a rapid increase in low carbon energy generation. Considering the current level of energy consumption and projected implementation rates of low carbon energy production, a considerable quantity of fossil fuels is projected to be used to fill the gap, and to avoid emissions of GHG and close the gap between the 1.5°C carbon budget and projected emissions, carbon capture and storage (CCS) on an industrial scale will be required. In addition, the IPCC estimate that large-scale GHG removal from the atmosphere is required to limit warming to below 2°C using technologies such as Bioenergy CCS and direct carbon capture with CCS to achieve climate safety. In this paper, we estimate the amount of carbon dioxide that will have to be captured and stored, the storage volume, technology, and infrastructure required to achieve the energy consumption projections with net zero GHG emissions by 2050. We conclude that the oil and gas production industry alone has the geological and engineering expertise and global reach to find the geological storage structures and build the facilities, pipelines, and wells required. Here, we consider why and how oil and gas companies will need to morph from hydrocarbon production enterprises into net zero emission energy and carbon dioxide storage enterprises, decommission facilities only after CCS, and thus be economically sustainable businesses in the long term, by diversifying in and developing this new industry.

**Keywords: CCS, carbon capture and storage, oil and gas industry (O&G), skills, market size and growth, negative emissions, grenhouse gas removal**



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# INTRODUCTION

## A Net Zero World

The United Nations Framework Convention on Climate Change (UNFCCC) Paris meeting in 2015 resulted in the Paris Agreement where 195 signatory nations agreed to undertake ambitious efforts to combat climate change in order to limit global warming to below 2°C with further ambitions to reduce this limit to well-below 2°C above preindustrial averages (UNFCCC, 2016). As global temperature is proportional to atmospheric greenhouse gas (GHG) concentration ($CO_2$, $CH_4$, $N_2O$, fluorocarbons, etc.) and their half-life in the atmosphere varies from decades to centuries, the world has a limited GHG budget to emit into the atmosphere before the 2°C limit is breached. The IPCC "Global Warming of 1.5°C" report indicated that cumulative net anthropogenic GHG emissions postindustrialization should not exceed an ~3 trillion tons $CO_2$ equivalent (Tt $CO_2$ eq.) carbon budget (CB) to avoid breaching the 1.5°C warming threshold (Rogelj et al., 2018). This CB uses the global warming potential (GWP*) from Allen M. et al. (2018). At the end of 2017, only ~800 Gt $CO_2$ eq. emissions remained to reach the CB. As currently in 2019 annual anthropogenic GHG emissions are ~40 Gt $CO_2$ eq./year, the world can only emit at that rate for a further 25 years before the CB is exhausted and emissions should be zero. However, in spite of global ambitions to the contrary, emissions are currently projected to increase each year making a likely overshoot on the CB. However, the recent downturn in economic activity and life-style changes due to the coronavirus disease 2019 (Covid-19) have resulted in a short-term reduction in emissions in 2020 (Le Quéré et al., 2020), some of which may become locked in by the "Green Recovery" policies and investment but will have a minimal impact on the CB.

It is impossible to achieve zero anthropogenic emissions as parts of food production, manufacturing, and transport cannot be emissions free. However, as the atmosphere can be treated as a reservoir of GHG, if these residual emissions can be balanced by GHG removal (GGR), then we can achieve net zero emissions (net zero). In addition, in the medium term, if net zero cannot be achieved by the end of the CB, then further GHG can be removed from the atmosphere to reduce atmospheric GHG concentrations. The leading technologies for GGR are either land based through photosynthesis and storage of carbon in the soil and vegetation or through physical removal and storage in a geological repository. Although changing land management to store soil carbon and afforestation to store vegetation carbon is effective, it has a limited capacity due to land availability and also reaches saturation, but it is reversible. This leaves a direct air capture (DAC) through physical and chemical devices which exists as prototype technology but require ~2,000 kWh or electrical and thermal energy per ton of $CO_2$ captured (Buettler et al., 2019) and bioenergy carbon capture and storage (BECCS). BECCS is a combination of existing technologies and essentially captures carbon from the atmosphere by photosynthesis, burns the biomass for energy, and captures the resulting $CO_2$ (Albanito et al., 2019). Both DAC and BECCS require $CO_2$ capture, transport, and storage in a geological repository [carbon capture and storage (CCS)]. In addition, decarbonization of the residual use of fossil fuels, be they oil, gas, or coal based, for electricity, heat, motive power, metal refining, or cement production requires that for net zero, the $CO_2$ emitted must be eliminated or captured and stored if their use is to be continued in a net zero economy (de Coninck and Revi, 2018).

## Current GHG Emissions Trajectory

The Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) shows that GHG emission growth has accelerated over the past decade despite policies to limit emissions (Edenhofer et al., 2014; IPCC, 2014). Most growth in emissions is driven by $CO_2$ from fossil fuel use in the energy and industry sectors. About half of cumulative anthropogenic $CO_2$ emissions between 1750 and 2010 occurred in the last 40 years (Edenhofer et al., 2014). Emissions continue to rise with increasing economic growth and population in non-OECD countries. This increase in emissions was paused during the 2008 banking crisis but subsequently continued to increase until the recent reduction caused by the Covid-19 pandemic, though this reduction is likely to be short lived (Forster et al., 2020; Le Quéré et al., 2020). In the IPCC special report SR1.5, several emission scenarios are tested to limit warming ~1.5°C; all show that net zero emissions must be achieved by 2050, and if a slower trajectory in reductions is followed, then the amount of negative emissions that are required to balance the cumulative emissions increases (Rogelj et al., 2018).

The current annual anthropogenic GHG emissions are ~40 Gt $CO_2$, and the consequences of continuing this rate of emissions is a global temperature increase exceeding the 2°C limit agreed to under the United Nations Framework Convention on Climate Change. This will significantly increase the risks to a range of natural and human systems over this century and beyond (IPCC, 2014). Urgent action is required to reduce emissions to avoid dangerous climate change (Edenhofer et al., 2014; Rogelj et al., 2018). The analysis shows that there is still time to act, but the window of opportunity is rapidly closing and that the longer we wait, the more costly and risky the solutions will be (Edenhofer et al., 2014). The carbon budget of ~1,000 Gt $CO_2$ remaining emissions should not be exceeded if more than a 2°C warming is to be avoided. With only ~20 years or slightly longer if the Covid-19 effect persists, to emit GHG gas at the current rate, this carbon budget should be used to create the infrastructure for a global low carbon energy production system to sustain a future low carbon economy, and it should not be squandered on supporting business as usual.

## Future Projections of Fossil Fuel Use

The current consumption of primary energy is predicted to continue to rise [IEA (International Energy Agency), 2019; BP, 2020], and by 2040, the entire global carbon budget of carbon dioxide emissions of ~1,000 Gt $CO_2$ eq. (Miller and Sorrell, 2014) allowable to give a 50:50 chance of meeting the 2°C target of global temperature increase will be used, and we will still have high emissions. The IEA's most optimistic sustainable development scenario predicts that net zero is reached by 2070, which misses the 2°C target [IEA (International Energy Agency), 2020b]. Even though the rate of increase slowed in 2019, without negative $CO_2$ emissions (Fuss et al., 2014), by 2040, emissions of GHG must be reduced to zero. However, based on the IEA-stated policies scenario [IEA (International Energy Agency), 2020a] which includes new measures and policies that promote energy efficiency and low carbon technologies, the IEA projects total energy demand will grow by 10% between 2019 and 2030, in spite of dropping 10% in 2020 due to Covid. In this scenario, coal demand is projected to drop from 2019−5,500 million tons coal (Mtce) to 4,800 Mtce by 2040, oil consumption is projected to increase from 2019 levels by 9 million barrels per day (Mb/day) to 104 Mb/day, gas consumption will rise by 30% to 5.4 trillion cubic meters (Tcm) [liquefied natural gas alone increases from 300 to 540 billion cubic meters (bcm)]. The BP Energy Outlook 2020 makes similar forecasts. Both the IEA and BP scenarios based upon current policies or governments and investment plans of brother oil and other energy companies and utilities show that at best if policies and investment plans do not change, GHG emissions will at best remain at the current levels. Clearly, the IPCC objective of reducing GHG emissions to zero is at odds with the current IPCC, IEA, and BP projections for fossil energy use, as by 2040 emissions should have reduced to zero, instead the IEA projects fossil fuel emissions to be 36.7 Gt $CO_2$/year and BP between 18 and 45, unless all the projected $CO_2$ emissions are geologically stored.

It is estimated that by 2040, only 15% of passenger cars will be electric (BP, 2020), for road transport overall, biofuels will make up 8% of road transport demand, the rest being supplied mainly by fossil fuels (BP, 2020). There will be a growing percentage of electrified trains and urban transport, but air and sea transport will remain fueled by fossil energy sources, and their emissions will not easily be captured, representing 21.6% of total emissions. Based on the IEA scenario, world electricity demand is projected to rise by 80% from current consumption by 2040 to 39,000 TWh, and the share in renewables will increase from 21% in 2012 to 33% by 2040 [IEA (International Energy Agency), 2018]. Installed capacity for renewables is projected to increase by 4,000 GW by 2040. This means that by 2040, total electricity generation will be 12,937 TWh from renewables of which 12% is bioenergy, 50% is hydro, 24% is wind, 2% geothermal, 8% solar PV, 2% concentrated solar, and a small amount of marine energy. Nuclear is projected to rise slightly from 11 today to 12% by 2040. This is lower than its peak in 1996 of 18% of total electricity generation. Due to the overall increase in electricity demand, the nuclear electricity generating capacity is predicted in this scenario to increase from 392 GW today to 624 GW by 2040. However, as most currently operating nuclear power stations will need to be decommissioned by this time, the entire 2040 capacity will be new. This leaves, by 2040, 55% of electricity generated from fossil fuel, which will result in ∼14.4 Gt of annual carbon dioxide emissions, out of the total emissions of ∼37 Gt $CO_2$e in the evolving transition scenario (BP, 2020). This is greater than the 13 Gt $CO_2$e emitted in 2010 by electricity generation.

## The Potential Carbon Capture and Storage and GGR Market

In summary, total energy demand will grow by 37% by 2040, and taking into account energy efficiency improvements and projected growth in non-fossil energy use due to the change in mix of fossil and other fuels in the IEA current policy scenario, this will cause a 20% increase in GHG emissions. If such improvements were not accounted for, oil consumption would be 23 Mb/d higher (+22%), gas consumption 940 bcm (+17%), and coal consumption 920 Mtce higher (+15%). GHG emissions are thus projected to rise by 20% by 2040, and if they were to continue at that rate beyond 2040, the world would be on-track for a 3.5+°C rise in temperature. If this scenario of fossil fuel use is realistic, then the carbon from its use should no longer be emitted to the atmosphere if the global temperature rise is to be limited to 2°C. CCS involves three phases: capture of the $CO_2$, its transport, and its geological storage. CCS from stationary use of energy is the most practical, and so the 55% of fossil fuel–generated electricity and industrial processes like metal refining and cement production should be the first targets. The total amount of $CO_2$ to store each year in the IEA current policy scenario from stationary use by 2040 is 24 Gt $CO_2$e, of which electricity generation accounts for 15.4 Gt $CO_2$e. However, the total emissions from anthropogenic activity including food production and the "difficult to eliminate" mobile emissions are 37 GT $CO_2$e/year, which for net zero must be eliminated or negated by negative emission using DAC, BECCS afforestation of other land-related GGR. This forms the upper limit for the CCS market, as shown in **Figure 1**.

Snøhvit in the Norwegian sector of the North Sea is a good example of a typical CCS storage system. It uses an amine separation system in an onshore LNG plant, a 153-km pipeline to transport the $CO_2$ offshore, a single horizontal well that injects around 0.7 Mt of $CO_2$/year into a saline aquifer, with a total capacity of 23 Mt (Equinor, 2020). Holloway (2009) estimates that the UK continental shelf has a storage capacity for 25 Gt $CO_2$, enough for 100 years of emissions from UK power stations at current levels, which were 184 Mt/$CO_2$ in 2015. However, this would require 260 installations similar to Snøhvit. This is comparable with the number of oil and gas production facilities in the UK continental Shelf. Scaling this globally to capture all fossil emissions from electricity generation worldwide by 2040 would need to store 15.4 Gt $CO_2$/year by 2040 due to the projected electricity generation mix and would thus need 20,500 of such installations [IEA (International Energy Agency), 2013] estimates GHG emissions of 13.36 Gt $CO_2$/year in 2012 from electricity production for comparison]. If installations for GGR to balance emissions from transport, farming, and industrial processes are considered in the IEA scenario of 37 GT $CO_2$e/year emissions, then the requirement is for 50,000 Snøhvit installations, unless emissions can be otherwise reduced.

## The Technology Readiness Level (ESA, 2008) of Carbon Capture and Storage

If fossil fuel use projections follow the IEA-defined policy scenario, decarbonizing the 55% of electricity generation by

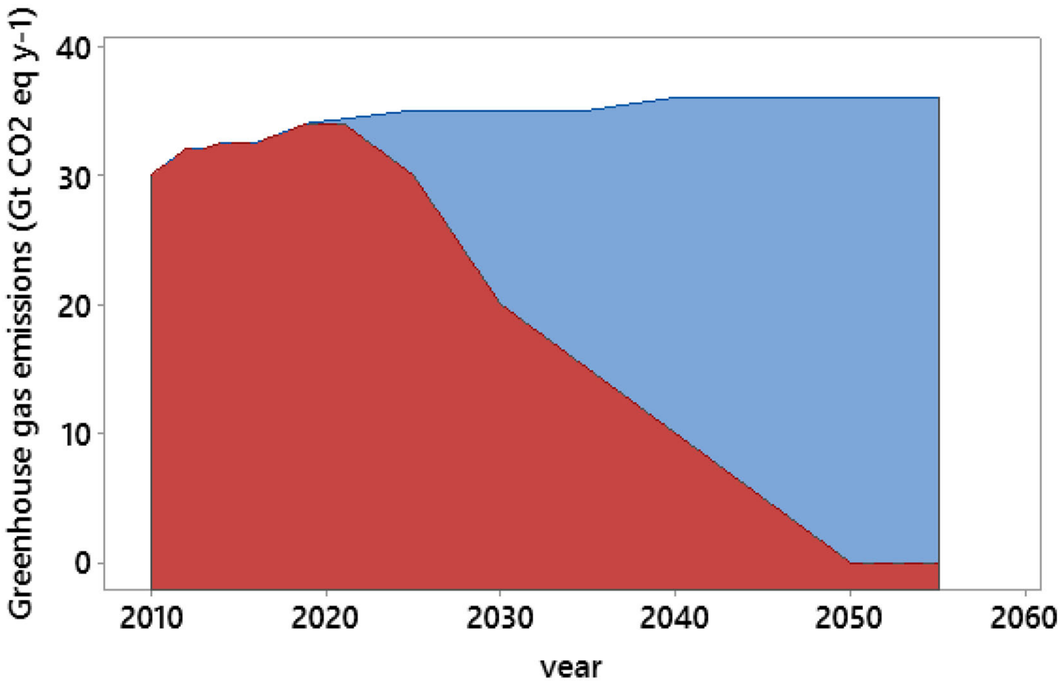


**FIGURE 1 |** This is a graph of projected emissions to 2055. The area under the red curve is the IPCC SR1.5 low-energy demand–projected net annual emission pathway to keep global warming below 1.5°C, reaching net zero by 2050. The area in blue is the difference between the projected emissions from the IEA for currently stated policy scenario and the desired net zero pathway. This is the potential CCS requirement to achieve net zero by 2050.

2040 will require a CCS industry capable of storing 15.4 Gt $CO_2$/year. To put this into perspective, current oil and natural gas production quantities are 4.2 and 3.1 Gt oil equivalents/year, respectively. $CO_2$ when liquid has a density of 770 kg/m$^3$ and a density of 1.977 kg/m$^3$ at 1 atmosphere and 0°C. The liquid density is similar to oil, and gas is denser than methane at 0.716 kg/m$^3$ under the same conditions. When $CO_2$ is injected into a geological formation, it can be stored in different forms, and this depends on the pressure and temperature of the geological formation relative to the pressure–temperature phase diagram of carbon dioxide (**Figure 2**). At formation temperatures, which are usually above 36°C, $CO_2$ is either a vapor below 90 bar or a supercritical fluid above, thus the $CO_2$, being less dense, will rise to the top of the reservoir. However, $CO_2$ is also soluble in water at the rate of 1.45 g/L at 25°C and 100 kPa, and since water saturated with $CO_2$ is denser, it will sink to the bottom of the reservoir.

The concept of storing the $CO_2$ gas in a geological formation relies on finding a porous rock into which the $CO_2$ can be injected with a seal mechanism that ensures the $CO_2$ is trapped. The type of seal depends on the mechanism to trap the gas in the rock formation. If it is stored as a gas, or critical fluid, then the seal must be at the top of the reservoir; however, if it is stored in solution, the seal must be at the bottom of the reservoir. In practice, the storage mechanism is a combination of both. Injecting $CO_2$ into a geological formation will increase the pressure, and the volume that can be injected is limited as by the geomechanical properties of the reservoir system, to avoid increasing the pressure to the point that it fractures the rock that created the seal. Typically, volumes >2% of the reservoir volume cannot be injected, unless some fluid is taken out of the rock (produced) to reduce the pressure, and in this case, the produced fluids have to be disposed of without harming the environment. This means that depleted oil and gas reservoirs can be used for storing $CO_2$ as they can be pressured to their original preproduction pressure. $CO_2$ can also be used to enhance oil recovery (EOR), both as a miscible agent, where the injected $CO_2$ is a supercritical fluid and dissolves in the oil causing it to swell and reduce it viscosity—thus increasing reservoir pressure and improving its mobility, or it can be used as an immiscible injection medium (as a gas/vapor) to facilitate repressuring the reservoir and gravity drainage. This is a mature technology for the oil and gas industry and $CO_2$ EOR is in widespread use in the USA. Pure $CO_2$ sequestration is less common and currently confined to demonstration projects, but the technology of locating the rock formation and drilling wells, construction of facilities, and operation of the injection wells is similar to that used in the finding and production of oil and gas. There are currently 18 CCS projects in the world and four in operation: in Salah in Algeria, operated by Sonatrach-BP-Equinor, and Snøhvit and Sleipner in the Norwegian sector of the North Sea operated by Equinor (2020). The first large-scale CCS for the power sector commenced operation in October 2014 at the Boundary Dam coal-fired power station in Saskatchewan, Canada, selling the $CO_2$ for EOR. There are other projects in the planning or construction phase indicating a technology readiness level (TRL) level of 8 or 9.

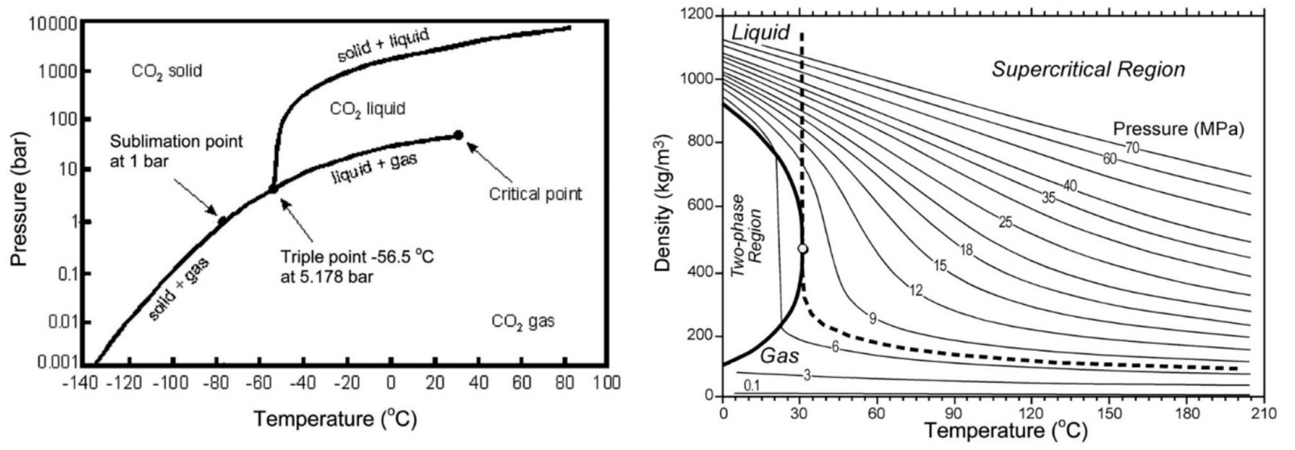


**FIGURE 2 |** Phase diagram of carbon dioxide (source: http://elements.geoscienceworld.org/content/3/3/179/F2.expansion.html).

The separation of $CO_2$ from other gases by the amine process is a mature technology that is used in many natural gas-processing plants and refineries and can be adapted to capture $CO_2$ precombustion to produce hydrogen for the actual combustion, or postcombustion from the exhaust gasses (Rochelle, 2009; Fuss et al., 2014), a TRL of 9. Anhydrous $CO_2$ in the gas phase or as a supercritical fluid is not corrosive at surface temperatures and can be transported using steel metallurgy but requires special elastomers for seals. However, $CO_2$ is corrosive when there is water present, forming carbonic acid, and pipe valves and pressure vessels require stainless steel metallurgy. The TRL level of this technology is 8–9.

There are other technologies, such as calcium looping, being developed, but these are not yet operational (Choi et al., 2009; Astolfi et al., 2019). There are other $CO_2$ disposal options, involving carbonation (rather than storage in depleted oil and gas reservoirs and saline aquifers) where leakage would not be a problem. These are now operational at pilot scale (Matter and Kelemen, 2009; Buettler et al., 2019). Another approach is carbon capture and use (CCU). There are several approach being researched such as a process to capture $CO_2$ in brine rich in Mg and Ca ion to form carbonates which can be used to make cement or as a chemical feedstock (Imbabi, private communication). This process in being developed by the University of Aberdeen with funding from Qatar and requires large amount of Ca- and Mg-rich brine to combine with gaseous $CO_2$. This is synergetic with the oil gas industry (OGI) as it produces large quantities of brine which for terrestrial locations creates a disposal problem, which will also be the case where CCS used saline aquifer carbonation for storage. Other CCU strategies such as using the $CO_2$ to produce fuel are being pursued; however, this is an energy-intensive process. The TRL of these technologies is below 7.

# ROLE OF THE OGI AND A POTENTIAL BUSINESS MODEL

Having established the global need for large-scale CCS to either decarbonize future fossil fuel use or provide sufficient negative emissions to achieve net zero and identified that in general all of the technologies are mostly at a TRL of TRL 8 or 9, the question is how can this embryo industry be ramped up in a timely fashion at scale and what policy levers are required to achieve this. In this section, we consider the role of the oil companies and potential business model.

## The Role of the Oil Companies

The technology and skills required for CCS (except DAC and bioenergy) are virtually identical to those employed in the exploration, production, and processing of hydrocarbons. The OGI employs earth scientists and reservoir engineers to build geological models to identify potential reservoirs and to model them statically and dynamically using well-data, cores, petrophysical logs, and test data. Drilling engineers drill the wells, production engineers design the well-completions, facility engineers design processing equipment, platforms, and pipelines, and civil engineers design transport facilities and roads, etc. In addition, license holders require legal and financial experts to negotiate contracts with land owners and governments. License holders share the expertise with Integrated Service Companies who provide most of the routine operational work.

Current experience of CCS in the Salah, Snøhvit, and Sleipner CCS projects (Equinor, 2020), and on producing, transporting, and injection $CO_2$ in EOR projects, demonstrates that there is little difference in the reservoir characterization, wells drilled, facilities design, or operations required to safely inject $CO_2$ into the ground. This is the case even if saline aquifers or deep rock mineralization is used for storage. The cost structure of CCS operations is going to be similar to gas injection facilities and wells that are used for secondary or tertiary oil and gas recovery techniques in the OGI [IEA (International Energy Agency), 2013; Irlam, 2017].

The main difference between producing oil and gas and storing $CO_2$ is the direction of flow and that the reservoir pressure is higher at the end of the project rather than depleted. It requires the same skills, technology, and safety ethos. The storage reservoirs have to be found, wells drilled, and facilities and pipelines built. Once the $CO_2$ has been injected into the reservoir, monitoring to check for leaks is required, and any remediation work undertaken. As the reservoir pressure is higher at the end of storage than the beginning, continuous monitoring of the reservoir integrity is required as unlike a depleted oil and gas reservoir, the pressure in the storage structure may not be balanced by the natural hydrostatic head in the rock formations above. The scale of the work to be undertaken will be of a similar magnitude to the current OGI work undertaken to find and produce oil and gas at the current rates (Pershad et al., 2012; Spence et al., 2014). The question remains: who will form this CCS industry? The OGI is an obvious starting point, but to ramp up an industry of such a magnitude would mean doubling the size of the OGI resources of personnel and investment from the level today. This would require a large investment in training of geoscientists and engineers for the industry which today, due to the "great crew change" (see below) and the cyclic nature of employment in the industry, struggles to find enough suitable qualified personnel. It would also require a huge investment in Geology and Geophysics surveys and infrastructure building. In the current economic climate, the big question is who pays for the investment needed to kick start this industry and how can it be made fairly as part of a wider transition to sustainable living in a post-Covid-19 context (Lippponen et al., 2017; Allen et al., 2020).

## The Cyclical Nature of the OGI

In the past 50 years, the OGI has been very cyclical due to rapid changes in the oil price. These changes are driven by supply and demand and perturbed by interruption in supply due to wars, civil unrest, changes in demand due to boom and bust cycles in the world economy, and political intervention to modify supply and thereby prices and disrupting technologies such as horizontal wells and fracking. Most oil and gas demand is satisfied by the long term or future contracts, the price of which changes slowly, and historically many gas contract prices are closely pegged to the oil price. However, the remainder is traded on the spot market, which defines the price of Brent and West Texas Intermediate crude oil, the Henry hub spot gas price in the USA, and the spot price of liquefied natural gas (LNG). These spot prices are volatile and very sensitive to the supply-demand balance. Even in an ideal world without any perturbation from policy or conflict, high growth in the world economy leads to an increase in consumption of energy, which tightens the margin between supply and demand, and oil and gas prices increase. As the prices go up, small- and intermediate-sized independent oil companies start to increase exploration and development (E&P) activity, followed by the majors, which increases the supply of oil and gas. However, as the high oil prices in turn lead to a slowdown in the world economy, the demand slackens, the spot price of oil and gas drops, and E&P activity slows. The OGI cycle, which tends to last around 5–7 years, repeats itself and tends to be out of phase with the boom and bust cycles of the world economy.

National oil companies, especially those in OPEC, and the majors with large portfolios of producing fields and exploration licenses, tend to modify their activity selectively in response to low oil prices and focus on lower-risk and lower-cost interventions, and low-risk exploration prospects to reduce overall costs and take a long-term view of the cycles. However, small- and medium-sized independents, who rely on cash flow to fund E&P activity, cut spending fast. The US Baker-Hughes rig count reflects this fluctuation in activity and has ranged between 287 and 4,500 active drilling rigs from 1975 to present (Baker-Hughes, 2020). Such drastic changes in E&P activity result in service and drilling companies releasing many skilled people, and they also stop hiring and reduce their training programs. This in turn, affects the prospects for graduate earth scientists and engineers, and University course intake on such courses is also cyclical. Many of the people released in a downturn do not return to the OGI as they find other jobs in the world economy, which is out of phase and hiring when E&P activity is low. This has led to a bimodal distribution in the age of skilled E&P workers and led to "the great crew change around 2000."

As generally the world economy is out of phase with the oil industry and consumes more energy when hydrocarbon prices are low (and OGI activity low), it also emits more $CO_2$. As an example, the Covid-19 pandemic has currently curtailed global economic activity and oil prices have fallen as a result and rig activity is the lowest since 1972 (Baker-Hughes, 2020). This means that oil and gas supply will lag demand if and when the economy recovers and emissions will pick up (Le Quéré et al., 2020). If there was a parallel CCS activity, which was part of the OGI, then the reduced resources required in the E&P part of the business could be reassigned to the CCS one and somewhat reduce the see-saw in activities.

## Potential Business Model

As oil and gas companies are to be involved in the creation of the CCS industry, the potential business model should be designed with due regard to the upstream oil and gas industry. The cost of producing oil and gas can be divided into operating costs (OPEX) and amortized capital costs (CAPEX). The CAPEX includes the cost of buying the license to explore and produce hydrocarbons, exploration costs, reservoir characterization costs, and the cost of building the infrastructure including drilling the wells, acquiring well and geological data, and constructing pipelines, platforms, and pads and processing equipment. CAPEX is amortized over a fixed period that not only depends on the license agreements and tax regime of the country but is also related to the size of the field and can be from 3 to 30 years. In addition, under some license agreements, provision has to be made for decommissioning of facilities, either in the form of a levy, an escrowed provision, or taxation. OPEX relate to the ongoing operation of the producing facilities and includes repair and maintenance, energy, personnel, well-health checks and well work-over, oil and gas transportation, marketing costs, and water disposal costs. The sum of the OPEX and amortized CAPEX divided by the production volume gives the lifting costs per barrel of oil (bbl). Typically, in the UK continental Shelf (UKCS), it ranges from \$23 to \$84/bbl (HM Revenue Customs, 2018). Profit before tax is the difference between the sales price and lifting costs. In the UKCS, the current tax rate is between 30 and 40% of the profit (HM Revenue Customs, 2018), depending on the license agreement. With the recent volatility in oil prices from \$140/bbl in 2009 to \$14/bbl in 2020, it is easy to understand changes in E&P activity in the UKCS, where many projects are producing oil at a loss at low prices for a period of time that could destroy the profitability of the overall project over its lifetime. This leads to caution in investing in new projects, raising the bar to exclude riskier high potential lifting cost projects. This is, in turn, can reduce the total oil and gas that will be produced in an area or country.

CCS OPEX and CAPEX include many of the components pertaining to E&P activity. Well-site and offshore oil and gas processing is replaced by injection compressors, injector well-completion tends to be simpler than producing wells, the metallurgy of the infrastructure is required to be $CO_2$ corrosion resistant, and there would have to be some monitoring of posterity for the safety of the storage facilities/reservoir, which is somewhat similar to the needs of nuclear waste disposal sites. The cost metric would be storage cost in \$ t/$CO_2$. The total cost of CCS would be the gas separation cost at the point of emissions plus the transportation and storage cost plus a mark-up for profit. Cost will be sensitive to distance between capture plant and geological storage and the depth of the geological formation. The section of the transport pipeline system on land will be more costly per kilometer due to the complex planning systems (CCS Cost Reduction Task Force, 2015).

The UK government's study of levelized electricity costs (UK Government - BEIS, 2016, 2020) per MWh for new generating capacity commissioned in 2030 would be as follows: First of a Kind (FOAK) combined cycle gas turbine generation with CCS (CCGT-CCS) ∼\$120/MWh, reducing to \$108 for an *N*th of a Kind (NOAK) by 2040. This is competitive with the current UK strike price of new nuclear (\$124/MWh for Hinkley Point) and offshore wind (which ranges from \$75 to \$232.5/MWh) (UK Government – BEIS, 2019). Currently, a UK coal-fired power station emits between 750 and 900 kg $CO_2$/MWh. This makes the cost of transporting and storing $CO_2$ around \$79.5/MW $CO_2$. The CCGT emits about half the $CO_2$ per kilowatt-hour and hence the cost is ∼40/t $CO_2$. In comparison, BP estimated that in Salah CCS land site, the separation, transportation, and storage cost was \$10/t $CO_2$ in 2000; however, the ongoing monitoring costs were not included. US DOE (Department of Energy), (2015) estimates a FOAK cost of adding CCS to a super-critical thermal power unit to be \$124–133/MWh and an NOAK for \$108/MWh. This gives a cost of avoided $CO_2$ of \$74–83/t $CO_2$ for FOAK and \$55 for an NOAK. They further gave estimates of the cost of avoided $CO_2$ for other industries for different counties depending on the access to geological storage. For countries with access to land storage, like the USA, this cost per ton of $CO_2$-avoided emission is as follows: iron and steel, \$77; cement, \$124; fertilizer, \$26; and biomass to ethanol, \$22.

Most of these costs for avoided emissions are < \$80/ton of $CO_2$, with cement being the most expensive. This is equivalent to the current carbon tax paid in the Norwegian Sector of the N sea, which includes the EU ETS. These carbon values have been used in Integrated Assessment Models (IAMs) to evaluate the Socio Economic Pathways (SSPs) to achieve Representative atmospheric GHG Concentration pathways (RCP) to limit global temperature rise to 2°C (RCP 2.6) and 1.5°C (RCP 1.8). All the models show that large quantities of CCS are required to reduce ongoing emissions and both afforestation and BECCS are required to remove 10 Gt of $CO_2$/year to achieve net zero by 2050. This highlights the urgent need to start the CCS industry and get on top of the technology, in order to ramp up to the scale required by 2050. \$80/t means that in 2050, the new global CCS industry will have an annual turnover of \$3 trillion, using the IEA emission figures of 37 GT $CO_2$e/year. The question is how does society pay for the storage.

## BEHAVIORAL, ECONOMIC, AND POLICY CHANGES TO KICK START CCS

A wide array of behavioral and policy changes are required to drive the technological measures needed to limit the increase in global mean temperature to 2°C or the Paris aspiration of 1.5°C above preindustrial levels. The recent IPCC report on Global Warming of 1.5°C demonstrated the large increase in risk to the earth's ecosystem services for an increase in warming from 1.5 to 2°C which may have a larger cost than the \$3 trillion annual CCS cost (Allen M. R. et al., 2018; Rogelj et al., 2018), so CCS needs to be kick started quickly to fully decarbonize energy use and provide infrastructure for GGR BECCS and DAC storage as well.

### Energy Use Systems and Economic Changes to Achieve Net Zero

Existing and affordable technologies such as nuclear, geothermal, wind, solar, bioenergy, and tidal electricity generation and heat provision are available to substantially reduce greenhouse gas emissions (Edenhofer et al., 2014). Their large-scale adoption will require a large investment in new infrastructure. Many studies, such as IEA [BP, 2020; IEA (International Energy Agency), 2020a] predict the continuing need to use fossil fuels to meet the growing demand for energy in order to achieve the socioeconomic objectives and sustainability goals in the global economy. If fossil fuels continue to be used, then combustion products cannot be released to the atmosphere. If they are, then in order to limit warming to 2°C, McGlade and Ekins (2015) suggest that 82% of coal reserves, 49% of gas, and 33% of oil will have to be left unburnt in the ground. Pragmatically, the only way that the world energy needs, predicted by the IEA-defined policy scenario, can be satisfied up to and beyond 2050 and at the same time reduce GHG emissions, is to capture and store carbon dioxide resulting from the fossil fuel burn in geological repositories (CCS).

It is clear that fossil fuel use for energy generation without CCS needs to be phased out [Edenhofer et al., 2014; Allen M. et al., 2018; IEA (International Energy Agency), 2020a] Combined energy-economic-climate modeling suggests that to achieve climate mitigation goals, annual investment flows for extraction of fossil fuels and fossil fuel power plants without CCS would need to decline, with increased investment flows into energy efficiency, power plants with CCS, and other modes of energy generation including renewables and nuclear (Edenhofer et al., 2014). This presents the oil and gas industry with some significant challenges, but CCS provides a significant opportunity, as many of the skills required for oil and gas extraction for energy are those required to locate suitable geological locations for $CO_2$ storage and to move the $CO_2$ from the point of generation to the long-term geological storage. In addition, the use of $CO_2$ for tertiary recovery is an established technology used in producing oil, and this provides symbiosis between the CCS and the fossil fuel production industries.

The same teams drilling wells for fossil fuel extraction in 2019 may be drilling wells for CCS in 2030. This may also smooth out the OGI boom and bust cycles. Furthermore, hydrocarbons are valuable commodities that provide a range of products other than energy and will be extracted for these purposes even if the hydrocarbons are not burned for energy generation; however, there must be an incentive to start the transition.

### Public Perception and Cost to Society

Currently, the public's perception of climate change is that "something needs to done" and the high media profile of a Swedish teenager Greta Thunberg and the galvanism of organizations like Extinction Rebellion and Greenpeace have created a sense of urgency about "doing something." However, the world economic system is wedded to continuous growth which is driven by consumers in all parts of the world wanting a leveling up of their economic situation and having food security, housing, health provision, and other aspects of higher standards of living. The concept of polluter pays is lost in the fear of having to actually change consumption habits or having higher prices for energy use. In addition, the millennium goals aim for an equitable standard of living for all humans and human nature interprets this as leveling up. Politicians are wary of changing policies about houses, energy use, and transportation that curtail growth for fear of reducing disposable income and not being re-elected. As a result, it is easy for NGOs and political parties to blame large corporations who produce the energy, materials, manufactured product, and food and demand they decarbonize so people can continue with their consumerism. The fossil fuel industry is demonized because it provides the fossil fuel for the economy to run when in fact, the oil and gas industry holds all the skills, expertise, capital, and assets that have the ability to decarbonize energy use. If "big bad oil" steps up to the plate to kick start the CCS industry, it will transform its image into the "savior of the climate" and avoid having its shares divested by well-meaning organizations.

### Government Policies

At the government level, energy security and climate change mitigation targets are often poorly aligned and policy is contradictory. At the industry level, there is limited engagement from the oil and gas industry with the climate change dialog, but where such engagement has occurred, the outcomes have been extremely useful. More dialog between large energy corporations and those interested in limiting climate change (including governments, environmental NGOs, academia, and wider society) can only help to build trust between the various stakeholder groups and to find a common ground for shared action. Taking the UK as an example, over the last decade, there have been several research and engineering projects that have been funded by the UK government and the EU to develop CCS technology up to funding front-end engineering designs (FEED). However, these stopped short of providing funding for building pilot commercial CCS–equipped power stations. In addition, using several fiscal levers has been introduced to decarbonize electricity generation. The first is essentially a tax on carbon emissions which adds cost to fossil fuel generation to augment. The second type is to encourage investment in low carbon generation. These are renewable obligation certificates (RoCs) up to 2005 for large-scale power stations and latterly Feed in Tariffs (FITs) for small-scale heat and electricity generation. More recently, the Contracts for Difference (CfD) to subsidize low carbon electricity/heat production has been introduced. The added cost or these schemes are actually passed on to the energy consumer though their consumption billing. In this scheme, power generators have to bid at CfD auctions which are the lowest price to be paid. In 2020, CCGT-CCS was added to the eligible low carbon technologies. These policy levers have resulted in lowering the carbon intensity of UK electricity from ∼850 $CO_2$e/kW in 1990 to an average of 241 in 2019 but had not yet encouraged commercial CCS to start.

## ACTIONABLE RECOMMENDATIONS

Several actions are recommended to spur the development of a CCS industry. These include push and pull incentives by governments, oil and gas industry transition to zero carbon, and changes to regulations relating to the abandonment of oil and gas wells and the decommissioning of offshore platforms and pipelines.

### Push and Pull Incentives by Governments

Currently (2020), the following six countries have set legally binding net zero GHG emission targets: the UK, Sweden, Norway, France, Denmark, and New Zealand and are setting carbon budgets (CBs) for future decades to ensure the transition to net zero. These CBs should be made legally binding. The UK for example has met all carbon budgets to date, set by the Committee for Climate Change (CCC), a UK government advisory body. Meeting these targets reduced total GHG emissions by 43% from 1990, mainly from energy provision, changing from coal- to gas-fired CCGT, and increasing the proportion of renewable energy to ∼30%. CCGT now generates ∼40% and as it provides most of the dispatchable power to cover for the intermittency of renewables, it will still be required in the future to 2040, unless sufficient large-scale electricity storage is developed to meet this demand. Thus, it requires decarbonization with CCS. In addition, CCS is required to decarbonize metal, chemical, and cement industrial processes as well as for GGR using BECCS and DACS. It is imperative that there is government financial support for, or investment in, the FOAK CCS plant in the UK for both power and industry. The first contracts for CfD for the early CCGT-CCS systems could also be a mechanism to support early CCS introduction. In addition, a licensing scheme, similar to that for O&G exploration should be put in place for $CO_2$ storage, and a mechanism for the long-term (centuries) responsibility for the storage should be put in place to transfer the liability to the government at some point in time.

In addition, a mechanism is required to promote carbon trading to replace the EU ETS scheme. The scheme in Norway uses EU ETS and has an additional carbon tax on top that brings the total $CO_2$ cost to ∼$80 a ton which is close to the estimated CCS carbon cost for Snøhvit (Energy Facts Norway, 2020). So, in order to create a supply chain for CCS and incentivize, its use such as carbon price in the UK would provide a carrot for the oil and gas industry to get involved in the business and also a stick to encourage industrial and power-generating companies to store their emissions. This means that the carbon tax and CCS cost need to be aligned; this would create a mechanism for the CCS industry to be economically viable. In addition, an evolutionary carbon balance approach was proposed by Zakkour et al. (2020), whereby fossil fuel resource holders manage outflows and inflows of carbon in the geosphere and create and maintain the market for geological $CO_2$ storage.

If the principle of "polluter (consumer or end user) pays" is applied, then carbon cost or the cost of carbon storage is added to the service, energy, or commodity being purchased. This inevitably will result in an addition to the cost of living and be inflationary. To avoid inequities, the government should facilitate investment in energy efficiency across all sectors. The housing sector should have improved new building insulation standards and also regulations to improve the energy efficiency of existing commercial and domestic housing and building stock. New housing developments should be organized around self-contained communities that include schools, health facilities, shops, and work places that can be accessed by active transport such as walking and cycling. The need for commuting should be reduced by improving Internet connectivity with fiber networks to enable home or local hub working locally. Investment in electrifying public transport should be prioritized over cars as electrifying all modes of transport with the current mix of bus, train, and car will considerably increase the need for low carbon electricity. Thus, with less electricity required per capita, the cost of living increase can be constrained.

## Industry Transition to Net Zero

In those countries that have net zero emission targets, the upstream oil and gas industries will have to make a transition to low carbon energy and are currently committed to eliminating operating GHG emissions. In general, these companies see the responsibility for eliminating GHG emissions from their product use as being further down the supply chain.

A report by SNC-Lavalin's Atkins Business called Engineering Net Zero (Atkins, 2020) quantified the challenge of moving to net zero while maintaining economic and social progress in the next 30 years. It identified that to decarbonize building, heating and transport of all kinds would require a massive investment on both electricity and hydrogen ($H_2$) production. Renewable electricity from tidal, wind, and solar would increase, but as it is intermittent, it requires dispatchable power source such as CCGT-CCS, or large-scale storage, which can be quickly switched on, with nuclear providing a base load and black start capability. $H_2$ would be used for decarbonizing transport using fuel cell technology for HGVs, buses, trains, and possibly aircraft that cannot be easily electrified. These issues are emphasized in the Committee on Climate Change (2019). $H_2$ will also be required for industrial process and building heat using the gas grid. $H_2$ can be made through electrolysis of excess renewable electricity, but the majority will be made by steam-reforming methane and using CCS. This provides a great boost in procurement of capital goods for all sectors of industry and energy transition for traditional O&G companies.

From this, it can be seen that most end uses for fossil fuels will require CCS so if companies that produce the oil, gas, and even coal also store the resulting carbon from their use, they will become carbon-neutral companies. An alternative for this is a viable carbon trading system that ensures net zero to the atmosphere. All the skills and technology for well-drilling and engineering, reservoir management, structure pipelines, and processing currently resides in the oil and gas industry so this transition could be seamless. O&G companies will morph into O&G and CCS companies.

In the UK, there are green shoots for the CCS and BECCS industry with a group of industrial companies in the planning stages of a $CO_2$ collection system in the Humber and Tyne valley regions. There is also a BECCS pilot plant, funded by the UK government and DRAX company, that is proving that $CO_2$ can be captured from the exhaust gasses of a large biomass burning power station. In NE Scotland, there is a pilot steam methane-reforming plant being built, funded by the UK government and EU, and located in the St. Fergus gas terminal. This is managed by the Pale Blue Dot Company with Shell providing the $CO_2$ transport and storage in their depleted Goldeneye gas field, which had been decommissioned. For other European countries, Equinor, Shell, and Total have formed an alliance to plan for an EU wide $CO_2$ collection scheme to dispose of $CO_2$ in the Norwegian sector of the N Sea building on their Sleipner experience. In the US and Canada the infrastructure exists for $CO_2$ transportation for large scale tertiary recovery schemes and in reality it just takes investment or tax breaks [e.g., Section 45Q tax credits for CCS (Congressional Research Services, 2020)] to expand this to CCS. From this, it can be seen that the sleeping giant of the oil and gas industry is awakening to the net zero era.

## Implications for Decommissioning

Oil and gas facilities and reservoirs are currently being decommissioned without regard for the carbon cost of doing so, both in terms of the potential reuse of the assets and actual deconstruction costs. In addition, wells are being plugged and abandoned with the well-sealing system being designed for the current status, reservoir fluids in place and the reservoir pressure, which is usually depleted. No regard is made of the potential reuse of the structures and reservoirs for $CO_2$ storage, which will usually mean repressuring the reservoir to its initial preproduction pressure. If the well-plugging does not consider potential re-pressurizing with $CO_2$ then that reservoir will not be able to be used for CCS. The structure will have the weakness of the abandoned wells, not designed for $CO_2$ containment, which will be very difficult to remediate after the well-head is cut below the mudline. Due to the large future requirement for CCS, all well-abandonments should be designed with this in mind and government regulation relating to this needs to change.

## Using Carbon Dioxide as a Feedstock for Manufacturing Low Carbon Products

The future potential to use the separated or stored carbon dioxide as a feedstock for low carbon products is an area attracting research. We have previously mentioned the combination of $CO_2$ with magnesium-rich brine to produce a cement that can be used to manufacture lightweight building material, thus storing the carbon. There are other mineralization pathways that can be used. Crop growing productivity can be enhanced by growing crops in an atmosphere with elevated $CO_2$ level as is currently done in many greenhouses; this is known as $CO_2$ fertilization. Finally, there is research into the production of synthetic and fuels and plastics from $CO_2$ plus energy from renewables. Stored $CO_2$ has the potential to have an intrinsic value.

## CONCLUSIONS

It is clear that CCS is technically feasible and that in order to achieve both net zero and the requirements for more energy production, this industry must be up and running at a large scale by 2050. At present, electricity generation using CCGT-CCS is estimated to be of comparable cost with nuclear and renewables so its use will not adversely impact millennium goals. Only the petroleum industry has the skills to start up and maintain this huge CCS industry. If it grasps this opportunity, its image will be transformed from climate pariah to global savior. The wheel of change appears to be starting to turn.

## AUTHOR CONTRIBUTIONS

AH conceived the project and provided insight into the oil and CCS industry. PS provided insight into the IPCC and 1.5 degree research. AH and PS provided insight into BECCS, wrote, and edited the paper. Both authors contributed to the article and approved the submitted version.

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# BECCS and DACCS as Negative Emission Providers in an Intermittent Electricity System: Why Levelized Cost of Carbon May Be a Misleading Measure for Policy Decisions

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Carbon dioxide removal (CDR) from the atmosphere is likely to be needed to limit global warming to 1.5 or 2°C and thereby for meeting the Paris Agreement. There is a debate which methods are most suitable and cost-effective for this goal and thus deeper understanding of system effects related to CDR are needed for effective governance of these technologies. Bio-Energy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS) are two CDR methods, that have a direct relation to the electricity system—BECCS *via* producing it and DACCS *via* consuming. In this work, we investigate how BECCS and DACCS interact with an intermittent electricity system to achieve net negative emissions in the sector using an energy system model and two regions with different wind and solar resource conditions. The analysis shows that DACCS has a higher levelized cost of carbon (LCOC) than BECCS, implying that it is less costly to capture $CO_2$ using BECCS under the assumptions made in this study. However, due to a high levelized cost of electricity (LCOE) produced by BECCS, the total system cost is lower using DACCS as negative emission provider as it is more flexible and enables cheaper electricity production from wind and solar PV. We also find that the replacement effect outweighs the flexibility effect. Since variations in solar-based systems are more regular and shorter (daily cycles), one could assume that DACCS is better suited for such systems, whereas our results point in the opposite direction showing that DACCS is more competitive in the wind-based systems. The result is sensitive to the price of biomass and to the amount of negative emissions required from the electricity sector. Our results show that the use of the LCOC as often presented in the literature as a main indicator for choosing between different CDR options might be misleading and that broader system effects need to be considered for well-grounded decisions.

**Keywords: negative emissions, BECCS, DACCS, variation management, electricity system modeling**

# INTRODUCTION

If the increase in global warming is to be restricted to less than 2°C with reasonable certainty, global greenhouse gas emissions must decrease by roughly half by the mid-21$^{st}$ century, as compared to the current levels, and continue to decline thereafter (Rogelj et al., 2013). To achieve the 1.5°C target set by the Paris Agreement, negative emissions will likely be needed in the second half of the century, to compensate for the emissions in the first part of the century or for sectors that are difficult to mitigate completely, such as agriculture (Fuss et al., 2014). Several ways exist to provide negative emissions: Bio-Energy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), afforestation, enhanced weathering etc. Captured $CO_2$ from biomass or air could also be used for production of fuels and material, however, their lifetime tends to be short leading to $CO_2$ being released to the atmosphere almost immediately and are thus not considered as negative emissions. For stringent climate scenarios BECCS together with afforestation has been seen as a main way of enabling negative $CO_2$ emissions. For example, the median amount of electricity provided by BECCS in the Intergovernmental Panel on Climate Change's (IPCCs) AR5 scenarios likely to achieve the 2°C target is 8 EJ in Year 2050 globally. DACCS on the other hand is only emerging as a negative emissions option in global climate scenarios (e.g., Realmonte et al., 2019). Although several technologies have the potential to enable negative emissions, BECCS has the advantage of simultaneously providing benefits other than mitigation (e.g., electricity and heat, biofuels, or pulp and paper). However, biomass is a limited resource and there are significant uncertainties related to how much of it can be provided to the energy system in a sustainable manner or without having a negative effect on other systems such as food supply or biodiversity (Slade et al., 2014; Creutzig et al., 2015). Furthermore, it is uncertain as to where in the energy system the available biomass should be used as there are several hard to abate sectors such as aviation or the chemical industry that may need biomass as feedstock. In addition, building a transport infrastructure for $CO_2$ can be difficult and costly. This has prompted interest in DACCS that does not have to be coupled with an emission source and can thus be placed near a storage location. Creutzig et al. (2019) also point out the modularity and related potential for fast learning as benefits of DACCS compared to BECCS. In addition, negative emissions from DACCS can be more easily verified, whereas to certify negative emissions from BECCS, the whole value chain must be evaluated. On the other hand, DACCS does not produce additional benefits besides negative emissions.

DACCS captures $CO_2$ from ambient air *via* a contactor to then release it into a relatively pure stream in a regeneration step. DACCS has the disadvantages of using air with very low $CO_2$ concentration (ca 400 ppm), compared to combined heat and power plants (CHPs) and power plants where $CO_2$ concentration in the exhaust can be about 20% (Garðarsdóttir et al., 2015). Two main types of DACCS technologies exist, a high temperature (HT) system using a liquid sorbent to capture the $CO_2$ and a low temperature (LT) system using a solid sorbent (Fasihi et al., 2019). Both systems have a thermal and electrical energy demand. The HT system is based on more developed carbon capture and storage (CCS) technology and the system has a large thermal energy demand where a temperature of ∼900°C is needed to regenerate the sorbent (*Negative Emissions Technologies Reliable Sequestration: A Research Agenda*, 2018). The high temperature in DACCS is usually achieved through natural gas combustion, but it could also be attained through combustion of biogas or by using a fully electrified system through an electric arc furnace. The LT system could use moisture, low-grade heat, vacuum or pressure to regenerate the sorbent (Fasihi et al., 2019). This system could be fully electrified by using a heat pump to provide for the low-grade heat for the regeneration process. As can be seen, both BECCS and DACCS have a connection to the electricity system—BECCS *via* the opportunity to produce electricity and DACCS via consuming it. Large amounts of electricity could be required if DACCS is implemented on a large scale and its heat demand electrified.

Significant changes are on the way in the electricity system. In recent years, the share of low-carbon electricity generation from wind and solar sources has expanded pointedly, and it is expected to continue to do so in the coming decades owing to lowered costs and policy incentives that are fuelled by climate and energy security concerns. However, large-scale expansion of wind and solar power creates a new set of challenges. The energy supplied from wind and solar technologies is variable in both the short and long terms. High levels of wind and solar power complicate systems operation by changing the shape of the residual load and exacerbating the uncertainty of supply. On the one hand, if significant amounts of intermittent capacity are installed in the system there may be an over-supply of electricity on windy and sunny days, which would result in periods of low electricity prices. On the other hand, when wind and solar power production is too low to meet the demand, other power plants must be deployed. Their full-load hours will, however, be reduced by wind and solar infeed, while requirements in relation to flexibility will increase compared to current thermal generation. Thus, the variability of solar and wind generation can be expected to have a strong influence on investment decisions in the electricity generation system, including investments in BECCS, over the coming decades but also on technologies using electricity as a fuel such as electrified DACCS.

When comparing negative emissions technologies, the cost of carbon per ton of captured $CO_2$ is often used as a measurement (Fuss et al., 2018). Whereas this measure may give an indication about the competitiveness of the technology, it also omits the context of the energy system these technologies are placed in and the effects they may have on the optimal system composition. Previous literature has mostly focused on assessing the role of BECCS in an energy system context (e.g., Bauer et al., 2018; Vaughan et al., 2018; Johansson et al., 2019; Lehtveer and Fridahl, 2020). Early studies that included both DACCS and BECCS have usually found DACCS to be too expensive to be competitive. For example, Fuss et al. (2013) investigated how abatement measures and negative emission technologies (NETs) (i.e., BECCS and DACCS) can be used to mitigate climate change during the period 2010–2099. The model uses marginal abatement cost curves together with $CO_2$ capturing costs for the NETs to determine the optimal mitigation strategy by minimizing the total system cost. The study assumes a marginal cost for DACCS of 550 US$/t$CO_2$ and a cost of 105US$/t$CO_2$ for BECCS for the whole period. It is found that BECCS is the NET deployed in combination with abatement measures to achieve an atmospheric $CO_2$ concentration of 435 ppm in 2100 with a discount rate of 5%. However, in a sensitivity analysis with a discount rate of 10%, abatement measures and BECCS are used in the early part of the century while DACCS gets deployed in the latter part of the century. More recently, Realmonte et al. (2019) used two different Integrated Assessment Models (IAMs) to investigate how DACCS can fit into a mitigation portfolio. The models include the HT system, the LT system, BECCS, and afforestation as NETs. The capturing costs are estimated to be between 180 and 300 $/t$CO_2$ currently for the HT system with potential to reach 100$/t$CO_2$ and 200–350 $/t$CO_2$ currently for LT system with potential reduction to 50$/t$CO_2$ as a floor cost. The cost includes capital cost and O&M costs but excludes costs for energy, which are determined by the model. The model uses a 20% annual growth rate cap for the technologies and two different carbon budgets to comply with the 1.5 and 2 °C targets. The results show that DACCS is deployed in both models but in the latter part of the century, while BECCS and afforestation are used in earlier periods. The LT system is preferred over the HT system. The main limiting factor for DACCS is found to be the speed it can be scaled up. Both of these studies have a limited time resolution for wind and solar infeed due to the scope of the models. The main difference between the studies is that Realmonte et al. includes more NETs and that they are using a lower capturing cost for DACCS which results in DACCS being more cost competitive. Breyer et al. (2020) use a linear programming model to analyse the dynamics of a variable renewable electricity system used to supply a DACCS system on an hourly scale. The Maghreb region, which has good conditions for solar insolation, is modeled with a focus on the years 2040 and 2050. A LT solid sorbent DACCS system is modeled where the electric and thermal energy needed is supplied through an off-grid decentralized electricity system. The electricity is produced by solar PV and wind power and to balance the system, batteries, and thermal energy storages (TES) are used. To supply the low temperature heat needed in the DAC system the TES and heat pumps are deployed. The study results in a projected capturing cost of $CO_2$ of 105, 70, 55€/t$CO_2$ in the years 2030, 2040, and 2050, and the DACCS system is concluded to be run almost continuously with 8,300 full-load hours (FLH) in a cost-optimized operation. The results show that the majority of the electricity generation supplying the DACCS system is solar PV and the DACCS system's electricity demand is almost as large as the total electricity demand of the entire Maghreb region. The study concludes that DACCS might be an economically beneficial opportunity for the region without considering the growing need for electricity in the region and resulting competition for resources. Thus, there is a lack of investigation and quantification of dynamics behind the choice between BECCS and DACCS in the intermittent energy system on sufficiently high time resolution and including the competition for wind and solar resources which has also been pointed out by Creutzig et al. (2019). The aim of the present work is to contribute to filling the current knowledge gap in three ways:

- First, analyse the role BECCS and DACCS take in the intermittent electricity system with requirement to produce negative emissions.
- Second, to determine which negative emissions technology is more cost-effective from the systems point of view under different wind and solar conditions.
- Third, to analyse the relation between system benefits and LCOC and its implications for policy decisions.

## METHODOLOGY

### Basic Model

We evaluate the role of BECCS and DACCS in a carbon-constrained electricity system by applying an investment model for electricity system set up as a linear programming problem. The model finds the lowest cost feasible solution for investing in and operating a system under given constraints over a year. The model, called eNODE (Electricity in Nodes), was first developed by Göransson et al. and is presented in detail in previous work (Göransson et al., 2017). The model is designed to give a good representation of variability and variation management on the intra-annual time-scale. eNODE represents the electricity system operation over a year with a temporal resolution of 3-hours. The start-up time, start-up costs, and minimum generation level of thermal generation are accounted for as suggested by Weber (2005). Thermal generation with improved flexibility was added to eNODE in a subsequent study (Garðarsdóttir et al., 2018). Furthermore, Johansson and Göransson (2020) have complemented eNODE with variation management strategies, including batteries, demand-side management (DSM), and hydrogen storage.

To accommodate a detailed description of inter-hourly variability, the geographical resolution is reduced, and eNODE is applied to one copperplate-region at a time. A green-field approach is adopted, which assumes as the starting point an empty system without any generation capacity in place. Thus, eNODE is not designed to create a realistic representation of any actual regional electricity system (e.g., existing or planned capacities) but instead to investigate the linkages and dynamics between the different parts of the electricity generation system. However, in order to assure realistic combinations of wind and solar resources and electricity demand, the wind, solar, and load data from actual regions in Europe for year 2012, a rather typical year, are applied. In this work, two example regions have been selected for their large differences in wind and solar resources: one region with good wind conditions (IE-Ireland) typical to costal Northern-Europe and one region with good solar conditions (ES3-central Spain) typical to Southern Europe. The reason to choose different resource conditions is that wind and solar infeed patterns are fundamentally different. Solar infeed has more regular daily cycles whereas wind variations tend to be on longer scales covering days and weeks. In addition, both sources exhibit a seasonal variation in Europe with solar infeed being higher during the summer period and wind infeed during the winter period.

The technology cost data, fuel prices, and data on renewable resources and generation profiles applied in this work are listed in the **Supplementary Material**. Four different types of variation management technologies are included in this work: (redox) flow batteries; lithium-ion (Li-ion) batteries; hydrogen storage; and DSM. DSM, as implemented here, implies that up to 20% of the hourly demand for electricity can be delayed for up to 12 h [see (Johansson and Göransson, 2020) for a complete description of the DSM implementation]. Fuel cells have been added to the technological data, in addition to the electrolyser and hydrogen storage. The addition of fuel cells creates an endogenous demand for hydrogen as a means of electricity storage. The costs and efficiencies for the electrolyser, fuel cell, and hydrogen storage, as well as for batteries are given in **Supplementary Material Table A3**.

## Model Development

eNODE contains three bio-based generation technologies with CCS option. Biomass-fuelled steam power plants with CCS (biomass CCS), as well as combined cycle gas turbines with CCS fuelled with bio-based methane (biomethane CCS) are modeled as negative emission technologies. In addition, a carbon-neutral mix of co-fired biomethane and natural gas with CCS (biomethane-NG CCS) has been added to the technology options. The capture rate, additional costs for the CCS part, and efficiency penalties are assumed to be equal to their corresponding fossil-fuelled versions. More information on the modeling of the bio-based CCS technologies can be found in Johansson et al. (2019).

For this study DACCS technologies were added to the model. As previously described, several system configurations for DACCS exists. In this study, three different configurations were considered, a fully electrified LT solid sorbent system and two versions of the HT liquid solvent system with different supply for the thermal energy demand; a fully electrified system and a system combusting biogas. Both economic parameters such as CAPEX, OPEX and start-up costs, and technical parameters such as start-up time, minimum load level and capture rate were added to the model and can be found in the **Supplementary Material**.

## Study Design

In this study, we model a system at year 2050 and assume that 10% of removal of $CO_2$ emissions compared to Year 1990 level emissions per year for the given region. The target was chosen in accordance to long-term modeling studies that indicate the need of net negative emissions in the middle of the century (Fuss et al., 2014). The costs of all technologies in the model represent about 2050 level. All the investment costs of all generation technologies and flexibility measures technologies are given in the **Supplementary Material**. We use cost data from Fasihi et al. (2019) for investment costs given for near term for DACCS in our *Base* case as the future cost of DACCS is highly uncertain and to our assessment rather optimistic in this study.

In the *Base case* all technology options are included. We also run a case where DACCS technologies are excluded to provide a comparison called *NoDACCS*. Both cases were applied to each of the two modeled regions. The cost of biomass is set to 30€/$MWh_{th}$ for these runs including both pre-processing and transport. The biomass value can be compared to the bioenergy index PIX (Pellet Nordic Index), which has remained rather stable within the range of 26–31 €/$MWh_{th}$ over the past years.

Further, based on the dispatch of technologies in the model, the LCOC was calculated for negative emission technologies present to determine the average cost for capturing one ton of $CO_2$ using a given technology in a specific case. The LCOC takes into account the running time of the NET and value of electricity produced at that hour given by the model as well as fuel cost for DACCS and reduction of total cost for BECCS as electricity can be sold as an additional product, see Equation (1).

$$LCOC = \frac{CAPEX \bullet CRF}{FLH} + OPEX_{fix} + OPEX_{var} + C_{Fuel} + C_{Transportation} + C_{Storage} - C_{Electricity} \quad (1)$$

where CAPEX is the capital expenditures, $OPEX_{var}$ and $OPEX_{fix}$ is the variable and fixed operating expenditures, $C_{Fuel}$ is the fuel costs, $C_{Transportation}$ is the transportation cost, $C_{Storage}$ is the cost for storing $CO_2$ and $C_{Electricity}$ is the revenue for selling electricity to the grid. CRF is the capital recovery factor and is calculated according to Equation (2).

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1} \quad (2)$$

where $i$ is the interest rate, which is set to 5% in this work and n is the lifetime of the technology. Furthermore, to illustrate the system effects, the LCOE based on model dispatch was calculated for solar PV, wind and BECCS technologies according to Equation (3). The LCOE is a measure to determine the average cost for generating one unit of electricity using given technology in a specific case.

$$LCOE = \frac{CAPEX \bullet CRF}{FLH} + OPEX_{fix} + OPEX_{var} + C_{Fuel} - C_{CO2} \quad (3)$$

where $C_{CO2}$ is the cost for carbon derived from the model run.

## Sensitivity Analysis

A Monte-Carlo analysis on sensitive parameters was also conducted to assess the robustness of the results. In Monte-Carlo analysis a large set of parameters is created, and the model is solved for each of them allowing thus to analyse the effect of the parameter values on the results. The parameters varied and their ranges can be found in **Table 1**. The cost of BECCS and other CCS technologies in the model is coupled to high temperature DACCS as it is essentially the same technology. The model was run for 200 different combinations of these parameters for both sunny (ES3) and windy region (IE).

**TABLE 1 |** Parameters varied in Monte Carlo analysis.

| Parameter | Range | Unit | Distribution |
|---|---|---|---|
| DACCS Low temperature CAPEX | 0.5–2 times the base value | €/t$CO_2$ capture capacity | Uniform |
| DACCS High temperature CAPEX | 0.75–1.25 times the base value | €/t$CO_2$ capture capacity | Uniform |
| Biomass cost | 15–45 | €/$MWh_{th}$ | Uniform |

## Limitations of this Study

Although this work provides important insights into the interactions among wind power, solar PV, and negative emission technologies; there are several limitations to this study. The addition of trade with neighboring regions would increase the possibilities for managing variations and for sharing investments. Thus, trade is likely to lower the total systems cost and offer additional measures for variation management and possibly storage, especially if trade with regions with hydropower is enabled. However, as the amount of hydropower available is limited, this would not change our findings fundamentally.

The model, eNODE, does not consider the existing capital stock. Similarly, the historical $CO_2$ emissions and emissions from other parts of the energy system are not considered. Depending on the investment pathway in the overall energy system, there may be little scope for any fossil $CO_2$ emissions or too little biomass to compensate for them and therefore limits to natural gas and BECCS combo that is allowed in our study for managing the variability. This could increase the competitiveness of DACCS as it is not dependent on biomass resource.

Furthermore, as this case study is applied to regions in Europe, the effectiveness of solar power is lower in our study than in many other regions of the world. However, due to more regular diurnal variations, solar PV based power is more easily managed by alternative strategies, such as short-term energy storage rather than biofueled complements. Wind variations, that are longer, and also seasonal demand variations, that are more common in colder regions, can however give some competitive advantage to BECCS compared to the LT DACCS system which may or may not be overweighed by other system effects.

# RESULTS

## Case Results

**Figure 1** shows the annual electricity generation for the two cases—*Base* and *NoDACCS*—in the two studied regions—ES3 and IE. In the *Base* case, both DACCS technologies and BECCS are available for providing negative emissions. However, DACCS outcompetes BECCS at the given price level for both regions. In the *Base* case when DACCS "LT" is acting as the only NET, the annual electricity generation increases compared to the *NoDACCS* case where the negative emissions are provided by BECCS. This is due to that DACCS consumes electricity and acts as a new load to the system, resulting in a higher total energy demand. The annual electricity generation is 4.7 TWh/year (5%) larger in the sunny region (ES3) and 2.6 TWh/year (8%) larger in the windy region (IE) compared to the case where DACCS technologies are not available. However, the total system cost is 5% lower in ES3 and 7% lower in IE in the *Base* case compared to the *NoDACCS* case.

Moreover, the DACCS LT solid sorbent system is consistently outcompeting the HT liquid solvent system for both regions. Therefore, the HT liquid solvent system is never shown in the results. In the *NoDACCS* case, BECCS is working as the only provider of negative emissions, but the technology is simultaneously generating electricity to the grid.

**Figures 2**, **3** show the dynamics in the modeled system. To do that, 2-week periods covering both good and less good variable renewable resource conditions were chosen. **Figures 2A,D** shows the electricity generation and the total electricity demand in ES3 during 2 weeks for the *Base* case and *NoDACCS* case respectively. During some hours, solar PV and wind power, together with the energy storage in the batteries, as seen in **Figures 2B,E**, provide for the entire energy demand in both cases. At other hours, peak generation of natural gas is used to fulfill the whole demand. The energy demand for DACCS LT together with the variation of electricity price for the *Base* case is shown in **Figure 2C**. The electricity price is low during hours with large electricity production from variable renewable generation and high when complementary and peak generation is needed. DACCS LT is responding to low-electricity prices that enable lower cost of carbon removal, which can be seen in **Figure 2C**, and is therefore mainly running when the electricity price is low. **Figure 2F** shows the electricity produced by BECCS and the variation of the electricity price in the *NoDACCS* case, showing that BECCS runs when electricity prices are high and complement to renewables is needed. One can also note that BECCS runs more continuously whereas DACCS LT is more often switched on and off.

**Figures 3A,D** shows 2 weeks of electricity generation in region IE in the *Base* case and *NoDACCS* case, respectively. Generation from wind and solar power is larger in the first week than in the second week in both cases due to better resource conditions. Therefore, variable electricity generation from wind and solar together with the energy storage in batteries covers the whole energy demand for almost all hours in the first week. In the second week, generation from variable renewables decreases and electricity generation from natural gas is needed to supply for the whole energy demand. **Figures 3B,E** show the energy storage in batteries for the *Base* case and *NoDACCS* case, respectively. Due to the IE system being wind dominated, the pattern of the energy storage level is more irregular in the IE case compared to the ES3 system, which is solar dominated. Moreover, the installed battery capacity relative to the amount of installed capacity of electricity generation is much larger for ES3 than IE, implying that batteries are better suited to handle solar variations that are more regular than wind variations. **Figure 3C** shows the electricity demand of DACCS LT together with the variation in electricity price while **Figure 3F** shows the electricity produced by BECCS along with the electricity price. Similar dynamics as in the solar-based system can be observed here.

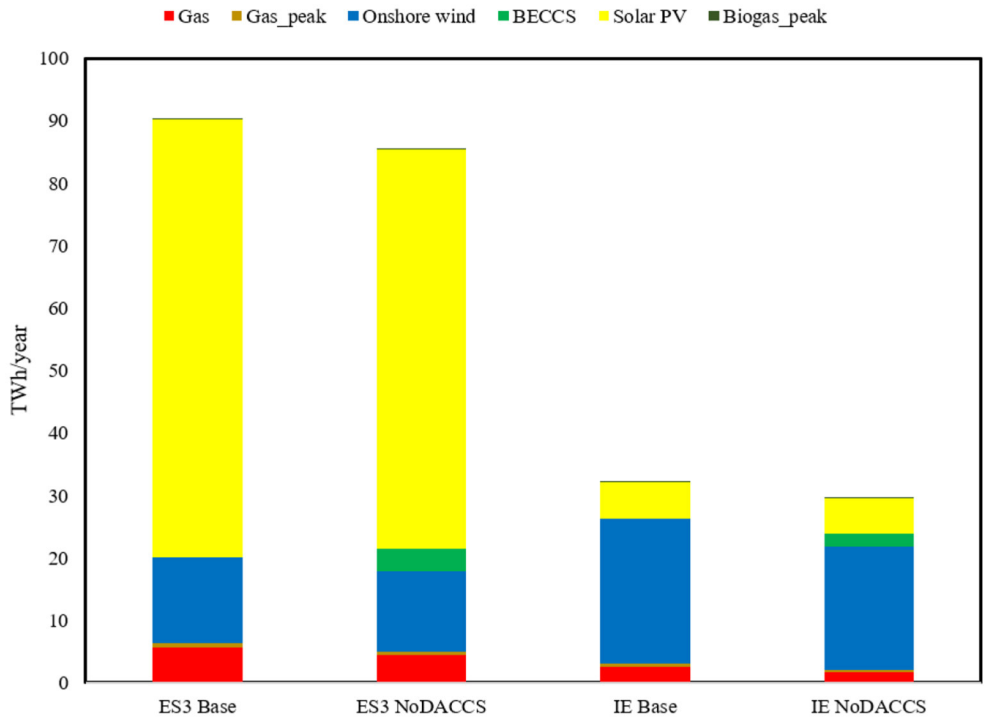


**FIGURE 1 |** Annual electricity generation in the Base case and in the NoDACCS case in regions ES3 (sunny) and IE (windy).

To be able to compare how much it costs to capture one ton of $CO_2$ for each region we calculate the LCOC based on the dispatch in the model. It is generally assumed that by using a technology with the lowest LCOC, the total cost of reaching low $CO_2$ levels will be minimized. **Figure 4** shows the LCOC for DACCS LT and BECCS respectively in different cases. The LCOC for DACCS LT is consistently larger than the LCOC for BECCS, meaning that it is more expensive to capture one ton of $CO_2$ using DACCS LT than using BECCS. The two largest costs for DACCS LT are the CAPEX and variable OPEX. As for BECCS, the largest costs are the fuel cost and CAPEX. This is in line with analysis from Creutzig et al. (2019) who also deem the land scarcity and resulting cost of biomass to be the largest determinant of cost of BECCS. The electricity produced by BECCS is sold to the electricity grid, resulting in an income for BECCS which is subtracted from the other costs for the total LCOC, see Equation (1). The costs for transporting and storing $CO_2$ varies between the regions based on (Kjärstad et al., 2013) but constitute only a minor part of the total cost in both regions. The costs for storage and transport of $CO_2$ are more expensive in IE compared to ES3. Note that the transport cost of $CO_2$ for DACCS is assumed to be zero since the technology could be placed on the storage site. In both cases DACCS LT is run for ca 4,500 FLH, whereas BECCS is run for ca 3,900 FLH if it has to replace DACCS LT. This is about half of the hours of the year and means that the levelized cost of both technologies could potentially be reduced by higher operating hours as capital costs would be then divided over more hours, however, this not cost-efficient from the system perspective.

The studied system provides two services: electricity and negative emissions. Thus, it is also relevant to analyse the LCOE in different set-ups. LCOE for selected technologies is shown in **Figure 5**. For BECCS it is assumed that the case specific price for $CO_2$ (i.e., a result from the *Base* or *NoDACCS* case) is received as an income and thus deducted from the LCOE, see Equation (3). The largest cost for both wind power and solar PV is the fixed OPEX, which is dependent on the load factor of the technology for unit of electricity generated. A larger load factor results in a lower fixed OPEX due to more hours to spread the costs over. This can be seen for wind power in the IE case where the load factor is larger, resulting in a decreased fixed OPEX and therefore also a reduced total LCOE. The LCOE for BECCS is consistently larger than that for wind power and solar PV for both ES3 cases. However, for the case where BECCS is present in IE (*NoDACCS*), the LCOE for BECCS is lower than the LCOE for solar PV. Moreover, the fuel cost has the largest impact on the LCOE for BECCS.

## Sensitivity Analysis

The results from the Monte Carlo analysis are shown in **Figures 6–8**. In the analysis both the cost of biomass and the CAPEX of CCS technologies was varied for 200 combinations for each region. In most of the cases DACCS LT is preferred both in windy and sunny regions, but the choice of BECCS or

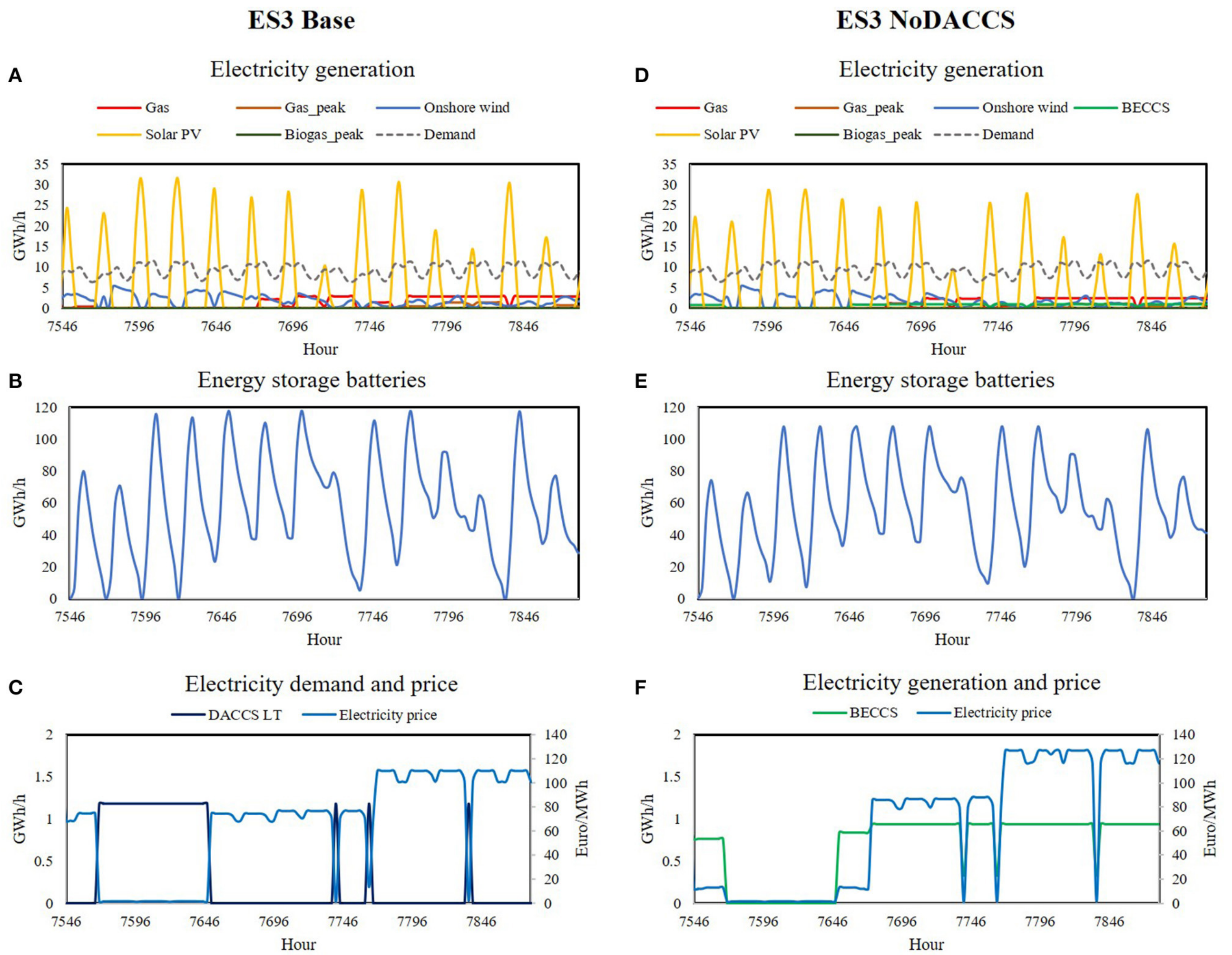


**FIGURE 2 | (A)** Electricity generation; **(B)** energy storage; and **(C)** electricity demand for DACCS and price for the Base case in region ES3 with in week 45 and 46 in year 2050. **(D)** Electricity generation; **(E)** energy storage; and **(F)** electricity generation by BECCS and price for the NoDACCS case in region ES3 with in week 45 and 46 in year 2050.

DACCS HT is significantly higher in the wind-based systems. In some instances (about 10–25% of the runs) both DACCS LT and BECCS/DACCS HT enter the system. BECCS and DACCS HT were grouped together in **Figure 6** due to their similar characteristics when it comes to flexibility and investment cost.

The results show a clear correlation between the cost of biomass and the choice of negative emissions technology (**Figure 7**). With a low biomass cost, BECCS is the preferred option in the sunny region whereas the results are varied for the windy region and depend on the cost ratio between the negative emission technologies. Sometimes both BECCS and DACCS LT are invested in in such cases. DACCS will become the preferred technology at higher biomass costs. It can also be seen that the biomass price required for DACCS to enter the system is higher for the solar PV-based system (ES3) than in the wind-based system (IE).

The cost relation between the CAPEX of DACCS LT and DACCS HT (and thus also BECCS as it is based on the same technology) has a much smaller effect on the results (**Figure 8**). DACCS HT enters the system only when it is significantly cheaper than DACCS LT, otherwise BECCS will be preferred as it has the additional benefit of being able to produce electricity at high price hours. Both DACCS LT and BECCS can be chosen at all CAPEX ratios in the sunny region and the cost of biomass is the main determining factor. BECCS is chosen in the windy region only when both biomass price and technology cost are favorable.

## DISCUSSION

In this analysis, we have used an electricity system model with high time resolution to analyse the role BECCS and DACCS can take in an intermittent electricity system. Our

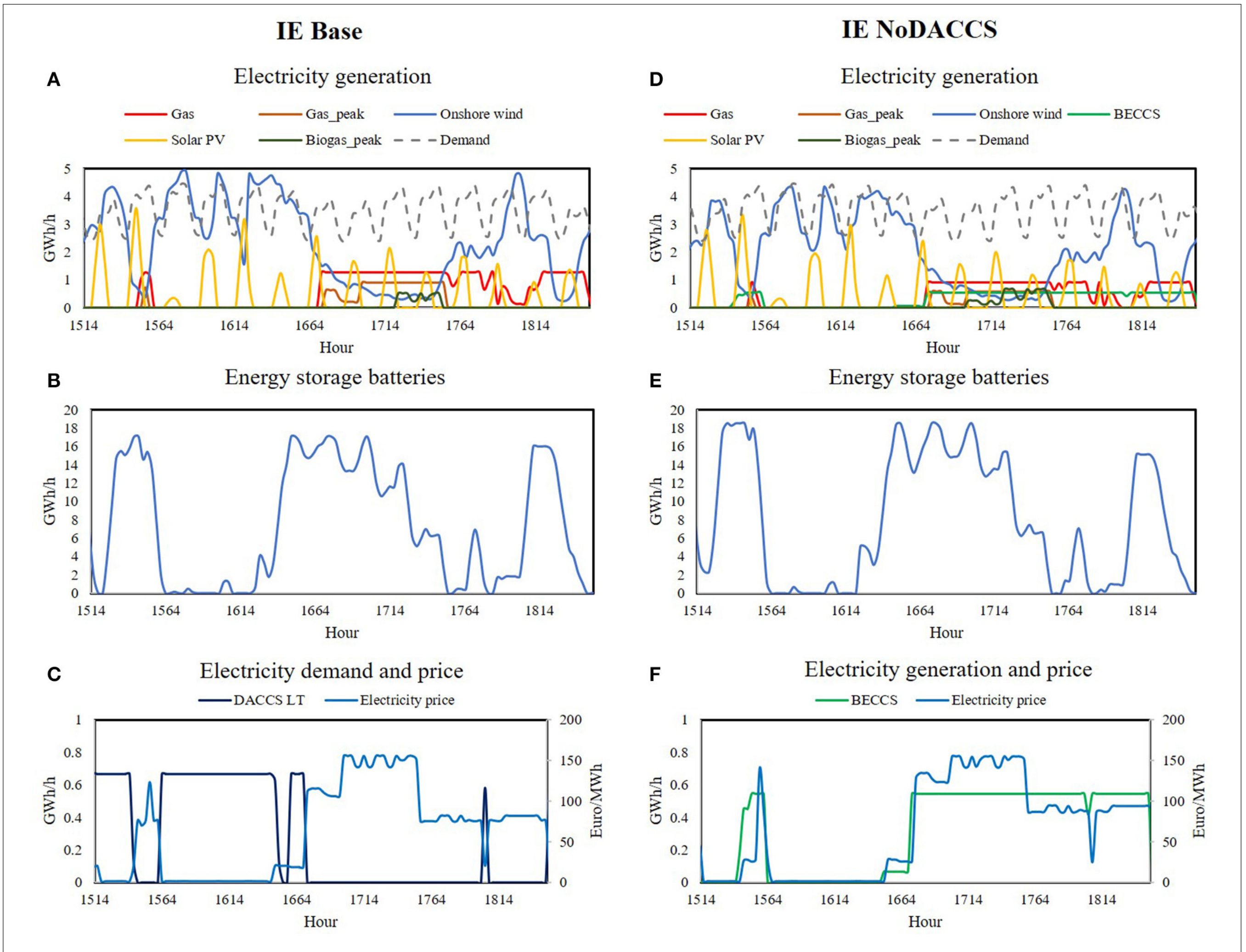


**FIGURE 3 | (A)** Electricity generation; **(B)** energy storage; and **(C)** electricity demand for DACCS and price for the Base case in region IE in week 9 and 10 in year 2050. **(D)** Electricity generation; **(E)** energy storage; and **(F)** electricity generation by BECCS and price for the NoDACCS case in region IE in week 9 and 10 in year 2050.

results demonstrate that these two technologies can have a fundamentally different role, especially when it comes to DACCS LT. DACCS LT is consuming electricity mainly at low price hours and reducing the need of energy storage. BECCS on the other hand, is run when wind and solar supply is low and electricity prices are high but also crowds out some renewable production due to its relative inflexibility. DACCS LT is chosen over BECCS and DACCS HT in most instances of sensitivity analysis as the most cost-effective option for the whole system.

Our results clearly show that other considerations than just LCOC may play a role in cost effectiveness of a negative emission technology. When comparing BECCS and DACCS as a part of a future electricity system, two main factors play a role besides the cost of technologies themselves. First, the flexibility of the technology and its ability to adapt to the variable electricity production. Here, DACCS LT has a clear advantage with a cyclical operation at 3 h intervals, whereas BECCS and DACCS HT need longer time for starting up and also have costs associated to starting and stopping operation. Secondly, the cost of electricity produced by the whole system becomes important. With DACCS as a negative emission provider more solar and wind electricity at cheaper cost is produced by the system compared to the system where BECCS provides some of the electricity. For low production hours of wind and solar-based electricity batteries and gas turbines are used to cover the lack of production instead of BECCS. The combination of this is cheaper on the system level than using BECCS to cover the low production hours. It is also interesting to note that the second effect outweighs the first one. Since variations in solar-based systems are more regular and shorter (daily cycles), one could assume that DACCS LT is better suited for such systems, whereas our results point in the opposite direction. DACCS LT is more often chosen in the windy system. This can again be explained when looking at LCOE production for different technologies (**Figure 5**). In the solar-based system LCOE of wind, solar PV and BECCS is much closer to each other, whereas in wind-based system the LCOE of wind is

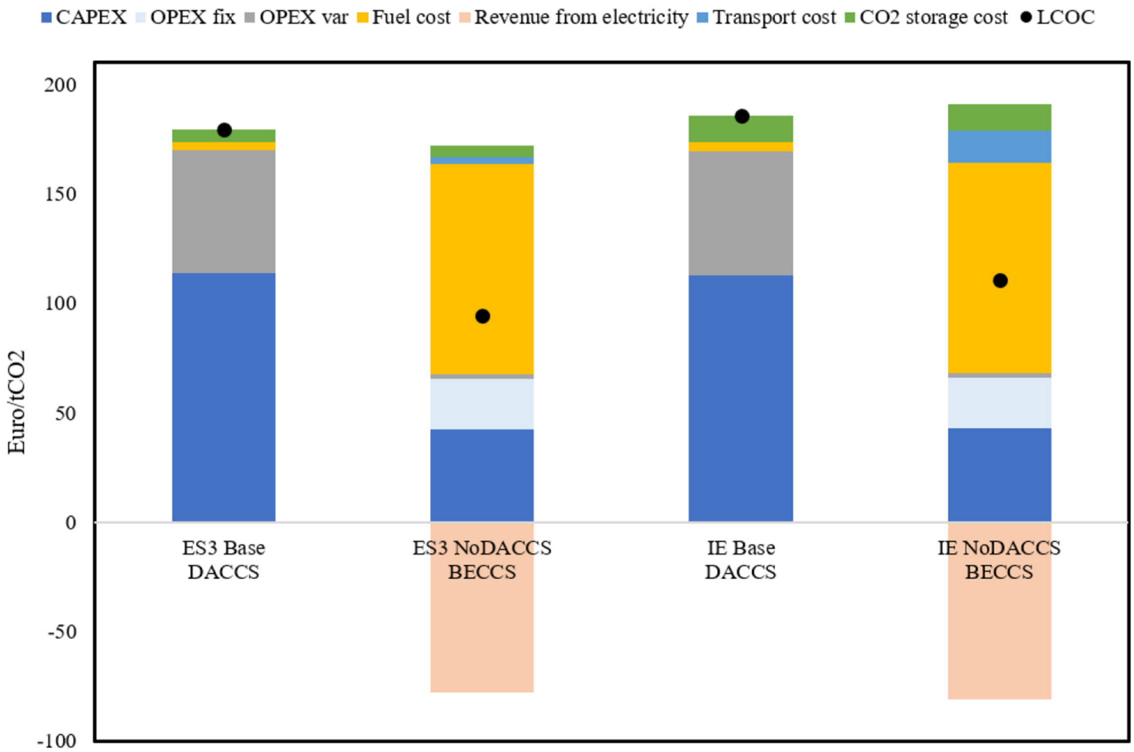


**FIGURE 4 |** LCOC calculated for DACCS and BECCS in regions ES3 (sunny) and IE (windy) for the Base case and the NoDACCS case respectively.

by far lower than others and solar PV becomes more expensive than BECCS due to larger variations in seasonal generation. This means that replacing the renewable (mostly wind-based) electricity with electricity from BECCS becomes more costly in this system. As the LCOC does not include either of the dynamics discussed above, it can give a misleading impression that BECCS is by far superior to DACCS LT for providing the system with negative emissions. In fact, the opposite is the case in our study. It should be kept in mind that this relation is also dependent on the amount of negative emissions required from the system. In our study the electricity is the main product and clearly outweighs the negative emissions in amount. In a system that is focused more on negative emission generation, the LCOC would have a greater importance than LCOE. However, it is not likely to be the case with larger-scale systems where electrification will play an important role in reaching the climate targets.

It is sometimes argued that the levelized cost could be a more accurate measure if only extra investments for CCS part are included and the revenue from the electricity sales ignored. This approach will, however, also miss the system dynamics that determine when the plant is run most cost effectively. Another common approach is to have purpose built renewable energy generation that usually assumes the best conditions for DACCS electricity consumption (Fasihi et al., 2019; Breyer et al., 2020). This may lower the cost for $CO_2$ captured *via* DACCS but has an opportunity cost of not using the renewable resource in the societally cost-effective way. In many regions the potential for renewables is limited by either land use constraints or by public acceptance of exploration of new sights. Therefore, an adequate comparison of different NETs requires an analysis of the whole system where they are placed.

As there is a large movement toward electrification in many sectors there will likely also be competition for low price electricity meaning that in case of large-scale electrification the fuel cost for DACCS may increase. Although the cost of fuel (electricity) is only a small part of the total cost of capturing carbon with DACCS LT, this may also have an effect on other dynamics in the system and should thus be studied further. From our results we see that there is a much larger over production of electricity compared to demand in the solar PV-based system and thus DACCS LT is more likely to remain competitive there if the renewable resource potential is limited. Otherwise, the opportunity cost of replacing electricity from variable renewables still applies and has a stronger effect in windy systems.

## CONCLUSIONS

Carbon dioxide removal (CDR) from the atmosphere is likely to be needed to limit global warming to 1.5 or 2°C and thereby meeting the Paris Agreement. Several methods exist for CDR and there is a debate on which methods are most suitable and cost-effective. Thus, deeper understanding of system effects related to CDR are needed for effective governance of these technologies. Bio-Energy with Carbon Capture and Storage (BECCS) and

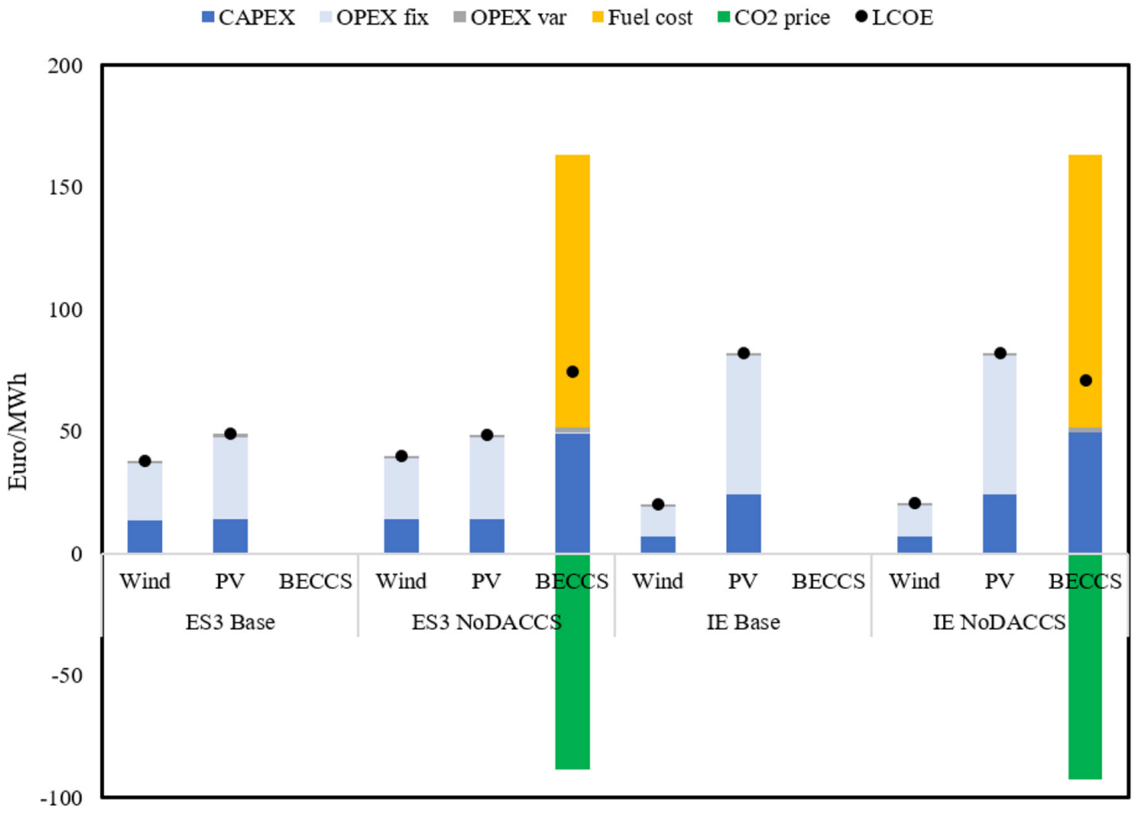


**FIGURE 5 |** LCOE calculated for onshore wind power, solar PV and BECCS for the regions ES3 (sunny) and IE (windy) for the Base case and the NoDACCS case respectively.

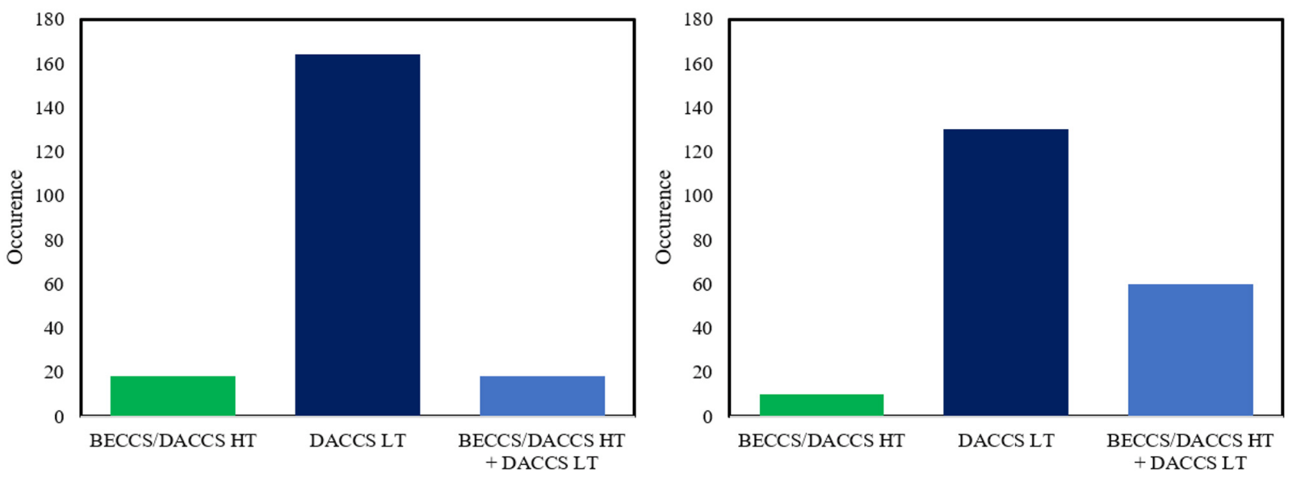


**FIGURE 6 |** Occurrence of different NETs or combination of them in Monte Carlo analysis (200 runs) in the regions ES3 (sunny) to the left and IE (windy) to the right respectively.

Direct Air Carbon Capture and Storage (DACCS) are two CDR technologies, that can have a direct relation with the electricity system—BECCS *via* producing it and DACCS via consuming. In this work, we investigate how BECCS and DACCS interact with an intermittent electricity system to achieve net negative emissions using an energy system model and two regions with

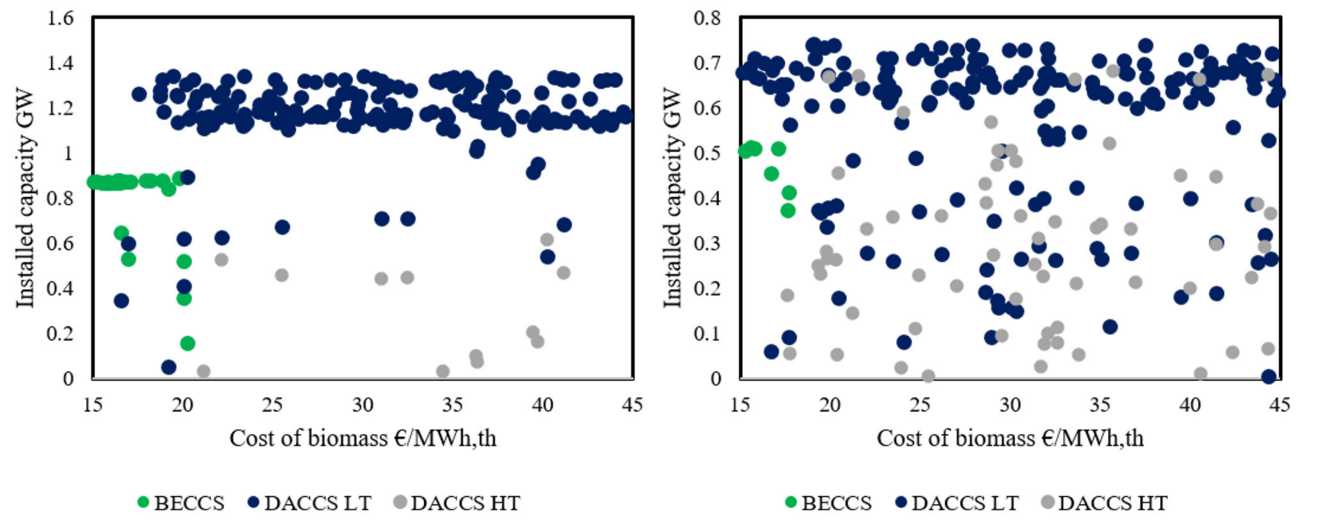


**FIGURE 7 |** The installed capacity of NETs compared to the cost of biomass in the regions ES3 (sunny) to the left and IE (windy) to the right respectively.

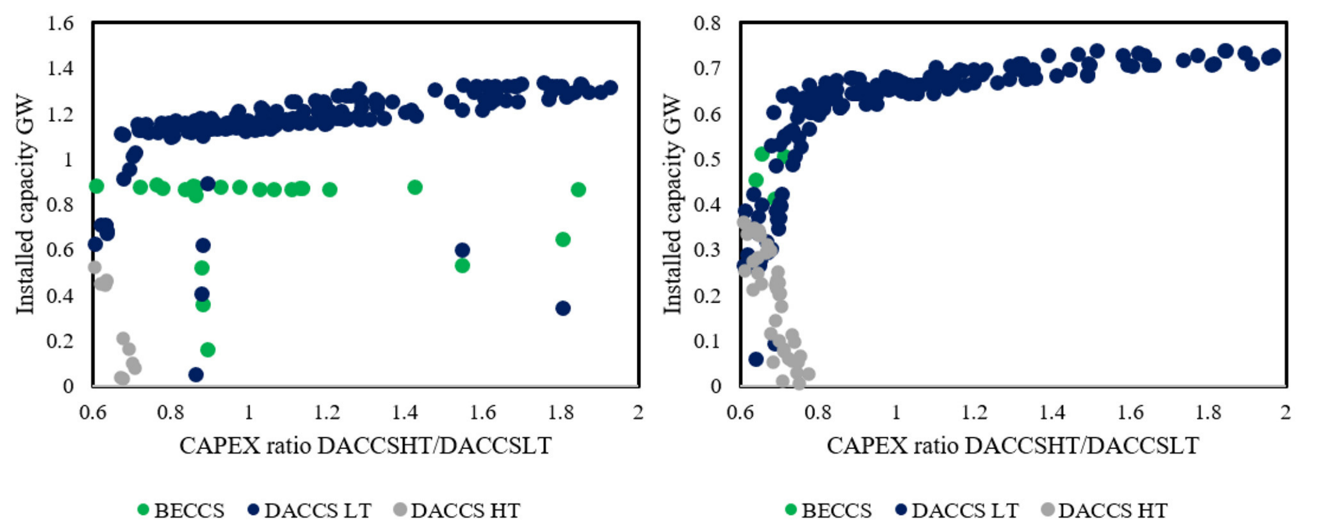


**FIGURE 8 |** The installed capacity of NETs compared to the CAPEX cost ratio of the electrified versions of LT solid sorbent DACCS and HT liquid solvent DACCS for the regions ES3 (sunny) to the left and IE (windy) to the right respectively. The CAPEX of BECCS is pegged to the CAPEX of HT DACCS in the model.

different wind and solar resource conditions. The analysis shows that DACCS has usually a higher LCOC than BECCS, implying that it is less costly to capture $CO_2$ using BECCS under the assumptions made in this study. However, due to a higher LCOE produced by BECCS, the total system cost is lower using DACCS as negative emission provider as it can be more flexible and enables cheaper electricity production *via* renewables and storage. The result is mainly sensitive to the price of biomass and to lesser extent to the investment cost relation between DACCS and BECCS. This indicates that the use of the LCOC as often presented in the literature as a main indicator for choosing between different CDR options might be misleading and that impact to the whole system operation needs to be considered for well-grounded decisions. We also see that low temperature DACCS is better suited for solar PV-based systems from the flexibility point of view as the variations there are more short term and regular and also due to the tendency to larger over generation of electricity. However, these benefits can be overweighed by the opportunity cost of lower total electricity production costs in windy systems, where the difference in LCOE of wind power and BECCS is large that difference in LCOE of variable renewables and BECCS in a sunny region.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

ML conceived the idea of the study and performed the modeling. AE collected the data. Both authors analyzed the results and wrote the paper.

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## SUPPLEMENTARY MATERIAL

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# Revisiting "Additional Carbon": Tracking Atmosphere–Ecosystem Carbon Exchange to Establish Mitigation and Negative Emissions From Bio-Based Systems

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Climate stabilization plans rely heavily on advanced bioenergy and bioproducts for substitution of fossil-based energy sources and materials, and increasingly, for negative emissions via the direct sequestration of biogenic carbon. Yet, there remain persistent, largely unresolved critiques of bioenergy assessment methodology, particularly in the areas of land use and biogenic carbon accounting. The concept of "additional carbon" calls for evaluating the climate performance of bio-based systems by whether feedstock production creates measurable new local agro-ecosystem uptake of carbon from the atmosphere. This concept is challenging to operationalize for first-generation biofuels, and has largely been advanced as a negative critique. However, carbon additionality is more straightforward to establish—and less critical to overall system mitigation performance—in advanced bioenergy systems. In this Perspective, I review the additional carbon critique, and why it is analytically challenging to address in first-generation biofuel systems based on conventional food crops with large existing markets. Next, I make a case that carbon additionality (1) is more readily achievable with cellulosic feedstocks, (2) is more directly observable for dedicated biomass crops, and (3) is not a strict requirement for achieving net mitigation in carbon-negative bio-based systems. I end by discussing how centering atmosphere–ecosystem carbon exchanges in bio-based system assessment could create new opportunities for enterprise-scale performance monitoring and verification, augmenting and diversifying the current reliance on model-based life-cycle assessment approaches.

**Keywords: biogenic carbon, biofuels, additional carbon, life-cycle assessment, bioproducts, BECCS, mitigation, negative emissions**

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## INTRODUCTION

While electrification and renewable electricity generation have made great headway in recent years, more than a quarter of all energy-related emissions will likely require a different decarbonization approach (Davis et al., 2018). Additionally, after years of accelerating greenhouse gas (GHG) emissions, most scenarios for achieving the temperature targets of the Paris Agreement now also include the wide-scale deployment of negative emissions (Vuuren et al., 2018). It is expected that biomass will pay a key role in climate stabilization as a feedstock for renewable transportation fuels (Fulton et al., 2015), industrial heat and power (Butnar et al., 2020), carbon-negative energy production (Fuss et al., 2014), and bio-product manufacturing (Fuhrman et al., 2020) in some combination.

Biofuels and bioenergy production are among the most well-studied bio-based systems, and have been a leading topic of life-cycle assessment (LCA) research and methodological development for more than four decades (Silva et al., 1978). However, there remains significant controversy around the climate change mitigation value of such systems, particularly with respect to land use and feedstock production (DeCicco and Schlesinger, 2018). Conventional LCA is a bottom-up approach that seeks to tabulate all cradle-to-grave GHG emissions associated with the supply chain of providing a good or service. If the total life-cycle emissions of bioenergy production and use are less than that of the competing conventional fossil-derived energy source, then emissions savings (mitigation) are inferred when bioenergy use replaces the fossil energy source. Emissions of biomass-derived "biogenic" $CO_2$ from bioenergy conversion and end use are often assumed to be carbon-neutral *a priori* (DeCicco et al., 2016), on the grounds that such carbon was recently fixed from the atmosphere during feedstock production, and an equivalent amount of carbon will be fixed again when the feedstock is subsequently re-grown. Changes in land use or land management for feedstock production are accounted for in terms of changes in above- or belowground ecosystem carbon stocks (Sheehan et al., 2003; Fargione et al., 2008), but biogenic carbon fluxes from the atmosphere into the feedstock and then back to the atmosphere during conversion and use are usually presupposed, or excluded from emissions accounting entirely.

## CARBON ADDITIONALITY

The concept of "additional carbon" suggests that the mitigation value of a bioenergy system is fundamentally dependent on, and should be evaluated explicitly in terms of, increased net photosynthetic uptake of atmospheric carbon in feedstock-producing agro-ecosystems (Searchinger, 2010; DeCicco, 2013; Haberl, 2013). Carbon uptake is usually understood to specifically mean net ecosystem production (NEP) (DeCicco, 2013). "A fundamental property of ecosystems" (Lovett et al., 2006) and "a central concept in C-cycling research" (Chapin et al., 2006), NEP reflects the difference between gross photosynthetic carbon uptake (i.e., gross primary production, or GPP) and carbon losses via ecosystem respiration ($R_e$):

$$\boldsymbol{NEP = GPP - R_e} \tag{1}$$

It can alternately be defined in terms of net primary production (NPP, i.e., net photosynthetic uptake by plants after correcting for their autotrophic respiration) and heterotrophic respiration ($R_h$):

$$\boldsymbol{NEP = NPP - R_h} \tag{2}$$

In systems with negligible inorganic carbon sources or sinks, NEP represents the total net $CO_2$-C uptake from the atmosphere by the ecosystem. Note however that the net ecosystem carbon balance (*NECB*) of an agricultural system is also affected by removals of carbon through the harvest (*Harv*) of grain or biomass:

$$\boldsymbol{NECB = NEP - Harv} \tag{3}$$

Proponents of carbon additionality assessment suggest that simplistic *a priori* assumptions of biomass carbon neutrality can mask carbon accounting baseline errors or unintended consequences from bioenergy systems. Production of first-generation biofuels from corn, soy, or sugarcane in the absence of additional NEP suggests that these feedstocks are simply being diverted from existing commodity markets. This undermines the basis of mitigation claims from such systems, and could lead to unintended consequences from compensatory agricultural extensification or intensification elsewhere [e.g., indirect land use change (ILUC)], or an overall reduction in food calorie production (Searchinger et al., 2015). Production of advanced bioenergy from cellulosic biomass feedstocks without increased NEP suggests that carbon is being "mined" from feedstock-producing ecosystems or sourced at the expense of future ecosystem carbon sequestration, and thus the benefits of reduced fossil fuel emissions are counteracted by a reduced ecosystem carbon sink (Searchinger et al., 2017; Schlesinger, 2018).

The concept of carbon additionality is illustrated in **Figure 1** by comparing reference-case ("ref") agricultural land management and fossil coal combustion for energy (**Figure 1A**) to an alternative bioenergy scenario ("bio") where coal is displaced by biomass sourced from agricultural residue collection (**Figure 1B**). Carbon fluxes associated with grain harvest and use for food or animal feed are assumed to be unchanged between the reference and stover-bioenergy scenarios, and thus are excluded from the accounting below for simplicity. The remaining relevant exchanges of carbon with the atmosphere in the reference case ($\Delta C_{atm,ref}$) consist of point-source emissions from coal combustion for energy ($E_{ref}$) and net carbon uptake by agro-ecosystems during business-as-usual agricultural production ($NEP_{ref}$):

$$\boldsymbol{\Delta C_{atm,\,ref} = E_{ref} - NEP_{ref}} \tag{4}$$

Conventional bioenergy systems seek to mitigate climate change through displacing fossil energy use with alternative biologically-derived energy sources. In the alternative bioenergy case, excluding upstream supply chain emissions (e.g., emissions associated with fertilizer production or farm operations) for simplicity, bioenergy feedstock production affects ecosystem carbon uptake ($NEP_{bio}$), and coal emissions are replaced with emissions of biogenic carbon from biomass combustion ($E_{bio}$):

$$\boldsymbol{\Delta C_{atm,\,bio} = E_{bio} - NEP_{bio}} \tag{5}$$

As described previously in Field et al. (2020), achieving net climate change mitigation (i.e., net reduction in atmospheric

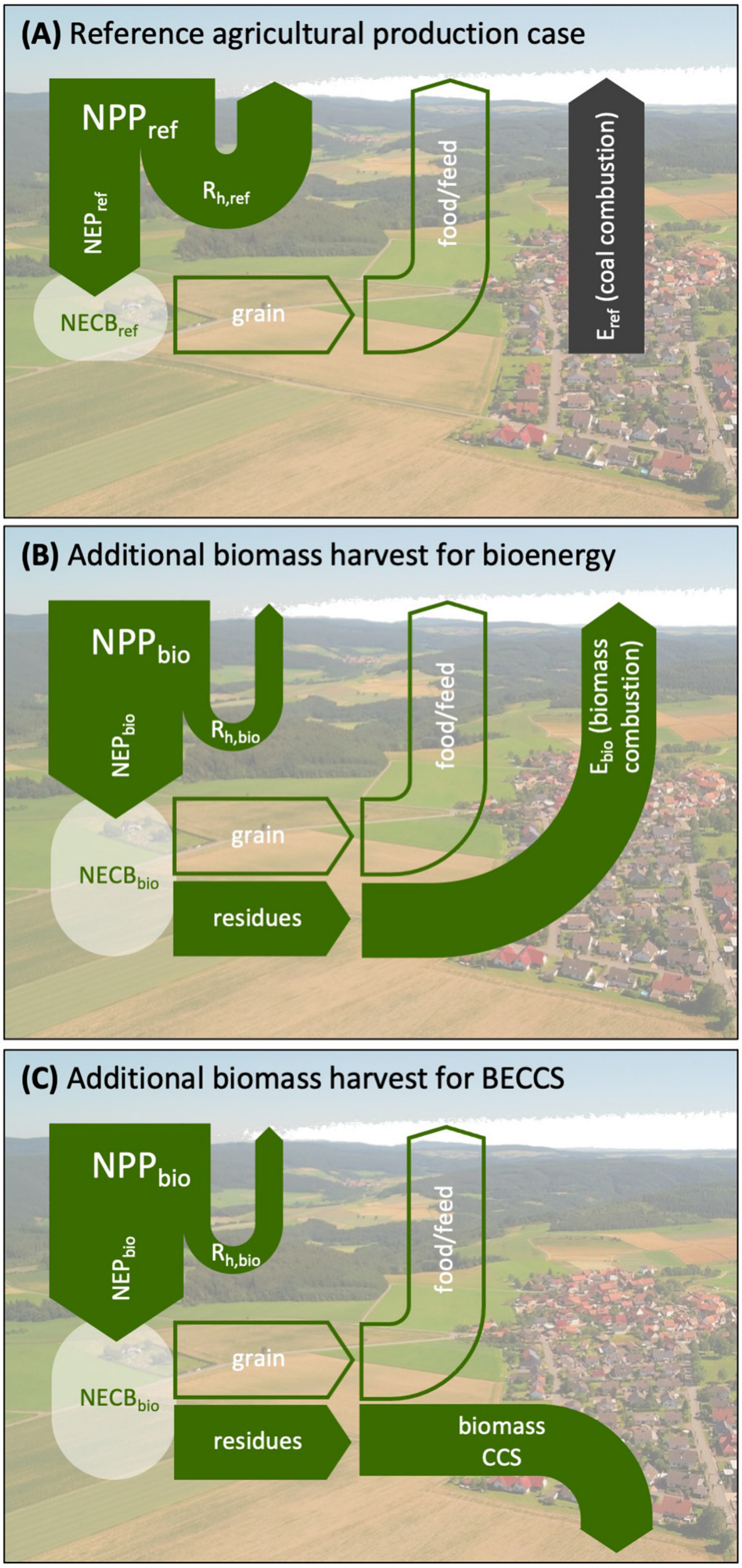


**FIGURE 1 |** Carbon exchanges with the atmosphere in the production of conventional and carbon-negative bioenergy ("bio") from new agricultural residue harvest, as compared to a reference case ("ref"). Fluxes of photosynthesis-derived "biogenic" carbon are shown in green; fossil carbon emissions from fossil fuel use in black. Net

*(Continued)*

**FIGURE 1 |** carbon exchange between the atmosphere and the agricultural landscape (net ecosystem production, or NEP) reflects the difference between net primary production (NPP) and heterotrophic respiration ($R_h$). **(A)** The reference case includes atmosphere–ecosystem fluxes from business-as-usual agricultural grain production, plus coal combustion for energy. **(B)** Conventional bioenergy production from biomass sourced from new agricultural residue collection, which displaces reference-case coal combustion. **(C)** A bioenergy with carbon capture and storage (BECCS) variant of scenario B, in which biogenic $CO_2$ from biomass combustion is geologically sequestered.

**TABLE 1 |** Illustrative example of changes to ecosystem–atmosphere and energy system–atmosphere carbon fluxes in response to corn stover collection for bioenergy production.

| | Ecosystem fluxes | | | | | | | Energy system fluxes | | | Net |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | NPP | $R_h$ | NEP | Harv | NECB | ΔHarv ($Harv_{bio}$ – $Harv_{ref}$) | ΔNEP ($NEP_{bio}$ –$NEP_{ref}$) | Harvested biomass LHV | Avoided coal emissions ($E_{ref}$) | Biomass emissions ($E_{bio}$) | Atmosphere C balance change ($E_{bio}$ – $E_{ref}$ – ΔNEP) |
| **Scenario** | Mg C $ha^{-1}$ $y^{-1}$ | | | | | | | GJ $ha^{-1}$ $y^{-1}$ | Mg C $ha^{-1}$ $y^{-1}$ | | Mg C $ha^{-1}$ $y^{-1}$ |
| ref: Grain harvest only | 13.9 | 8.3 | 5.6 | 5.3 | 0.3 | – | – | – | – | – | – |
| bio1: Near-term grain and stover harvest | 12.7 | 8.3 | 4.4 | 8.7 | −4.3 | +3.4 | −1.2 | 137 | 3.3 | 3.4 | +1.3 |
| bio2: Long-term grain and stover harvest | 13.9 | 4.6 | 9.3 | 9.9 | −0.6 | +4.6 | 3.7 | 185 | 4.5 | 4.6 | −3.6 |
| bio3: Near-term grain and stover harvest w/CCS | 12.7 | 8.3 | 4.4 | 8.7 | −4.3 | +3.4 | −1.2 | 137 | 3.3 | 0 | −2.1 |
| bio4: Long-term grain and stover harvest w/CCS | 13.9 | 4.6 | 9.3 | 9.9 | −0.6 | +4.6 | 3.7 | 185 | 4.5 | 0 | −8.2 |

*Reference case is shown in gray highlight.*

carbon load) from such a system implies:

$$\Delta C_{atm,\,bio} < \Delta C_{atm,\,ref} \quad (6)$$

$$E_{bio} - NEP_{bio} < E_{ref} - NEP_{ref} \quad (7)$$

Coal combustion releases $CO_2$ to the atmosphere at a rate of 24.4 g C $MJ^{-1}$ on a lower heating-value basis as per the GREET model (Wang, 1996). Combusting corn stover produces $CO_2$ at a roughly equivalent rate (25 g C $MJ^{-1}$, based on data from Tanger et al., 2013). Because energy system emissions are roughly equivalent in both cases ($E_{bio} \approx E_{ref}$), Equation (7) simplifies to:

$$NEP_{bio} > NEP_{ref} \quad (8)$$

In other words, any net mitigation from a bioenergy system is dependent on increased NEP flux from the atmosphere to the agricultural landscape where the biomass feedstock is produced. As per Equation (3), if the increase in carbon removal from new biomass harvest exceeds the increase in net carbon uptake by the system (NEP), then the biomass carbon is not fully "additional," but rather comes at the cost of reduced ecosystem carbon storage (NECB). Thus, carbon additionality refocuses assessment from tracking changes in ecosystem carbon stocks to tracking equivalent changes in atmosphere-ecosystem carbon flux.

An illustrative quantitative example is developed in **Table 1**. Reference-case ecosystem fluxes associated with corn grain production ("ref") are taken from Cates and Jackson (2019) for a 3-year experiment in Wisconsin. That study estimates a NEP value of 5.6 Mg C $ha^{-1}$ $y^{-1}$ and grain export of 5.3 Mg C $ha^{-1}$ $y^{-1}$ averaged across all cover crop treatments, which together imply a small positive residual NECB (0.3 Mg C $ha^{-1}$ $y^{-1}$). A whole-plant silage harvest treatment from the same study is analogous to the case of adding stover harvest for bioenergy production ("bio1"). NPP was reduced slightly (−1.2 Mg C $ha^{-1}$ $y^{-1}$) under that management system, but carbon harvest increased by 3.4 Mg C $ha^{-1}$ $y^{-1}$. The measured heterotrophic respiration rate was unchanged compared to the reference case over this relatively short experimental timeframe, which implies no increase in NEP (in fact a small decrease). Over this short time horizon, there is no system-level benefit to the atmosphere from trading coal emissions for stover biomass emissions, since that stover production was not associated with additional net agro-ecosystem carbon uptake (i.e., no carbon additionality), but rather came at the cost of reduced NECB (i.e., reduced litter and soil carbon in the system).

However, over longer time-frames we would expect $R_h$ rates to drop as soil organic matter levels reach a new equilibrium in response to stover removal (Kim et al., 2018). To construct a hypothetical longer-term equilibrium stover removal scenario ("bio2") we assume no reduction in long-term productivity with stover harvest, and that only 20% of the carbon in harvested stover would have been stabilized as soil organic matter had it been retained. The remaining 80% of the harvested stover carbon is "additional" since it would otherwise be respired back to the atmosphere during stover decomposition, and its harvest increases agro-ecosystem NEP by decreasing $R_h$ (Searchinger, 2010). When used for energy production, the harvested biomass carbon displaces a roughly-equivalent amount of carbon from coal combustion, and the net atmosphere carbon load is decreased by approximately the amount of long-term NEP increase from feedstock production. Note that carbon additionality is distinct from the idea of ecosystem carbon sequestration, and feedstock production can be partially additional, i.e., lead to increased local agro-ecosystem carbon uptake from the atmosphere (NEP) despite some reduction in ecosystem carbon storage (NECB, as is illustrated in the "bio2" case).

## CARBON ADDITIONALITY CHALLENGES FOR FIRST-GENERATION BIOFUELS

NEP and net ecosystem exchange (NEE, which is equivalent to NEP, but calculated from the perspective of the atmosphere and thus uses the opposite sign convention) have been measured in variety of bioenergy feedstock-producing landscapes via eddy covariance techniques (Skinner and Adler, 2010; Gelfand et al., 2011; Zeri et al., 2011, 2013; Drewer et al., 2012; Bernier and Paré, 2013; Zenone et al., 2013; Wagle et al., 2015; Sharma et al., 2017; Abraha et al., 2018). However, such data is seldom used directly in life-cycle assessments or other estimates of system-level GHG mitigation in bio-based systems. Though the concept of additional carbon is straightforward, its assessment in first-generation biofuel systems is not necessarily so.

Corn, soy, and sugarcane are fungible food commodities with large global markets, subject to large-scale supply and demand trends and market perturbations independent of biofuel production (De Kleine et al., 2017). As such, any changes in cultivation area, management intensity, or agricultural technology development associated with the scale-up of biofuel production must first be isolated from those background trends and perturbations in food and feed markets before they can be attributed to the biofuel sector. This requires detailed market analysis and modeling (Oladosu et al., 2011; Khanna et al., 2020), and the resulting estimates of biofuel performance are very heavily influenced by the conditions of a fundamentally unobservable "no-biofuel" counterfactual reference case (Babcock, 2009; Koponen et al., 2018). In addition, much of the crop mass used in first-generation biofuel production ends up in useful co-products such as corn oil, distillers grains, or soy meal, further entwining biofuel production with existing markets and introducing more dependencies around the arbitrary choice of co-product allocation method (Finnveden et al., 2009; Malça and Freire, 2010). Thus, establishing carbon additionality in such systems is more an economic and LCA attribution problem (relying on economic modeling, trade analysis, LCA allocation conventions, etc.) than an issue of carbon cycle measurement *per se*. As such, previous studies of carbon additionality from first-generation biofuels are necessarily coarse in their spatial and temporal scale, limited by model resolution and data availability to evaluating regional- or national-scale trends over multi-year periods. While this can shed light on the sustainability of the industry as a whole, it has limited value for the design, optimization, or verification of individual bioenergy systems.

Despite these challenges around verifying carbon additionality in first-generation biofuel systems, steady improvements in bioenergy production technology are paving the way to advanced system designs that might circumvent much of this ambiguity. Biofuel production from non-edible woody and herbaceous "cellulosic" biomass has been a major area of research since the US Renewable Fuel Standard was expanded in 2007 (Steiner and Buford, 2016; Peters, 2018). Compared to first-generation biofuels, advanced bioenergy systems have a) multiple routes to increased NEP, b) more identifiable atmosphere–ecosystem feedstock fluxes, and c) more opportunities for direct enterprise-level carbon sequestration. While these ideas are developed below in the context of bioenergy, there are many commonalities for the production of bio-plastics, mass timber, and other elements of the wider developing bioeconomy.

## MULTIPLE ROUTES TO INCREASED NEP IN CELLULOSIC BIOMASS PRODUCTION

There are multiple potential routes to feedstock production in existing agricultural landscapes that increase NEP while avoiding wide-scale indiscriminate land use change. As per Equation (2), NEP can be increased via increasing NPP, decreasing $R_h$, or a combination thereof. These are consistent with the concept of "sustainable intensification," which seeks to increase the per-area productivity of agricultural systems through increased crop growth and/or reduced waste (Tilman et al., 2011; Heaton et al., 2013; Yang et al., 2018; Mouratiadou et al., 2020).

Input intensification (e.g., greater use of fertilizers and irrigation) and adoption of higher-yielding crop varieties are conventional routes to increased agricultural NPP, though Heaton et al. (2013) review additional opportunities for bioenergy-focused sustainable intensification. They define temporal intensification as cultivating additional crops during the fallow portion of existing crop rotations, for example, growing winter oilseeds within conventional cotton-based rotations in the southeastern US (Kumar et al., 2020). Such approaches can have important co-benefits including reduced erosion, increased soil carbon, and reduced nutrient losses (Tonitto et al., 2006; Jian et al., 2020). Spatial intensification of agricultural landscapes involves converting under-utilized or unsustainably-cultivated land to dedicated energy crops. This might include "marginal" land of intermediate productivity (Gelfand et al., 2013) or agricultural land that has previously been degraded (Tilman et al., 2006), abandoned (Campbell et al., 2008), or placed into conservation easements (Gelfand et al., 2011). This could also include sub-field scale integration of perennial energy grasses in areas of problematic topography or soils, which currently produce negative economic returns under conventional crops and contribute disproportionately to erosion and nutrient leaching (Brandes et al., 2018). Perennial grasses can achieve higher NPP than many annual crops due in part to a longer growing season (Dohleman and Long, 2009). Eddy flux covariance studies have observed dedicated energy grasses such as Miscanthus and switchgrass to have approximately double the average annual NEP of conventional corn–soy rotations (Zeri et al., 2011, 2013) or continuous corn cultivation (Abraha et al., 2018). However, such NEP results are highly sensitive to prior land use and time since energy crop establishment (Abraha et al., 2018), and some studies show substantially lower NEP values for those crops (Skinner and Adler, 2010; Drewer et al., 2012), suggesting significant regional- and site-level variability.

Alternately, cellulosic feedstocks can be produced from harvesting agricultural residues such as corn stover (Domínguez-Escribá and Porcar, 2010; Heaton et al., 2013; Mouratiadou et al., 2020) that would otherwise largely be respired back to the atmosphere. Such feedstocks are additional to the extent that they increase agro-ecosystem NEP by reducing $R_h$ (Searchinger, 2010). Stover removal is not completely additional as it does lead to some reduction in soil carbon levels (Xu et al., 2019), particularly in the short-term as demonstrated by both modeling studies (Kim et al., 2018) and carbon flux measurements (Cates and Jackson, 2019). Soil organic matter is foundational to soil health and fertility (Campbell et al., 2018), and extreme organic matter loss can compromise agricultural system function (Tiessen et al., 1994). Erosion control and soil moisture management impose further constraints on the amount of residue that can be sustainably removed in different settings (Graham et al., 2007). However, these constraints might be lessened to some degree with the co-adoption of complementary conservation practices such as tillage intensity reduction or winter cover-cropping (Kim et al., 2018; Qin et al., 2018).

## IDENTIFYING ECOSYSTEM–ATMOSPHERE EXCHANGE WITH DEDICATED BIOENERGY CROPS

Dedicated perennial energy crops will likely be the largest source of cellulosic biomass feedstocks for a future US advanced bioeconomy (U.S. Department of Energy, 2016). Large federal research programs support the development of improved varieties of perennial energy grasses such as switchgrass, Miscanthus, and energycane, and short-rotation woody crops such as poplar (Steiner and Buford, 2016; Peters, 2018). Subsidies have also been offered to encourage their establishment in the landscapes around bioenergy facilities (Miao and Khanna, 2017). These dedicated bioenergy feedstock crops have often not previously been domesticated or improved, and lack large existing markets. As such, any future development and deployment of such crops can be confidently attributed to the bioenergy and bioproducts sectors.

The uniqueness of these dedicated crops also creates opportunities to cheaply and transparently monitor their growth and performance using remote sensing (RS) techniques. RS is widely used to map the extent of conventional crops in the US at fine spatial scales (Boryan et al., 2011), and has been applied to track expansion of corn cultivation during the growth of the ethanol industry (Wright and Wimberly, 2013; Wright et al., 2017; Lark et al., 2020). Differentiation of grassy land covers such as native grassland, managed pasture, hay production, and dedicated bioenergy grasses has historically been problematic for RS-based land use mapping (Kline et al., 2013). However, advanced methods show promise for identifying warm-season grasses (Wang et al., 2014, 2017) and even individual species such as Miscanthus (Xin and Adler, 2019) in cellulosic bioenergy production landscapes. Further refinement of such methods may enable precise, transparent, and low-cost mapping of dedicated energy crop plantings, as well as the previous land uses they replaced.

Beyond just land cover, RS is also increasingly applied to assess ecosystem carbon stocks and fluxes directly. Recent advances support using solar-induced florescence to sense GPP, lidar to measure standing biomass, and column $CO_2$ concentration measurement and source/sink inversion modeling to estimate NEP (Xiao et al., 2019). Gu et al. (2012) have used RS techniques to produce high-resolution maps of NEP under current land cover, in order to identify low-productivity marginal lands to target for conversion to bioenergy crops. Many bioenergy critiques (Righelato and Spracklen, 2007; Haberl, 2013; Searchinger et al., 2017) focus not on the carbon value of current-day land use, but rather on the "opportunity cost" of producing bioenergy in lieu of reforestation or alternate land-based "natural climate solutions" (Griscom et al., 2017). However, RS approaches are also beginning to be used in the assessment and monitoring of NEP provided by such natural solutions (Gerlein-Safdi et al., 2020). Together, these methods may enable the direct observation of carbon additionality by tracking the carbon uptake of land before and after conversion to dedicated energy crops, and in comparison to alternative natural solutions. This would transform many nuanced sustainability questions that are currently subject of scenario analysis and model-based inference into a matter of direct observation and measurement at relatively fine spatial scales.

## CARBON ADDITIONALITY IN CARBON-NEGATIVE SYSTEMS

Traditional bioenergy systems aim to achieve climate benefits principally through the displacement of fossil emissions. However, advanced bioenergy and other bio-based systems increasingly target the sequestration of biogenic carbon in soils, geological reservoirs, and durable bio-based products, termed "carbon management" (Canadell and Schulze, 2014), "negative emissions," or "carbon dioxide removal." Perennial feedstock crop cultivation promotes sequestration of soil organic carbon (Qin et al., 2016) in amounts that significantly affect system-level climate performance (Yang and Tilman, 2020).

New research suggests that enhanced rock weathering can be widely deployment on croplands for additional sequestration of inorganic carbon (Beerling et al., 2020). A variety of "carbon negative" bioenergy production technologies have also been proposed including the co-production of biochar soil amendments (Lehmann, 2007) or pyrolysis liquids for geological sequestration (Schmidt et al., 2019), and point-source carbon capture and storage (CCS) applied to biomass power plants (Fuss et al., 2014; Sanchez et al., 2015) and biorefineries (Field et al., 2020; Gelfand et al., 2020; Hanssen et al., 2020).

These various negative emissions options have different implications for system-level mitigation performance. Ethanol fermentation produces a $CO_2$ byproduct, the sequestration of which creates additional mitigation beyond the fossil fuel displacement value of the main fuel product. This can be viewed as increasing the carbon efficiency of the system, i.e., achieving greater climate benefits per unit of feedstock consumed (Field et al., 2020). Further, in a bioenergy with carbon capture and storage (BECCS) system, the same mass of carbon can both displace fossil emissions via bioenergy production, and be captured and sequestered via CCS (**Figure 1C**), thus effectively doing double-duty from a mitigation perspective. In the simplified examples illustrated in **Figure 1C** and quantified in **Table 1**, the addition of CCS to the near-term stover removal scenario ("bio3") prevents $CO_2$ from biomass combustion from being re-emitted back to the atmosphere. As a result, the system achieves net climate benefit compared to the reference case due to the avoidance of emissions from coal combustion, even in the absence of carbon additionality of the biomass feedstock. When CCS is applied to the carbon-additional long-term stover removal scenario ("bio4"), substantial mitigation is achieved via both displacing coal emissions, and from the geological sequestration of biogenic carbon (effectively creating a carbon pump from the atmosphere to the geosphere). Adding CCS introduces additional parasitic energy requirements that are not considered in this simplified example, though analysis of a hybrid fuel-and-power production system concept suggests that CCS integration can approximately double overall net system mitigation performance (Liu et al., 2011).

Similar logic is potentially applicable to other bio-based systems as well. For example, mass timber production may have mitigation value through both the displacement of emissions-intensive conventional building materials (steel, concrete, etc.) and via the sequestration of biogenic carbon in the timber itself.

## DISCUSSION

Bioenergy and bioproduct assessment has been heavily reliant on model-intensive LCA approaches subject to large and potentially irresolvable methodological uncertainties (Warner et al., 2013; DeCicco et al., 2016). However, as advanced bio-based supply chains become more distinct from conventional agricultural production, and more reliant on mitigation via the direct sequestration of biogenic carbon, new opportunities arise to directly observe feedstock-related carbon fluxes which have previously been the source of much critique and controversy. Remote sensing of additional ecosystem carbon uptake at the scale of feedstock-sheds would establish a data-rich foundation for monitoring individual bioeconomy enterprises without the need for bespoke, resource-intensive studies (Field et al., 2018).

Direct observation of atmosphere–ecosystem carbon exchange does not address all feedstock-related sustainability critiques or serve as a full replacement for conventional bio-based system LCA. Those conventional approaches are still needed to calculate supply-chain emissions associated with upstream fertilizer production and farm operations, for example. However, such emissions are typically modest in cellulosic systems. In contrast, the measurement of ecosystem–atmosphere exchanges centers the more contentious issues of land availability, system scale, and biogenic emissions accounting in ways that conventional LCA cannot. There are other system-level effects such as ILUC that exist largely outside the provenance of individual feedstock producers, bioenergy companies, or even many policy jurisdictions, and which cannot directly be observed (Babcock, 2009). But even there, RS approaches can help constrain the underlying land use change modeling with observational estimates of any existing agricultural production being displaced by feedstock crops.

Climate benefits are not a guaranteed outcome of bio-based systems, but rather the result of systems thinking and design—including innovations in technology, assessment, and policy—to maximize mitigation potential while minimizing the risk of unintended consequences. Prime and even marginal arable land are a finite resource, and arbitrarily-wide deployment of any land-based mitigation approach will at some point conflict with the food system (Fuhrman et al., 2020; Stenzel et al., 2021) and/or with biodiversity preservation (Stoy et al., 2018; Seddon et al., 2019). In light of these challenges, some recommend taking a highly precautionary approach to the development and deployment of bio-based systems (Searchinger, 2010; DeCicco and Schlesinger, 2018). However, centering the observation of atmosphere–ecosystem carbon exchanges in bio-based system assessment may provide a different path. The assessment community might take inspiration from the imperative of "ecological forecasting," which calls for a near-term iterative approach to ecological modeling that can be continuously evaluated and updated in light of the flood of new measurements becoming available in that field (Clark et al., 2001; Dietze et al., 2018). Similarly, a greater focus on observed atmosphere–ecosystem carbon exchange in bio-based system assessment could support near-term iterative performance evaluation for individual bio-based enterprises or land-use policies, in support of sustainable decarbonization.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## AUTHOR CONTRIBUTIONS

JF devised and wrote the manuscript.

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