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The Oxymoron of Carbon Dioxide Removal: Escaping Carbon Lock-In and yet Perpetuating the Fossil Status Quo?

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There appears to be a paradox in the debate over carbon dioxide removal (CDR) technologies. On the one hand, CDR is recognised as a crucial technical option to offset residual carbon emissions from fossil fuel use, so that it can help a transition to the net-zero energy system. But on the other hand, a serious concern is raised about CDR as a way to circumvent necessary emissions reduction, hence perpetuating the status quo of fossil fuel use. This apparent paradox of CDR, however, has less to do with technology itself but more with the difficulty to move away from *carbon lock-in*—the deeply entrenched fossil-fuel-based energy system. The challenge of decarbonisation is indeed about eroding the deep lock-ins that perpetuate the production and consumption of fossil fuels. To understand the role of CDR in overcoming carbon lock-in, looking back the past debate on carbon capture and storage (CCS) is instructive. Although both CCS and CDR are criticised for keeping the fossil status quo, there is a crucial difference between them. Unlike CCS, CDR can possibly avoid the risk of *reinforced lock-in*, given its physical decoupling from fossil fuel use. And yet CDR has the risk of *undue substitution* that continues unjustly fossil carbon emissions. A change of the framing question is thus needed to puzzle out the paradox of CDR. To rightly place CDR in the challenge of rapid decarbonisation, we should ask more how CDR technologies can be used in alignment with a managed decline to fossil fuel production.

Keywords: carbon dioxide removal, negative emissions technologies, carbon capture and storage, carbon lock-in, mitigation deterrence, fossil fuels, decarbonisation

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INTRODUCTION

Achieving the climate goal of the Paris Agreement of keeping global temperature rise well below 2 or 1.5°C requires rapid, deep decarbonisation of the entire global economy (Rockström et al., 2017). This basically means that the world must transition, at *unprecedented* pace, from fossil-fuel-based energy systems into the ones powered by non-carbon energy sources such as renewable, nuclear and hydrogen energy. The pace of change required is really extraordinary. In 2020, by wrecking the global economy, the COVID-19 pandemic caused the largest drop in global CO_2 emissions in a single year, by about 7% relative to 2019 (Friedlingstein et al., 2020; Le Quéré et al., 2021). For meeting the 1.5°C target, the roughly same rate of emissions reduction will have to happen every year until 2030 (IPCC, 2018; UNEP, 2019).

However, the infrastructural inertia of fossil fuel energy system is already jeopardising the challenge of rapid decarbonisation. If existing (and already proposed) fossil-fuel-burning electricity and industry facilities were allowed to operate for historical average lifetimes (e.g., 40 years for power plants), the "committed emissions" from existing energy infrastructure would likely exceed the remaining carbon budget for 1.5°C (Tong et al., 2019). To have a reasonable chance of meeting the 1.5°C target, therefore, not only should a new construction of fossil-fuel power plants be banned but also the early retirement of existing infrastructure must be pursued (Cui et al., 2019; Fofrich et al., 2020). Or otherwise, the current fossil fuel infrastructure has to be retrofitted with carbon capture and storage (CCS) or compensated by carbon dioxide removal (CDR) technologies.

Here, the pictures of "decarbonising" energy systems become murky. On the one hand, there is a growing call for deliberately reducing—and even prohibiting—the production and consumption of fossil fuels (Green, 2018; Piggot et al., 2018, 2020; Rosenbloom and Rinscheid, 2020). The assumption of such a call is that building an anti-fossil fuel norm and increasing the risk of stranded assets through financial divestment and other means will lead to more immediately phasing out fossil fuels and hence accelerating a transition towards non-fossil energy. On the other hand, there is a wide recognition that full decarbonisation would be infeasible without CDR options that offset "residual emissions" from fossil fuels—particularly from the hard-to-abate sectors such as steel and cement manufacturing, long-distance freight, shipping or aviation (Davis et al., 2018; Luderer et al., 2018). The prospect of CDR technologies stems from our *perception* that a complete phase-out of fossil fuels is impractical (at least for a required timescale). The risk of becoming stranded may also be effectively avoided by retrofitting fossil fuel infrastructure with CCS (Johnson et al., 2015).

Fossil fuel use is deeply entrenched in our economy and culture. Our society as a whole is built around fossil fuel energy infrastructure. Given this entrenchment—often called *carbon lock-in*—the role that CDR technologies play in energy decarbonisation is both crucial and risky. Whilst CDR is largely seen as part and parcel of decarbonising fossil fuels, there remains a serious concern that CDR might be used as an excuse for perpetuating the reliance on fossil fuels. This sounds like an oxymoron. It's partly because whether CDR sustains (unnecessarily) fossil fuel dependence is an ideological question—the answer can differ by political preferences between radicalism and pragmatism. But it is also rooted in the difficulty to overcome carbon lock-in by steering the managed decline of fossil fuels.

The challenge of decarbonisation is to erode the deep lock-ins that perpetuate the incumbent fossil-fuel-based energy system. In this article, I explore how carbon removal methods will help or hinder the unlocking of carbon lock-in.

To understand the relationship between carbon removal and carbon lock-in, looking back the past debate on carbon capture technology is illustrative. This is because both CCS and CDR receive the same criticism of perpetuating the lock-in to fossil fuels. However, such criticism often overlooks a crucial, underlying difference between CCS and CDR. As shall be discussed later, whilst CCS involves the risk of *reinforced lock-in* through an increase of the infrastructural inertia, CDR is associated more with the risk of *undue substitution*—allowing unjustly the continued fossil emissions by carbon offsetting. Recognising this difference is key to the understanding of the role of CDR in decarbonisation.

The idea of CCS emerged as a pragmatic response to overcoming carbon lock-in with leaving the existing fossil fuel infrastructure in place. Despite initial enthusiasm, the CCS progress has stagnated, and its promise of decarbonising fossil fuels is yet to be delivered. Now a policy focus is shifting from "capture" (retrofit with CCS) to "removal" (compensation by CDR). This may signal a new promise of overcoming carbon lock-in. And yet the promise of CDR is seen as a latest example of "technologies of prevarication" that may justify another delay of essential mitigation and preserve the status quo (McLaren and Markusson, 2020).

To puzzle out this apparent paradox of CDR, I argue, we need to change the framing of a question to be asked. Rather than asking whether CDR will perpetuate fossil fuels, we should pose a different kind of question: How can CDR technologies be used in alignment with a managed decline to fossil fuels? This eventually comes down to the challenge of mitigating a resistance from old fossil incumbents and involving them more progressively into the politics of decarbonisation.

THE CONUNDRUM OF UNLOCKING CARBON LOCK-IN

Despite a growing sense of urgency for avoiding dangerous climate change, the world is still staggering to embark on rapid decarbonisation. What makes the challenge of decarbonisation so daunting is the self-perpetuating inertia of fossil-fuel-based energy system, which inhibits the emergence of low-carbon alternatives and slows the pace of change towards a sustainable energy future. This energy system's inertial resistance to change is generally known as *carbon lock-in* or sometimes referred to as *fossil fuel lock-in* (Unruh, 2000, 2002). The challenge of rapid decarbonisation is practically about how fast we can move away from—or "unlock"—carbon lock-in (cf. Bernstein and Hoffmann, 2019).

Since Unruh (2000) coined the term carbon lock-in, the concept has attracted a fair amount of scholarly attention for identifying the causes, types or mechanisms of lock-in (e.g., Cairns, 2014; Bertram et al., 2015; Erickson et al., 2015; Seto et al., 2016; Buschmann and Oels, 2019; Janipour et al., 2020; Trencher et al., 2020). A seminal review of the relevant literature by Seto et al. (2016) suggested three types of lock-in that are mutually reinforcing and create collective inertia: infrastructural, institutional, and behavioural lock-ins. Some argue that other forms of lock-in (e.g., cognitive or discursive lock-in) should also be taken into account (Buschmann and Oels, 2019; Trencher et al., 2020). An important point is however that the interactions among technological infrastructures, governing institutions, social practises and cognitive frames give rise to an entrenchment of the energy system that favours the continued use of carbon intensive technologies. Not a single individual factor but a complex *socio-technical entanglement* does cause and sustain carbon lock-in (cf. Cairns, 2014).

Lock-in is the outcome of path dependent processes driven by the mechanism of increasing returns or self-reinforcing positive feedback. Once in place, any locked-in systems—technological, social, political, economic, and cultural—are resistant to changes and seek to keep the status quo. Crucially, as Seto et al. (2016) pointed out, lock-in favours the status quo but is normatively neutral: it can be either positive or negative (for an example of positive lock-in, see Ürge-Vorsatz et al., 2018). Lock-in becomes a problem when already entrenched systems inhibit changes deemed desirable. In this respect, carbon lock-in is arguably a negative condition because it perpetuates high carbon emissions, leading to dangerous consequences.

Moreover, lock-in is not a "permanent condition" but rather a "persistent state" that creates systemic barriers to alternatives (Unruh, 2000). As Cairns (2014) noted, the term lock-in perhaps serves more like a metaphor than in a literal sense of the word. Whether a particular system is "locked in" or not depends on the one's normative view on the timescale within which desired changes *should* happen. Insomuch as a rapid fossil fuel phase-out becomes a political and moral imperative, there is now (we could say) an ever-greater sense among the public of *being* locked into resistant fossil energy regime.

Despite that, carbon intensive technologies such as coal-fired power plants are particularly difficult to unlock. This is because these technologies are costly to build but relatively inexpensive to operate over long infrastructure lifetimes (Erickson et al., 2015). Large capital costs and long lead times create substantial sunk costs; and therefore, prematurely retiring coal-fired power plants would necessarily bear significant financial costs, which in turn makes such a decision politically difficult (cf. Trencher et al., 2020).

FROM CAPTURE TO REMOVAL—ESCAPING CARBON LOCK-IN?

The difficulty to unlock carbon lock-in provides a political economic ground that CCS and CDR could come into the politics of decarbonisation. On the surface, these technological options are appealing because they *promise* to decarbonise fossil fuel infrastructure while preserving it. There is however an important difference between CCS and CDR. That is, since CCS is mainly assumed to be retrofitted with fossil-fuel-burning facilities like coal or gas power plants, CCS deployment is largely inseparable from fossil fuel *use*. On the other hand, CDR use is not necessarily physically tied to the infrastructure that burns fossil fuels. CCS entails the risk of deepening carbon lock-in, which hinges on the infrastructural *inseparability* of CCS from fossil fuel use. A policy shift from CCS to CDR can possibly avoid this risk of reinforced lock-in. Given the physical *separability* from fossil fuel use, CDR is nevertheless associated with the risk of undue substitution for cutting fossil carbon emissions.

CCS and the Risk of Reinforced Lock-In

In the early phase of CCS debate, those who advocated CCS appeared to view this technological option as a sort of pragmatic compromise that could resolve the political dilemma arises from carbon lock-in. To justify the investment into CCS research and development, CCS was often presented as a "bridging technology" towards a renewable energy future (Hansson and Bryngelsson, 2009; Meadowcroft and Langhelle, 2009; Vergragt et al., 2011). The metaphor of bridge was used to emphasise that CCS is a temporary solution to buy time only until better options (i.e., renewables) become available.

This bridge framing fitted well into the perception of CCS advocates that industrial economies are deeply locked into fossil-fuel-burning technologies such as coal power plants, so unlocking them (right now!) is too costly. Because of their recognition—not ignorance—of the difficulty in overcoming carbon lock-in, retrofit with CCS might appear more pragmatic than immediate phase-out. The appeal of CCS was predicated exactly on its promise as a non-disruptive "end-of-pipe" technology to allow the continued use of fossil fuels while mitigating CO_2 emissions (Unruh and Carrillo-Hermosilla, 2006).

Though it might sound reasonable at that time, framing CCS as a bridging technology has turned out be the opposite. As the cost of renewable electricity generation has fallen dramatically over a decade, renewable energy is now the cheapest source of electricity in many places (IEA, 2020). While on the other hand, the progress in CCS development stalled and the technology has not been yet deployed at scale (Reiner, 2016; Bui et al., 2018). The slow progress in CCS was partly due to a lack of political and economic support for closing the financial gap, necessary to operate large-scale demonstration projects (Gaede and Meadowcroft, 2016). Rather than a bridge to renewable energy, the framing of CCS is now "recalibrated" as a *long-term* solution for fully decarbonising the whole energy system (Bui et al., 2018).

More importantly, however, the bridge framing was wrong with its presumption that CCS could somehow provide a way out of carbon lock-in. Instead, it is largely believed that adding CCS on fossil-fuel power plants would risk deepening or reinforcing carbon lock-in—known as *reinforced carbon lock-in* (Unruh and Carrillo-Hermosilla, 2006; Markusson and Haszeldine, 2010; Vergragt et al., 2011; Markusson, 2012; Shackley and Thompson, 2012; Stephens, 2014). This is because "adding CCS" means the building of an entirely new infrastructure for capturing, transporting and storing CO_2 underground as an integrated socio-technical system. Building new CCS infrastructures (capture facility, pipeline, and geological storage) requires large capital investments with long lead-times. This increases substantially the infrastructural inertia of fossil fuel energy system, keeping it in place for several decades. CCS would likely reinforce the lock-in of—and make it difficult to transition away from—fossil fuel system.

It is however worth noting the nuances of the term "reinforced lock-in." Although CCS perpetuates the use of fossil fuels, if worked successfully, it could abate CO_2 emissions from fossil fuel use, which is not necessarily bad. The reinforced lock-in becomes a serious problem when new fossil-fuel power plants are constructed on the promise that CCS will be installed at some point in the future (so-called "capture readiness") but will never actually be deployed, then leaving these plants *unabated* (Markusson and Haszeldine, 2010; Shackley and Thompson, 2012). In short, the over-promise of CCS has the risk of a further lock-in to unabated fossil fuels. According to Markusson and Haszeldine (2010), the only safe way to make sure to avoid this risk of *unabated carbon lock-in* is to not build new fossil plants in the first place.

CDR and the Risk of Undue Substitution

Alternatively, the risk of reinforced lock-in can possibly be avoided by shifting a policy focus from CCS onto CDR (Vergragt et al., 2011). The so-called engineered CDR methods such as bioenergy with CCS (BECCS) or direct air carbon capture and storage (DACCS) use almost identical technologies for CO_2 transport and storage to those used for fossil energy CCS (FECCS). Both BECCS and DACCS are a sort of cousins of CCS-family technologies. However, unlike FECCS, which is retrofitted with fossil fuel facilities, the deployment of BECCS and DACCS does not have to be *physically* coupled with fossil fuel infrastructure (cf. Markusson, 2012). For example, the value of BECCS does not rest only on its ability to provide negative emissions; it also comes from the fact that BECCS serves as an alternative energy source to fossil fuels (Köberle, 2019). FECCS makes an already heavy fossil-fuel system even heavier, but this is not necessarily true for CDR. Theoretically at least, CDR can offset CO_2 emissions from fossil fuels without reinforcing the lock-in to them.

Nevertheless, there is a serious concern about CDR that might deter or delay necessary mitigation (Markusson et al., 2018; McLaren et al., 2019). This concern over "mitigation deterrence" (or otherwise known as "moral hazard") originally comes from the debate over solar geoengineering or solar radiation management (SRM) (see McLaren, 2016). In the geoengineering debate, one of the most lingering, serious concerns is that SRM might become *undue substitution* for mitigation to stop global warming. It is widely recognised that SRM cannot replace mitigation since it doesn't address CO_2 emissions. Despite that, the concern over mitigation deterrence remains acute. This is because SRM has the characteristics that it can act quickly to stop the warming and its use comes with a low-price tag. So, there is a real risk that SRM may well be used as a "cheap, fast and imperfect" substitute for costly mitigation (Keith et al., 2010).

CDR faces the similar concern as dose SRM about being used as poor substitutes for mitigation (Markusson et al., 2018). This is partly because CDR and SRM were often grouped together under the common rubric "geoengineering." Yet this concern over undue substitution is real for CDR. Take for example terrestrial CDR methods such as afforestation.

Afforestation (or tree planting) is now often viewed as a form of land-based CDR methods. But afforestation has also long been recognised as an "accepted" mitigation strategy. For example, the removal by afforestation and reforestation was included in the Kyoto Protocol under the land-use, land-use change and forestry (LULUCF) category. However, there was a huge, political controversy over this decision to include biological carbon sinks as mitigation options (Dooley and Gupta, 2017; Moe and Røttereng, 2018; Carton et al., 2020). The use of terrestrial carbon sinks as carbon offset was—and is still—severely criticised as a way to circumvent necessary mitigation, thereby perpetuating the continued use of fossil fuels.

Ironically, this fear of mitigation deterrence is rooted in an exact reason why CDR is recognised as a crucial policy option. CDR is politically appealing because it *decouples* the nature and cost of emissions reduction from emissions sources in time and space (Kriegler et al., 2013; Lomax et al., 2015). Offsetting by CDR can provide an alternative route to reducing emissions at sectors or sources that are difficult to decarbonise directly, such as aviation or shipping (Davis et al., 2018). As a result, fossil fuels can continue to be used in these hard-to-abate sectors, but this continued reliance on fossil fuels may not necessarily be considered "undue" substitution.

After all, whether CDR causes mitigation deterrence is a matter of definition of *substitutability* between "emissions reduction" and "negative emissions." As Markusson et al. (2018) argued, if the policy goal was determined only in narrow economic terms (e.g., reducing net emissions in the least cost way), the widespread use of CDR might appear a rational choice. But this would likely lead to *misperceived* substitutability that causes harmful consequences and undermines the integrity of mitigation policy. For example, the unrestricted use of land-based CDR might create a perverse incentive to offset industrial carbon emissions from fossil fuels by terrestrial carbon sinks with no considerations of social, ethical and environmental impacts (Dooley and Gupta, 2017; Dooley and Kartha, 2018). Likewise, the prospect of overshoot—i.e., that future large-scale CDR will compensate delayed mitigation today—does not only justify the slow act on mitigation but also risk putting future generations on an unjust gamble (Anderson and Peters, 2016; Lenzi et al., 2018; Asayama and Hulme, 2019).

To prevent such undue substitutions, there is a growing number of the proposals for the "appropriate" use of CDR. For example, McLaren et al. (2019) argue for setting two separate targets for emission reduction and carbon removal rather than a single "net-zero" target. Smith (2021) emphasises the importance of a greater transparency for different storage risks of biological and geological sinks. Others also suggest the principles for guiding the decisions about carbon removal and carbon offsetting (Allen et al., 2020; Morrow et al., 2020).

However, what is the "appropriate" use of CDR is inherently a *political* question. This is actually not so much about technology itself. Rather it is more about how political interests of fossil fuel industry tamper with the use of CDR methods.

DIVORCE FROM FOSSIL FUEL INTERESTS

As discussed above, CCS and CDR typically receive the same criticism made against them: that is, both technologies perpetuate the continued use of fossil fuels. From this perspective, the core aim of both CCS and CDR is to reduce or cancel out fossil CO_2 emissions while preserving (to some degree) the existing fossil fuel infrastructure. Indeed, Markusson et al. (2017), for this reason, have even proposed that CCS and CDR (including SRM) should be referred to as "clean fossil" technologies that promise to defend the incumbent fossil interests and more broadly the fossil-fuel-based economy. But is it really the case that both CCS and CDR must inevitably be closely tied to fossil fuel interests?

In this regard, the relationship between CCS and fossil fuel interests is fairly straightforward. In the public discourse, CCS has been repeatedly described as a pragmatic compromise—or "political glue"—that brings together the competing interests between climate change mitigation and fossil fuel dominance (Hansson and Bryngelsson, 2009; Tjernshaugen and Langhelle, 2009; Pollak et al., 2011; Asayama and Ishii, 2017). From the viewpoint of fossil fuel industry, CCS has an *instrumental* value of serving as a "hedge" to defend their interests and maintain the status quo (Gunderson et al., 2020).

That the material interest of fossil fuel industry is strongly attached to CCS is also evident in a fact that the countries in advance of CCS demonstrations are so far major fossil fuel producers such as Australia, Canada, Norway and the United States (Gaede and Meadowcroft, 2016; Reiner, 2016). CCS with enhanced oil recovery (EOR) is particularly instrumental for those fossil-fuel-rich countries in justifying the continued extraction of massive fossil reserves. This is also why CCS investment from the government is strongly criticised as an additional form of "fossil fuel subsidy" (Stephens, 2014) and is faced with the public scepticism of its legitimacy (Mabon and Littlecott, 2016).

However, not all fossil fuel companies got actively involved in CCS development as their corporate climate strategies. Tjernshaugen (2012) found that the companies like ExxonMobil who took a resistant strategy (i.e., denying the scientific reality of global warming and opposing the governmental regulations) largely stayed away from CCS activities. On the other hand, those companies like BP and Statoil were more actively engaged with promoting CCS as a legitimate mitigation option. These differences show clearly that the fossil fuel industry is far from being homogeneous in its approach to climate change. On top of that, they suggest that the *promise* of CCS—rather than its actual use—has the power of defending fossil fuel interests, regardless of whether or not such promise is delivered.

Meanwhile, CDR has a more modest relationship with fossil fuel interests. In a sense, CDR seems like an "orphan technology"—the technology that does not have the private sector (i.e., the parent), who is willing to bear the costs of its development despite its apparent public benefit (Wagner, 1992). Without any financial support from the public sector, CDR technologies would be more likely to go undeveloped. Whilst the similar argument can be made for CCS development (cf. Gaede and Meadowcroft, 2016), CCS *deployment* is largely inseparable from fossil fuel use (except its application to industrial processes). On the other hand, CDR need not necessarily be of principal interest to fossil fuel companies but to a much wider range of actors, because its use is physically decoupled from fossil fuel use.

The physical decoupling does not of course mean that CDR is independent from the financial and political interests of fossil fuel industry. As seen above, there is always the risk that CDR could be used expediently as a substitute for cutting fossil carbon emissions. For example, a global oil major Shell recently announced that the company sought to achieve net-zero carbon emissions by 2050, but their net-zero pledge resorts to carbon offset from tree planting to a large degree (Ambrose, 2021). In January 2020, the World Economic Forum launched the One Trillion Trees initiative for the fight against climate change. And this captured immediate attention from former US President Donal Trump who sowed doubt on global warming and withdrew from the Paris Agreement. As Ellis et al. (2020) argued, this renewed attention to tree planting may risk being a dangerous diversion from the efforts to end the use of fossil fuels (see also Carton et al., 2020; Seymour, 2020).

At the end of the day, what really matters to the governance of CDR seems to be the prevention of fossil fuel interests from having an "undue" influence on policy decisions about the development and deployment of CDR technologies.

ALIGN WITH FOSSIL FUEL DECLINE

Here, I argue that, rather than asking whether CDR will perpetuate the status quo of fossil fuel use, we should flip the question and ask instead: How can we align the use of CDR methods with managing a phase-out of fossil fuel production? Insomuch as CDR deployment could be compatible with the continued use of fossil fuels, it could also be aligned with the managed decline to fossil fuels. This is because, unlike CCS, CDR can be physically independent of specific emission sources (Kriegler et al., 2013; Lomax et al., 2015). CDR development and fossil fuel decline doesn't have to come into conflict with each other.

For example, fossil fuel divestment emerged as the global social movement that aims at undermining the legitimacy of fossil fuel industry (Rosenbloom and Rinscheid, 2020). While being successful as effective media campaigns for spreading an anti-fossil fuel norm (Green, 2018), the divestment movement largely failed to alter the capital flow into fossil fuel stocks in financial markets as a whole (Mormann, 2020). This is, according to Mormann (2020), partly due to the movement's focus on divestment from fossil fuel stocks but little guidance on reinvestment choices. Here, we can take advantage of the funds divested from fossil fuel stocks to reinvest into the development of CDR technologies. Such reinvestment strategy may face a backlash from climate activist groups. But assessing and informing the risk and benefit of financial investment on CDR technologies could help investors to make better investment decisions. There is no reason to preclude CDR as low-carbon investment choices.

Furthermore, we need to pluralise our views on fossil fuel incumbencies (Turnheim and Sovacool, 2020). The divestment movement often portrays fossil fuel companies as villains that irremediably resist the change and therefore should be dismantled all together. But not all fossil fuel companies are created equal (cf. Mormann, 2020). This was evidenced by different strategies on CCS activities among big oil companies (Tjernshaugen, 2012).

It is true that some fossil fuel companies, particularly in the US, were behind the organised denial machine to sow doubt on global warming (Dunlap and McCright, 2011; Supran and Oreskes, 2017). A dark history of climate change disinformation by fossil fuel industry should not be ignored. Nevertheless, it is also true that the industry's *expertise* is applicable not only to the extraction of fossil resources themselves; many fossil fuel companies also have significant geological and engineering expertise as well as capital assets that could be repurposed for large-scale CDR deployment (Hastings and Smith, 2020).

Catalysing a rapid phase-out of fossil fuels disrupts the financial stability of fossil fuel industry. It is no surprise that such efforts meet the resistance of incumbent fossil regime (Geels, 2014). But not all incumbents will remain stuck in old paradigms—their behaviours and strategies change over time following the political dynamics (Turnheim and Sovacool, 2020). They may seek to leverage their resources to diversify into new domain of activities. Here, CDR could become a political middle ground for mitigating a regime resistance and involving old incumbents more progressively into a low-carbon transition. Practically, this means that fossil fuel industry should morph into the "carbon disposal industry," the core mission of which focuses primarily on permanent storage of CO_2 in geological reservoirs (Allen et al., 2009; Buck, 2020; Hastings and Smith, 2020).

Of course, this kind of industrial transformation will not happen on its own. Nor will fossil fuel industry make a shift by itself. It is only through raising political pressures that we could perhaps "responsibly incentivise" fossil fuel industry to make a radical change towards carbon disposal industry (cf. Bellamy, 2018). And to get a democratic grip on such transition, it is crucial to articulate geological CO_2 disposal as a *public good* rather than private enterprises (Buck, 2020).

CONCLUSIONS

Since the Paris Agreement, the net-zero target has emerged as an anchor of climate policy debate (Geden, 2016). Accordingly, the boundary between mitigation and CDR becomes increasingly blurred (Cox et al., 2018; Minx et al., 2018). Now CDR methods are more or less normalised as an "extension of mitigation" or "unconventional mitigation" (Geden and Schenuit, 2020).

From the viewpoint of carbon budget, insofar as positive emissions are being compensated by negative emissions, the risk of "mitigation" deterrence might appear as a marginal concern. So, why are we still debating about how to "mitigate" carbon emissions? It is precisely because "decarbonising" the energy system cannot be taken as synonymous with meeting the "net-zero" target. There are many different decarbonisation pathways towards a net-zero future. What is hidden under this ambitious policy goal is the contested politics on the ground about decarbonising fossil fuels.

A climate policy tends to focus on the technicality of reaching net-zero emissions. This is evident in the fact that the phrase "fossil fuels" is missing from the text of the Paris Agreement (Piggot et al., 2018). It may however risk losing slight of a real challenge in the politics of decarbonisation—how to erode the deep lock-ins that perpetuate the production and consumption of fossil fuels. Perhaps the debate on CDR governance too has been narrowly caught up in delivering the promise of net-zero. But, as curbing fossil fuel supply is becoming a major topic in the climate policy conversation (Piggot et al., 2020), now is a time to turn around the question about the role of CDR in energy decarbonisation.

Gaede and Meadowcroft (2016) argued that CCS was a "Janus-faced technology" that could both slow and accelerate the transition to a decarbonised energy future. Likewise, CDR is a double-edged sword for rapid decarbonisation. CDR could be a useful complement to balancing out "recalcitrant" emissions from the hard-to-abate sectors. At the same time, they could serve as an expedient substitute for reducing "superfluous" emissions to preserve the status quo of fossil fuel use. This dilemma is however not so much a problem of technology. CDR is at the middle of our love and hate relationship with fossil fuels. To get out of this dilemma, we should ask more how developing CDR technologies can be aligned with managing the decline to fossil fuel production.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

The author confirms sole responsibility of the study conception, analysis, and manuscript preparation.

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REFERENCES

Allen, M., Axelsson, K., Caldecott, B., Hale, T., Hepburn, C., Hickey, C., et al. (2020). *The Oxford Principles for Net Zero Aligned Carbon Offsetting*. Oxford: Smith School of Enterprise and the Environment, University of Oxford. Available online at: https://www.smithschool.ox.ac.uk/publications/reports/Oxford-Offsetting-Principles-2020.pdf (accessed June 10, 2021).

Allen, M. R., Frame, D. J., and Mason, C. F. (2009). The case for mandatory sequestration. *Nat. Geosci.* 2, 813–814. doi: 10.1038/ngeo709

Ambrose, J. (2021). Shell to expand gas business despite pledge to speed up net zero carbon drive. *The Guardian*. Available online at: https://www.theguardian.com/business/2021/feb/11/shell-grow-gas-business-energy-net-zero-carbon (accessed June 10, 2021).

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

Asayama, S., and Hulme, M. (2019). Engineering climate debt: temperature overshoot and peak-shaving as risky subprime mortgage lending. *Clim. Policy* 19, 937–946. doi: 10.1080/14693062.2019.1623165

Asayama, S., and Ishii, A. (2017). Selling stories of techno-optimism? The role of narratives on discursive construction of carbon capture and storage in the Japanese media. *Energy Res. Soc. Sci.* 31, 50–59. doi: 10.1016/j.erss.2017.06.010

Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nat. Energy* 3, 532–534. doi: 10.1038/s41560-018-0156-6

Bernstein, S., and Hoffmann, M. (2019). Climate politics, metaphors and the fractal carbon trap. *Nat. Clim. Chang.* 9, 919–925. doi: 10.1038/s41558-019-0618-2

Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M., and Eom, J. (2015). Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technol. Forecast. Soc. Change* 90, 62–72. doi: 10.1016/j.techfore.2013.10.001

Buck, H. J. (2020). Should carbon removal be treated as waste management? Lessons from the cultural history of waste. *Interface Focus* 10:20200010. doi: 10.1098/rsfs.2020.0010

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., et al. (2018). Carbon capture and storage (CCS): the way forward. *Energy Environ. Sci.* 11, 1062–1176. doi: 10.1039/C7EE02342A

Buschmann, P., and Oels, A. (2019). The overlooked role of discourse in breaking carbon lock-in: the case of the German energy transition. *Wiley Interdiscip. Rev. Clim. Chang.* 10:e574. doi: 10.1002/wcc.574

Cairns, R. (2014). Climate geoengineering: issues of path-dependence and socio-technical lock-in. *Wiley Interdiscip. Rev. Clim. Chang.* 5, 649–661. doi: 10.1002/wcc.296

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., and Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *Wiley Interdiscip. Rev. Clim. Chang.* 11:e671. doi: 10.1002/wcc.671

Cox, E. M., Pidgeon, N., Spence, E., and Thomas, G. (2018). Blurred lines: the ethics and policy of greenhouse gas removal at scale. *Front. Environ. Sci.* 6:38. doi: 10.3389/fenvs.2018.00038

Cui, R. Y., Hultman, N., Edwards, M. R., Mcjeon, H., Iyer, G., Patel, P., et al. (2019). Quantifying operational lifetimes for coal power plants under the Paris goals. *Nat. Commun.* 10:4759. doi: 10.1038/s41467-019-12618-3

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., et al. (2018). Net-zero emissions energy systems. *Science* 360:eaas9793. doi: 10.1126/science.aas9793

Dooley, K., and Gupta, A. (2017). Governing by expertise: the contested politics of (accounting for) land-based mitigation in a new climate agreement. *Int. Environ. Agreements Polit. Law Econ.* 17, 483–500. doi: 10.1007/s10784-016-9331-z

Dooley, K., and Kartha, S. (2018). Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *Int. Environ. Agreements Polit. Law Econ.* 18, 79–98. doi: 10.1007/s10784-017-9382-9

Dunlap, R. E., and McCright, A. M. (2011). "Organized climate change denial," in *The Oxford Handbook of Climate Change and Society*, eds. J. S. Dryzek, R. B. Norgaard, and D. Schlosberg (Oxford: Oxford University Press) 144–160.

Ellis, E., Maslin, M., and Lewis, S. (2020). Planting trees won't save the world. *The New York Times*. Available at: https://www.nytimes.com/2020/02/12/opinion/trump-climate-change-trees.html (accessed June 10, 2021).

Erickson, P., Kartha, S., Lazarus, M., and Tempest, K. (2015). Assessing carbon lock-in. *Environ. Res. Lett.* 10:084023. doi: 10.1088/1748-9326/10/8/084023

Fofrich, R. A., Tong, D., Calvin, K. V., de Boer, H. S., Emmerling, J., Fricko, O., et al. (2020). Early retirement of power plants in climate mitigation scenarios. *Environ. Res. Lett.* 15:094064. doi: 10.1088/1748-9326/ab96d3

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., et al. (2020). Global carbon budget 2020. *Earth Syst. Sci. Data* 12, 3269–3340. doi: 10.5194/essd-12-3269-2020

Gaede, J., and Meadowcroft, J. (2016). "Carbon capture and storage demonstration and low-carbon energy transitions: explaining limited progress," in *The Palgrave Handbook of the International Political Economy of Energy*, eds T. van de Graaf, B. K. Sovacool, A. Ghosh, F. Kern, and M. T. Klare (London: Palgrave Macmillan), 319–340.

Geden, O. (2016). An actionable climate target. *Nat. Geosci.* 9, 340–342. doi: 10.1038/ngeo2699

Geden, O., and Schenuit, F. (2020). *Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy*. Berlin: Stiftung Wissenschaft und Politik. doi: 10.18449/2020RP08

Geels, F. W. (2014). Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. *Theory, Cult. Soc.* 31, 21–40. doi: 10.1177/0263276414531627

Green, F. (2018). Anti-fossil fuel norms. *Clim. Change.* 150, 103–116. doi: 10.1007/s10584-017-2134-6

Gunderson, R., Stuart, D., and Petersen, B. (2020). The fossil fuel industry's framing of carbon capture and storage: faith in innovation, value instrumentalization, and status quo maintenance. *J. Clean. Prod.* 252:119767. doi: 10.1016/j.jclepro.2019.119767

Hansson, A., and Bryngelsson, M. (2009). Expert opinions on carbon dioxide capture and storage—a framing of uncertainties and possibilities. *Energy Policy* 37, 2273–2282. doi: 10.1016/j.enpol.2009.02.018

Hastings, A., and Smith, P. (2020). Achieving net zero emissions requires the knowledge and skills of the oil and gas industry. *Front. Clim.* 2:601778. doi: 10.3389/fclim.2020.601778

IEA (2020). *World Energy Outlook 2020*. Paris: International Energy Agency.

IPCC (2018). *Global Warming of 1.5°C*. Geneva: World Meteorological Organization.

Janipour, Z., de Nooij, R., Scholten, P., Huijbregts, M. A. J., and de Coninck, H. (2020). What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production. *Energy Res. Soc. Sci.* 60:101320. doi: 10.1016/j.erss.2019.101320

Johnson, N., Krey, V., McCollum, D. L., Rao, S., Riahi, K., and Rogelj, J. (2015). Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants. *Technol. Forecast. Soc. Change* 90, 89–102. doi: 10.1016/j.techfore.2014.02.028

Keith, D. W., Parson, E., and Morgan, M. G. (2010). Research on global sun block needed now. *Nature* 463, 426–427. doi: 10.1038/463426a

Köberle, A. C. (2019). The value of BECCS in IAMs: a review. *Curr. Sustain. Energy Rep.* 6, 107–115. doi: 10.1007/s40518-019-00142-3

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G., and Klein, D. (2013). Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Clim. Change* 118, 45–57. doi: 10.1007/s10584-012-0681-4

Le Quéré, C., Peters, G. P., Friedlingstein, P., Andrew, R. M., Canadell, J. G., Davis, S. J., et al. (2021). Fossil CO_2 emissions in the post-COVID-19 era. *Nat. Clim. Chang.* 11, 197–199. doi: 10.1038/s41558-021-01001-0

Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., and Minx, J. C. (2018). Weigh the ethics of plans to mop up carbon dioxide. *Nature* 561, 303–305. doi: 10.1038/d41586-018-06695-5

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

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., et al. (2018). Residual fossil CO_2 emissions in 1.5–2°C pathways. *Nat. Clim. Chang.* 8, 626–633. doi: 10.1038/s41558-018-0198-6

Mabon, L., and Littlecott, C. (2016). Stakeholder and public perceptions of CO_2-EOR in the context of CCS—results from UK focus groups and implications for policy. *Int. J. Greenh. Gas Control.* 49, 128–137. doi: 10.1016/j.ijggc.2016.02.031

Markusson, N. (2012). Born again: the debate on lock-in and CCS. *Energy Environ.* 23, 389–394. doi: 10.1260/0958-305X.23.2-3.389

Markusson, N., Dahl Gjefsen, M., Stephens, J. C., and Tyfield, D. (2017). The political economy of technical fixes: the (mis)alignment of clean fossil and political regimes. *Energy Res. Soc. Sci.* 23, 1–10. doi: 10.1016/j.erss.2016.11.004

Markusson, N., and Haszeldine, S. (2010). "Capture ready" regulation of fossil fuel power plants—Betting the UK's carbon emissions on promises of future technology. *Energy Policy* 38, 6695–6702. doi: 10.1016/j.enpol.2010.06.039

Markusson, N., Mclaren, D., and Tyfield, D. (2018). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Glob. Sustain.* 1:e10. doi: 10.1017/sus.2018.10

McLaren, D. (2016). Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Fut.* 4, 596–602. doi: 10.1002/2016EF000445

McLaren, D., and Markusson, N. (2020). The co-evolution of technological promises, modelling, policies and climate change targets. *Nat. Clim. Chang.* 10, 392–397. doi: 10.1038/s41558-020-0740-1

McLaren, D., Tyfield, D., Willis, R., Szerszynski, B., and Markusson, N. (2019). Beyond "net-zero": a case for separate targets for emissions reduction and negative emissions. *Front. Clim.* 1:4. doi: 10.3389/fclim.2019.00004

Meadowcroft, J., and Langhelle, O. (2009). *Caching the Carbon: The Politics and policy of Carbon Capture and Storage*. Cheltenham: Edward Elgar Publishing.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Lenzi, D., et al. (2018). Negative emissions-Part 1: research landscape, ethics and synthesis. *Environ. Res. Lett.* 13:063001. doi: 10.1088/1748-9326/aabf9b

Moe, E., and Røttereng, J.-K. S. (2018). The post-carbon society: rethinking the international governance of negative emissions. *Energy Res. Soc. Sci.* 44, 199–208. doi: 10.1016/j.erss.2018.04.031

Mormann, F. (2020). Why the divestment movement is missing the mark. *Nat. Clim. Chang.* 10, 1067–1068. doi: 10.1038/s41558-020-00950-2

Morrow, D. R., Thompson, M. S., Anderson, A., Batres, M., Buck, H. J., Dooley, K., et al. (2020). Principles for thinking about carbon dioxide removal in just climate policy. *One Earth* 3, 150–153. doi: 10.1016/j.oneear.2020.07.015

Piggot, G., Erickson, P., van Asselt, H., and Lazarus, M. (2018). Swimming upstream: addressing fossil fuel supply under the UNFCCC. *Clim. Policy* 18, 1189–1202. doi: 10.1080/14693062.2018.1494535

Piggot, G., Verkuijl, C., van Asselt, H., and Lazarus, M. (2020). Curbing fossil fuel supply to achieve climate goals. *Clim. Policy* 20, 881–887. doi: 10.1080/14693062.2020.1804315

Pollak, M., Phillips, S. J., and Vajjhala, S. (2011). Carbon capture and storage policy in the United States: a new coalition endeavors to change existing policy. *Glob. Environ. Chang.* 21, 313–323. doi: 10.1016/j.gloenvcha.2011.01.009

Reiner, D. M. (2016). Learning through a portfolio of carbon capture and storage demonstration projects. *Nat. Energy* 1:15011. doi: 10.1038/nenergy.2015.11

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., and Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science* 355, 1269–1271. doi: 10.1126/science.aah3443

Rosenbloom, D., and Rinscheid, A. (2020). Deliberate decline: an emerging frontier for the study and practice of decarbonization. *Wiley Interdiscip. Rev. Clim. Chang.* 11:e669. doi: 10.1002/wcc.669

Seto, K. C., Davis, S. J., Mitchell, R., Stokes, E. C., Unruh, G., and Ürge-Vorsatz, D. (2016). Carbon lock-in: types, causes, and policy Implications. *Annu. Rev. Environ. Resour.* 41, 425–452. doi: 10.1146/annurev-environ-110615-085934

Seymour, F. (2020). Seeing the forests as well as the (trillion) trees in corporate climate strategies. *One Earth* 2, 390–393. doi: 10.1016/j.oneear.2020.05.006

Shackley, S., and Thompson, M. (2012). Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? *Clim. Change* 110, 101–121. doi: 10.1007/s10584-011-0071-3

Smith, S. M. (2021). A case for transparent net-zero carbon targets. *Commun. Earth Environ.* 2:24. doi: 10.1038/s43247-021-00095-w

Stephens, J. C. (2014). Time to stop investing in carbon capture and storage and reduce government subsidies of fossil-fuels. *Wiley Interdiscip. Rev. Clim. Chang.* 5, 169–173. doi: 10.1002/wcc.266

Supran, G., and Oreskes, N. (2017). Assessing ExxonMobil's climate change communications (1977–2014). *Environ. Res. Lett.* 12:084019. doi: 10.1088/1748-9326/aa815f

Tjernshaugen, A. (2012). Technological power as a strategic dilemma: CO_2 capture and storage in the international oil and gas industry. *Glob. Environ. Polit.* 12, 8–29. doi: 10.1162/GLEP_a_00095

Tjernshaugen, A., and Langhelle, O. (2009). "Technology as political glue: CCS in Norway," in *Caching the Carbon. The Politics and Policy of Carbon Capture and Storage*, eds J. Meadowcroft and O. Langhelle (Cheltenham: Edward Elgar Publishing), 98–124.

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., et al. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target. *Nature* 572, 373–377. doi: 10.1038/s41586-019-1364-3

Trencher, G., Rinscheid, A., Duygan, M., Truong, N., and Asuka, J. (2020). Revisiting carbon lock-in in energy systems: explaining the perpetuation of coal power in Japan. *Energy Res. Soc. Sci.* 69:01770. doi: 10.1016/j.erss.2020.101770

Turnheim, B., and Sovacool, B. K. (2020). Forever stuck in old ways? Pluralising incumbencies in sustainability transitions. *Environ. Innov. Soc. Trans.* 35, 180–184. doi: 10.1016/j.eist.2019.10.012

UNEP (2019). *Emissions Gap Report 2019*. Nairobi: United Nations Environment Programme.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy* 28, 817–830. doi: 10.1016/S0301-4215(00)00070-7

Unruh, G. C. (2002). Escaping carbon lock-in. *Energy Policy* 30, 317–325. doi: 10.1016/S0301-4215(01)00098-2

Unruh, G. C., and Carrillo-Hermosilla, J. (2006). Globalizing carbon lock-in. *Energy Policy* 34, 1185–1197. doi: 10.1016/j.enpol.2004.10.013

Ürge-Vorsatz, D., Rosenzweig, C., Dawson, R. J., Sanchez Rodriguez, R., Bai, X., Barau, A. S., et al. (2018). Locking in positive climate responses in cities. *Nat. Clim. Chang.* 8, 174–177. doi: 10.1038/s41558-018-0100-6

Vergragt, P. J., Markusson, N., and Karlsson, H. (2011). Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in. *Glob. Environ. Chang.* 21, 282–292. doi: 10.1016/j.gloenvcha.2011.01.020

Wagner, J. L. (1992). Orphan technologies: defining the issues. *Int. J. Technol. Assess. Health Care* 8, 561–565. doi: 10.1017/S0266462300002269

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