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Rethinking Net-Zero systems, spaces, and societies: “Hard” versus “soft” alternatives for nature-based and engineered carbon removal

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ABSTRACT

Carbon removal – also known as negative emissions technologies, or greenhouse gas removal – represents a core pillar of post-Paris climate policy, signaling for enhancing and constructing carbon sinks to balance emissions sources on route to ambitious temperature targets. We build on Amory Lovins’ “hard” and “soft” alternatives for energy pathways to illuminate how foundational experts, technologists, and policy entrepreneurs think about different modes of resource inputs, infrastructure and livelihoods, and decision-making, regarding ten nature-based and engineered carbon removal approaches. Based on 90 original interviews, we show that hard and soft paths reflect different conceptions of systems, spaces, and societal involvement. We highlight that pathways depend on diverging concepts of economies-of-scale (capturing carbon at the largest possible scale, versus catalyzing systemic co-benefits) and carbon management (a waste product within conventional climate governance, versus diverse end-uses and values to be diversely governed). Our analysis further emphasizes two key uncertainties: whether renewables can be upscaled to allow synergies rather than tradeoffs between carbon removal and more widespread energy demands, and whether carbon certification can expand spatially to navigate long supply chains, and conceptually to incentivize diverse co-benefits. Experts remain motivated by antecedent concerns over land-use management and extractive industries, and that exploitative systems will – without guardrails – be replicated by inertia.

1. Introduction

Carbon removal – also known as negative emissions technologies – represents an emerging pillar of post-Paris climate policy for enhancing and constructing carbon sinks to balance emissions sources on route to ambitious temperature targets. A variety of approaches, scales of rollout, innovation and policy incentivization templates, and thematic concerns have been proposed by expert networks across multiple sectors. Alongside academic scoping (Minx et al., 2018), R&D based at industries and start-ups has escalated (Bourzac, 2017; Boettcher et al., 2021; Nemet et al., 2018). Feasibility, risk, and life cycle assessments (Clery et al., 2021; Forster et al., 2020; Terlouw et al., 2021; Kreuter and Lederer, 2022) as well as calls for policy frameworks are proliferating (Honegger and Reiner, 2017; Cox and Edwards, 2019; Schenuit et al., 2021; Mohan et al., 2021), as Net Zero (or carbon neutrality) commitments ripple through states and companies in the global North (Rogelj et al., 2021; IEA, 2021). Fig. 1 underscores just how significant carbon removal technologies are expected to become by mid-century.

In this paper, we show that Amory Lovins’ *“hard” and “soft” alternatives* (1976, 1979) richly illuminate how 90 key experts, innovators, and policy entrepreneurs are thinking about nature-based and engineered carbon removal approaches at a foundational stage in their collective development. To spur new thinking about American energy strategy in the face of the, 1970s fuel crises, Lovins distinguished two archetypes for future energy systems: an incumbent ‘hard’ pathway that would seek energy security by hugely expanding and entrenching dependence on fossil fuels and nuclear, set against a novel ‘soft’ pathway that would prioritize energy efficiency, renewables, and bridging fuels fit to a diverse range of societal uses (Ibid.).

Decades on, these pathways remain relevant for mapping spaces and societal involvement surrounding emerging carbon removal systems. Forms of carbon capture and storage particularly leverage the entrenched fossil fuel infrastructures Lovins sought to erode, as well as the much-strengthened (and ‘hardened’) renewable sector that he

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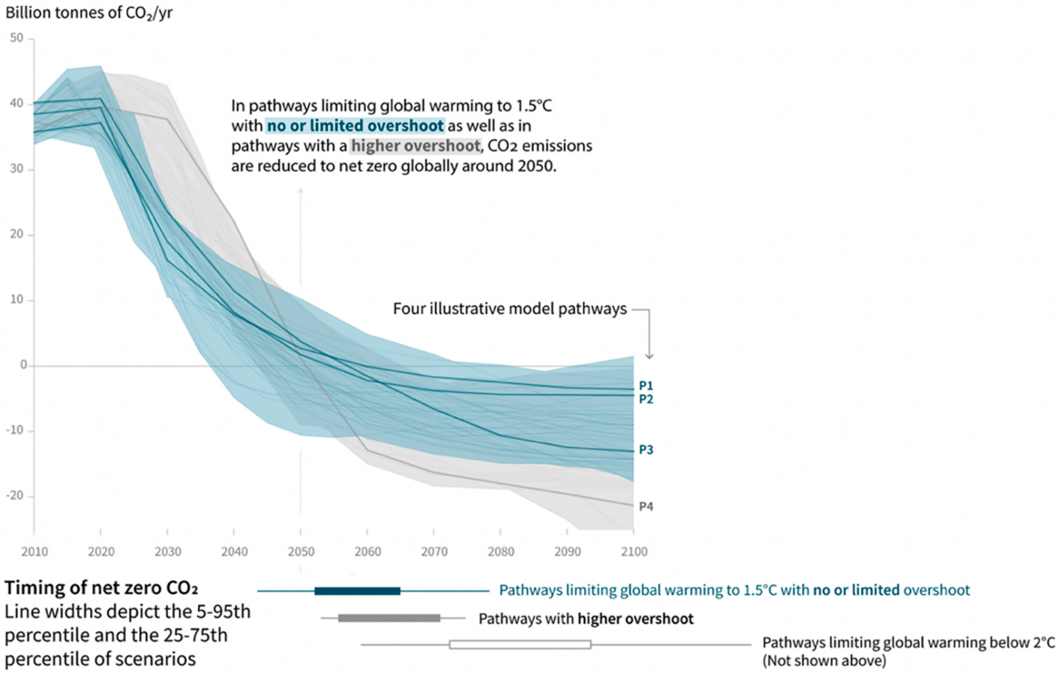

Fig. 1. Global total net CO2 emissions. Source: IPCC 2018, modified from Figure SPM3a.

wanted to galvanize (Creutzig et al., 2019). More importantly, his pathways juxtapose key rationalizations and practices through which carbon removal approaches can be assessed, scaled, and governed. Indeed, beyond spurring the fierce debate within energy policy and scholarship (Yulish, 1977, Daly, 1979; Nash, 1979, Morrison and Lodwick, 1981) that still informs study of the sector today (Burke and Stephens, 2018), Lovins' pathways have been similarly adapted to contrast modes of governance in fields as diverse as food systems (Ramankutty and Dowtalabadi, 2021), water (Brooks, 2005), and adaptation (Sovacool, 2011). Our focus is on carbon removal's current knowledge economy: the academic experts, policy entrepreneurs, and technologists making the case for – and against – different visions of rollout and upscaling. Sovacool (2011, p. 1178) highlights that Lovins intended to illustrate "less [about] the technologies involved, and more about the way that policymakers, planners, and system builders think."

Section 2 lays out our research design, where we provide adapted definitions of hard and soft paths that better correspond to the context of carbon removal and describe our interview protocol. Sections 3 and 4 map these expert perspectives into four pathways that cross Lovins' hard and soft paths with two macro-suites of *nature-based* (3.1, 3.2) and *engineered* approaches (4.1, 4.2). We take care to point out where carbon removal approaches straddle these categories – but in broad strokes, the characteristics of nature-based and engineered approaches have distinct implications for the hard and soft alternatives. Section 5 discusses the key concepts and uncertainties on which hard and soft paths most clearly diverge (5.1), explores the room for carbon removal to manoeuvre between hard and soft paths (5.2), and near term policy (5.3).

To our knowledge, this study brings to bear a combination of the largest expert interviewee pool, spectrum of approaches, and topical range of questions on how carbon removal could – or should – develop. Our goal is firstly to draw together a rapidly evolving literature through the proxy of a qualitative, large-N elicitation with key experts, technologists, and policy actors; secondly, by adapting Lovins' energy pathways, to construct alternative, diverging landscapes for the energy needs and carbon products, built and social infrastructure, and governance of nature-based and engineered approaches.

2. Research design and conceptual approach

A common way to parse carbon dioxide removal efforts has been along a *nature-based* to *engineering* spectrum. Nature-based approaches describe biological, ecosystem-based sinks with a relative focus on spatial and livelihood trade-offs in the age-old use of terrestrial and marine environments. Engineered approaches are technological or chemical in nature, with a relatively stronger reliance on antecedent systems of resource extraction, carbon capture and storage (CCS) as well as transportation infrastructures. Our corpus and scope of technologies includes both archetypes, as well as approaches that combine characteristics of nature-based and engineered approaches, which we label these as hybrid approaches (Annex 1) (Fig. 2).

2.1. *Interview protocol*

We engaged a multi-disciplinary group of 90 prominent academics and technologists (Annex 2) embodying a wide range of disciplinary backgrounds, topical expertises, and both critical and supportive perspectives, backed by peer-reviewed publications or patents between 2011 and 2020.

We relied on semi-structured interviews (O'Sullivan, Rassel and Berner, 2010), for several reasons. We see a large-N elicitation of expert views as a reasonable proxy for a systematic literature review in an evolving and rapidly growing debate. Indeed, the most highly-cited literature review in carbon removal – a trilogy involving dozens of authors (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018) – does not exhaust the available literature or the fullest range of approaches, while largely focusing on techno-economic elements. We wished to capture a timely update of emerging topics in academic, innovation, and policy circles that may not exist in published research, and to allow unvarnished perspectives which may be edited out in peer review. Finally, we wanted to juxtapose points of view and encourage conversations that highlighted alternatives or syntheses. This was ultimately valuable for the structuring of data into comparative pathways, finding overlaps between them, and developing richer source of data on carbon removal.

We engaged our experts with seven questions sets, with room to pursue unexpected lines of inquiry (Table 1). The question sets were

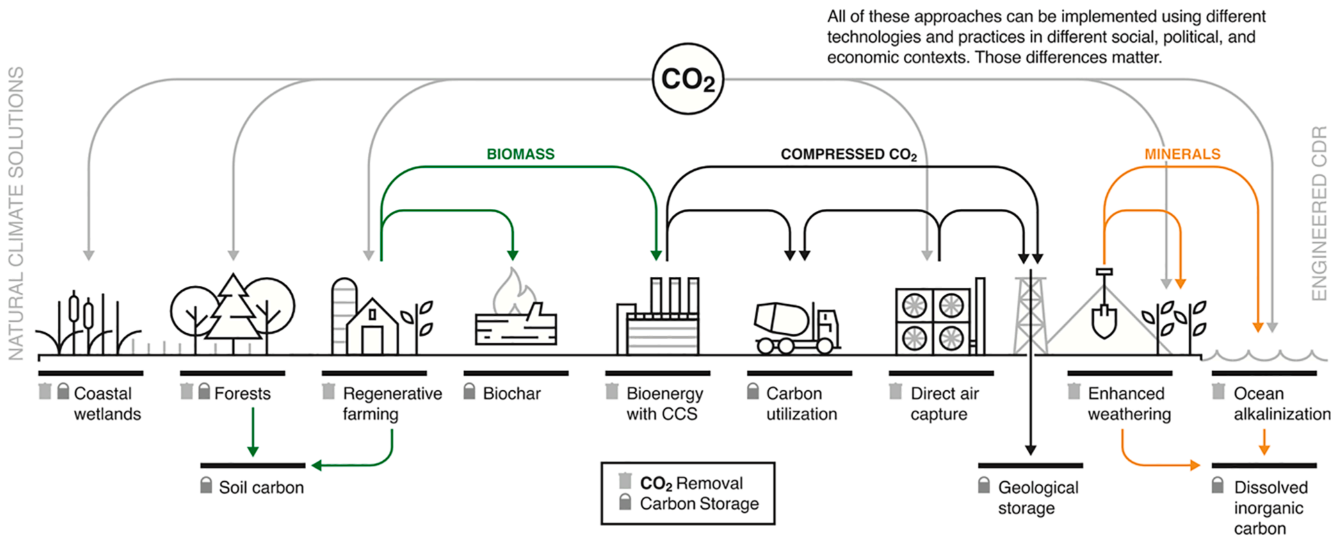
All of these approaches can be implemented using different technologies and practices in different social, political, and economic contexts. Those differences matter.

Fig. 2. A spectrum of nature-based and engineered carbon removal approaches. Source: Morrow et al., 2020, figure by Matt Twombly. See also Annex 2 for a textual description of approaches.

chosen to reflect a wide range of themes – from technical, assessment, or policy innovation (1–3), to prospective couplings with different sectors and systems (2–3), to risks and governance (4–7), to dimensions of justice and sustainability (5 and 6).

We clarified with interviewees that they could decide whether to speak to any or all of: (a) a specific carbon removal approach, (b) a grouping, (c) or a collective, emerging strategy for creating and enhancing carbon sinks. This produced a spectrum of approach-specific and landscaping data, balanced between leveraging the interests and expertises of our interviewees and making emergent inquiries.

In reporting our data, we adapt an ethnographic approach, using both aggregate statements and illustrative quotes. To organize our data, we used NVIVO (a commonly used software for managing qualitative data) to conduct a tripartite mapping: by carbon removal approach, by the themes embodied by the seven question sets in Table 1, and by a host of tailored sub-themes that were constantly evolving and reiterated within the author team. We then used NVIVO, with data thus categorized, to source quotes speaking to – and helping to further nuance and detail – Lovins' hard and soft paths as applied to carbon removal (Section 2.2, following). For attributing quotes, we use a system of partial anonymity, to strike a balance between permitting honesty over sensitive emerging issues and allowing the reader to gauge the credibility of the experts. Experts are referred to in-text only by a respondent number (e.g. R65 for Respondent 65 out of 90) that does not match the order in the list.

Table 1
Interview question sets.

1. Innovation	Which particular options have high or low innovation potential in technical, communication, societal appraisal, and policy dimensions?
2. Coupling	What energy systems or other sociotechnical systems could or should be coupled to carbon removal?
3. Business models	What business models and markets could carbon removal create or disrupt?
4. Risks	Which serious risks (e.g., social, political, military, ethical, environmental) may arise?
5. Sustainability	What are the synergies and trade-offs of deployment for the Sustainable Development Goals and other societal objectives?
6. Justice	What vulnerable groups could be affected, positively or negatively?
7. Actors	Who are the relevant (or most important) actors (or stakeholders / networks), e.g. for commercialization, development, and/or acceptability?

Source: Authors.

2.2. Adapting Lovins' pathways to carbon removal

Sovacool (2011) distils Lovins' hard and soft energy paths (e.g. Lovins, 1976; 1979) into the following elements (Table 2).

We adapted Lovins' hard and soft definitions to carbon removal across three components –broadly stated to be generalizable across technically distinct approaches (Table 3, below), and streamlined from the framework of lifecycle stages or spatial scales used in Brock et al.'s (2021) and Sovacool's (2021)'s political ecology mappings of solar energy and low-carbon transitions respectively. The first describes *resources*: energy inputs (fossil fuels, renewables, bioenergy), other resource inputs (minerals, chemicals, fertilizers, water), and outputs (second-life carbon products, or carbon-as-waste). The second is *infrastructure, livelihood, and ownership*: dimensions of siting, manufacturing or growing, operation, transportation, storage, and carbon disposal or use. If 'resources' are about inputs and outputs, this component describes the built and societal infrastructure that surrounds carbon removal development. The third is *decision-making*: homing in on governance, planning and policy, especially vis-a-vis strategies and terms of reference in global climate governance.

Hard pathways for nature-based and engineered approaches focus on maintaining the prevailing market-driven mode of climate governance, i.e., sinking or storing carbon as a top priority, as well as maximizing the scale of carbon capture. Resource usage is high and part of conventional extractive industry. Energy inputs may be based on fossil fuels – but as Lovins (1976, 1979) points out, even renewable energy designed to prioritize scale over diversity of end-use would be part of a hard path. Infrastructure, livelihoods, and ownership can be described as industrial-scale, industry-facing, centralized, uniform, top-down, and aggregate. Decision-making focuses on the ease, calculability of large-scale carbon capture in monitoring, reporting and verification (MRV), and a more status quo approach to finance and technology transfer under the Common But Differentiated Responsibilities (CBDR) principle of the climate regime.

By contrast, *soft pathways* focus relatively more heavily on being plural in orientation, pursuing systemic, multi-dimensional versions of sustainability, and attaining local co-benefits. Regarding the latter, they may prioritize community well-being, or local resilience and other policy goals as a result, rather than envisioning climate protection as the sole aim. Key resource inputs and outputs are planned towards

Table 2
Lovins' hard and soft energy paths.

A hard energy path	A soft energy path
• depends on non-renewable resources such as coal, uranium, oil and natural gas, • is poorly matched in scale and quality to energy end-uses, • is complex and cannot be understood by any single person, • lacks resilience, so failures affect the entire system, and • has proven incapable of adapting to sudden changes in energy demand.	• depends on diverse and distributed resources, providing energy in smaller quantities, from decentralized sources, • is renewable, operating on non-depletable fuels, • utilizes modular and simpler technologies, well matched to the technological capabilities of communities • modular, or matched in scale to energy needs, and • qualitative, or matched in energy quality to end-use needs.

Source: Modified from Sovacool, 2011.

renewable energy systems and developmental co-benefits. Infrastructure, livelihoods, ownership is described as small-scale, smallholder-facing, distributed, plural, situated, and bottom-up. Decision-making aims to cope with the messy distribution of co-benefits in MRV, and at attaining greater equity through CBDR.

In the following Sections 3 and 4, we lay out our pathways, beginning with hard and soft nature-based paths, followed by the engineered paths, foregrounded in Table 4 (below). It breaks down our interview data in relation to the questions asked and across two different archetypes of carbon removal: nature-based and engineered. As Table 4 summarizes, each of these archetypes lend themselves to 'hard' or 'soft' pathways, resulting in a matrix of four distinct options (shaded in Table 4): the nature-based pathways of *Big Nature* (Section 3.1) and *Small Nature* (3.2), alongside the engineered pathways of *Industrial Capture* (4.1) and *Distributed Capture* (4.2). We incorporated discussion of hybrid approaches (that combine characteristics of nature-based and engineered approaches) into nature-based and engineered pathways, wherever they overlapped in the three components of *resources*; *infrastructure, livelihoods, and ownership*; and *decision-making.*

3. Results: pathways of nature-based carbon removal

Following Osaka et al (2021), we warn against treating 'naturalness' as a fig-leaf for environmental and social harms. We use the term 'nature-based' as purely definitional: approaches that leverage terrestrial and marine ecosystems as sinks. This includes land-use practices grouped under forestry management (avoided deforestation, afforestation, reforestation), and agricultural management (biochar, soil sequestration), overlapping with ecosystems restoration. Carbon-removal objectives are also expanding into ecosystems-management and aquaculture practices in marine spaces (blue carbon, marine biomass). Issues surrounding terrestrial carbon removal can be transposed onto well-documented North-South and urban–rural conflicts between the agriculture and forestry sectors, as well as the maintenance of ecosystem services (Dooley and Kartha, 2018; Ericksen, 2008; Gerber, 2011). These logics are newly transported to coastal and international ocean waters – where human usage and legal regulation is similarly heavy and contested, but whose implications for carbon removal are only now the subject of preliminary inquiry (Boettcher et al., 2021).

Trade-offs in the use of physical space for subsistence are key to the development of nature-based hard and soft paths – between energy (food crop, next-generation biomass, or marine biomass), agriculture (and aquaculture), and storage (maintaining forest or coastal carbon stocks, with possible benefits for biodiversity and ecosystems services). This calculus is exacerbated by two conditions. Space used for direct subsistence is a key nexus of hunger, poverty (alleviation), and local economic development for hundreds of millions. Ownership and user rights in these spaces, moreover, is subject to entrenched power dynamics, with smallholders and indigenous communities historically at odds with monoculture agriculture and forestry, along with carbon-crediting projects.

3.1. Big nature – hard pathways

3.1.1. Resources

Experts pointed out that multitudinous agriculture, aquaculture, forestry, and ecosystems management practices are technically mature responses in the near-term to the Paris Agreement's demands for carbon sinks. The question is whether natural sinks contain sufficient scale (R49, R80). IPCC mitigation modeling pathways in the Fifth Assessment Report (AR5) or the Special Report on 1.5C oversold the potential scale while understating the ecosystems implications of biomass growth (for bioenergy CCS) and afforestation and reforestation (R69, R85) – even if these are a "*placeholder [as] something modellable*" (R47) for more diverse incoming approaches (R64). Nevertheless, the implied scale demands tremendous, even illusory resource inputs. R7 makes a representative argument:

> *There are land-use issues and food-security risks, water-use and fertilizer-use risks to do with switching to bioenergy CCS on the scale that is imagined or modelled… Huge areas of land would be needed – bioenergy plantations; forested land has to be cleared into fast-growing monocultures, such as fibrous grass; huge areas taken away from food.*

Marine biomass (e.g. kelp forests) as an input to bioenergy CCS is also speculative (R44, R45, R54). And at particular scales – for example, in the plans of Running Tide, an innovation-oriented initiative – it poses a massive infrastructure challenge. R9 notes that "*100 million of these buoys out in the ocean*" would have *"impacts in terms of maritime transportation lanes, invasive species, and so forth.*" R86 adds, regarding large scale ocean alkalinization: "*if we were to try and raise the alkalinity of a*

Table 3
Conceptualizing hard and soft paths for energy and carbon engineering technologies.

Lovins' definitions	**Hard**: Non-renewable, supply driven, poorly matched to end-use, complex, not resilient, unadaptable	**Soft**: Renewable, demand driven, matched to diverse end-uses, simple, modular, adaptable
Adaptation to carbon removal in a life cycle assessment		
Resources	Fossil (bridging options), high resource inputs, carbon as stored waste	Renewables, resource inputs and outputs integrated into local economic and developmental co-benefits
Infrastructure, livelihoods, and ownership	Industrial-scale, industry-facing, centralized, uniform, top-down, representative, aggregate	Small-scale, smallholder- and local concern- facing, distributed, plural/situated, bottom-up, deliberative, plural
Decision-making	Market-driven climate governance; Planetary scale of carbon capture; Carbon calculability (MRV), Status quo CBDR	Plural, systemic sustainability; Local co-benefits; Co-benefits distribution (MRV), Equity CBDR

Source: Authors, adapted from Lovins, 1976; Lovins, 1979, Sovacool, 2011, and expert interview data (N = 90).

Table 4
Summarizing carbon removal pathways.

	Hard	**Soft**
Nature-based carbon removal	**Section 3.1**	**Section 3.2**
(e.g., afforestation and reforestation, biochar, soil sequestration, blue carbon and seagrass, ecosystem restoration)	*Big Nature* (food crops, biomass, macro-forestry)	*Small Nature* (biochar, eco-restoration, blue carbon, agro-forestry, next-gen biomass and kelp)
Hybrid carbon removal	Incorporated across 3.1 or 4.1	Incorporated across 3.2 or 4.2
(e.g., enhanced weathering, ocean alkalinization, bioenergy carbon capture and storage)	e.g. Split in bioenergy (3.1) and carbon capture and storage (4.1) components; Split in enhanced weathering between land-use (3.1) and mining connections (4.1)	e.g. Split in bioenergy (3.2) and carbon capture and storage (4.2) components; Split in enhanced weathering between land-use (3.2) and mining connections (4.2)
Engineered carbon removal	**Section 4.1**	**Section 4.2**
(e.g., carbon capture and storage / utilization, direct air capture and storage)	*Industrial capture* (industrial direct air capture and storage, bioenergy carbon capture and storage)	*Distributed capture* (flue-gas carbon capture and storage, carbon utilization, modular, direct air capture and storage)

Source: Authors, based on expert interview data (N = 90) as well as authors' personal knowledge.

global ocean, we'd need the entire world shipping fleet [and] a mining industry that's probably as big as the rest of the mining industry, almost, as exists today."

Biochar and enhanced weathering might reduce reliance on the large-scale use of manufactured fertilizers as an input to agricultural activity (R22, R49) – but could lean equally into facilitating biomass growth for large-scale monocultures. R62 notes:

> *The reason why you might do enhanced rock weathering is you do it on agricultural land… if you can get crops growing better as well as create carbon sequestration. [But] then you think about the great Midwest in the US or in Brazil … or in the palm oil plantations in Southeast Asia and sugar cane in Australia … The argument is always that bioenergy crops will compete with food production.*

3.1.2. Infrastructure, livelihood, and ownership

Experts drew attention to mostly negative precedents of North-South land-use conflicts in climate, biodiversity, and food systems governance, as well as newly emerging practices in the context of post-Paris carbon removal. The value of fast-growing monoculture afforestation or reforestation is reluctantly noted for its advantages for rapid scaling (R88). However, large-scale landscape alteration "*can lead to changes in precipitation patterns*" (R70) or create "*ecological deserts*" (R40), surrendering co-benefits for biodiversity and ecosystems services, flood mitigation, and soil health presented by indigenous flora and carbon stocks (R88). Monocultures would also be more vulnerable to climate impacts (such as wildfires) or pests, increasing the risk of leakage and eroding confidence in storage permanence (R88). Nor is potential repurposing of "*marginal*" land or "*non-fertile*" soil edifying, as "*these may contain specialized and rarer ecosystems"* (R77) or reinforce *"the bias that only populated land is valuable*" (R99).

Monoculture-style biomass growth or afforestation might take place on land primarily used for food production, eroding the key means of sustenance and poverty alleviation for smallholder economies, replacing older, more diverse, and resilient farming practices (R15, R23). Experts recalled global and regional food crises that were partially driven by widespread turns towards cultivation of biofuel cash crops (R22, R77). The greatest critique was reserved for a long, indicative history of land- (or coast-) grabbing and dispossession of marginalized populations – typically smallholders (farmers and fishermen) and indigenous communities (R7, R10, R15, R17, R23, R44, R49, R51, R56, R66, R69, R74, R84, R88). Such activities are often hidden within market signals and incentives for smallholders to take on new crops and cultivation techniques, or to relinquish their land, which are usually highly inequitable and offer little alternative choice or avenues for legitimate opposition.

Often, there is a race-to-the-bottom when it comes to laws protecting land tenure and environmental standards for offsets (R7). Populations become dependent on economies reliant upon single commodity production in a 'Dutch disease' situation and subject to precarious food or carbon pricing in global markets (R83), or on production of carbon-removal credits as a "*phantom commodity*" (R10). Revenue arguably transferred between urban and rural economies, or between the North and South, as part of land purchases (R51) or financing and crediting (R84) tends to be captured by elites rather than shared equitably. R84 argues:

> *Carbon farming … could potentially bring an extra financial stream to rural areas that need it. But I fear that when we look beyond Europe at, for instance, how the Clean Development Mechanism and afforestation and reforestation under REDD+ has worked, there have been massive social consequences. They've been easy to ignore by the countries and companies that have been buying the credits, because they're not responsible for the issuing of the credits and how they are created. But they can use those credits and claim to be environmentally friendly …*

3.1.3. Decision-making

A key antecedent is the difficult MRV and carbon accounting first posed by the Kyoto Protocol's land use, land use change, and forestry track (LULUCF), incorporated with agriculture, forestry and other land use (AFOLU), and rolling over into REDD+: the financing and crediting mechanism by which developing countries are compensated for avoiding deforestation (R80). Historically, the forestry sector has been favored by companies through voluntary carbon markets for offsets that are easy to generate, have MRV processes that maximize credits, and is subject to carbon leakage through pests, fire, and erosion (R15, R23, R87, R88). If allowed to provide vast amounts of cheap offsets, large-scale land-sector carbon removal creates excessive flexibility in meeting emissions targets, delaying decarbonization and permitting greenwashing (R15, R23, R29, R56, R69, R84, R87). High-emissions economies in the Paris era, or the fossil fuel (R55), heavy industry (R4), and aviation sectors (R24), may continue to seize opportunities for such "*creative accounting*" (R15). R15 echoes calls for a "*barrier between fossil and biogenic carbon removal and avoidance"*, and to "*only do CDR that is land based and impermanent, to compensate for emissions that come from that sector. And that if you want to find ways to compensate for residual emissions that come from fossil fuels, then you will need to look at a much more permanent form of CDR."*

Countries with sizable forestry sectors are taking a keen interest in providing biomass inputs to bioenergy CCS – Sweden (R15, R31) and the US (R12), with some speculating about interests of Northern countries vis-a-vis forested developing nations in the tropics for harvesting biomass (R44). Some urge for differentiation between types of carbon stocks – while "*it would be crazy to clear a 3,000-year-old redwood, [in certain countries] we have no such old trees. They're all managed. We need a reasonable discussion about when to clear which forest … and how you use the wood [in light of] carbon fluxes*" (R61). But others highlight the need for guardrails against the demand for large-scale carbon removal altering existing landscapes, especially in a globalized context. R55 notes:

> *… systems for other resources have been set up and optimised in the absence of a carbon removal demand [are] going to be reconfigured. Just look at Drax [a British biomass power station] and the 3,500-mile supply chain for their wood pellets that… through their business lenses, they can say, 'Yes, makes sense for us to import by ship from southeastern USA' … and that then locks in a particular form of forestry over the decades.*

The global aspect of a carbon-removal economy touches upon CBDR in funding and capacity building – the same issues historically raised by other land and forestry governance mechanisms at the UNFCCC. R69 argues that*"many of the large carbon dioxide removal potential often is in tropical countries, which, arguably, should not be the ones paying for carbon-dioxide removal for emissions they have not caused."* Moreover, governance dimensions extend beyond the climate regime. The prospect of upscaled, monoculture forestry intersects with the biodiversity regime in terms of the erosion of traditional livelihoods based on ecosystem services, and with large-scale biomass in raising concerns on food security.

3.2. Small nature – soft pathways

3.2.1. Resources

Soft paths, in contrast, envision "*nature-based solutions that have also a net biodiversity gain*" (R35). These might firstly alter ecosystems' resource inputs. In agricultural management, next-generation approaches to biomass energy that rely on crop residues or algae, could reduce dependence on food crops (R10, R22). Another avenue might expand biomass growth in marine areas – with a care to avoid the same dynamics of coast-grabbing as feature in the hard paths (R9, R44, R45, R54). Biochar (R22, R37) and enhanced weathering (R49, R62) both offer opportunities to reduce reliance on chemically intensive fertilizers. Actors here could even be households (storing carbon in their backyards or lawns) or apartment complexes (storing carbon on rooftop gardens).

In forestry management, IPCC pathways have treated afforestation and reforestation as key means through which new carbon stocks are (re)created (IPCC, 2014, IPCC, 2018). Experts highlight that treating this related but distinct pair of approaches without nuance, and primarily relying on monoculture plantations, follows hard paths (R15, R23, R77). R77 argues for forestry management to prioritize the preservation of standing ecosystems, and then to only pursue afforestation and reforestation that reflects diverse ecosystems services:

> *A first priority must, of course, be protecting natural forest where it still exists. The second would be reforestation where that is possible and appropriate … and where a competition for land is, then it would not be full reforestation, but a shift from plain-field agriculture to agroforestry. Afforestation is a double-edged sword. If … you would plant [grasslands today] all with trees and forests, you would never have any kind of compensation for that loss of biodiversity.*

R23 highlights an opportunity for renewed thinking on landscapes as more than carbon sinks, and more for its intrinsic and developmental value: "*I guess what has shifted a bit with the focus from REDD+ to carbon removal, is more conversation about ecosystem restoration.*".

3.2.2. Infrastructure, livelihood, and ownership

For soft paths of agricultural management, the co-benefits to local, rural development are key, rather than the scale of carbon capture. Such efforts would leverage relationships to organic, small-scale, polyface farming. The focus here is less on maximizing yield, and more on intercropping and other approaches to regenerate and maintain the health of soils; without the heavy use of fertilizers, and with the aid of biochar, enhanced weathering, and soil-sequestration amendments (R22, R40, R80). Indeed, some see an opportunity for a "*long thin tail*" of bespoke applications to "*transform agriculture and also suck up CO_2*" (R90). R77 argues that small-scale land-use management also offers a solution for the sources of emissions in the developing world:

> *… old, high-industrialised countries have a strong dominance of CO2, and mostly from the energy, transport and similar sectors. But [if developing] countries would really focus on methane reduction, be it from waste heaps, cattle or rice agriculture, that would be a significant contribution to the global effort.*

In forestry and ecosystems management, many argued for a renewed focus on avoided deforestation: the preservation of existing carbon stocks, with co-benefits for the rural (often indigenous) communities in developing countries that serve as their primary stewards and users (R15, R23, R55, R77). R23 notes:

> *[The] leading cause of deforestation now is industrial agriculture … You really need to go back to land management and land ownership in order to protect lands. In some cases that could be formal protected areas, conservation status; in many, many cases it's likely to be securing or recognising customary land rights. Often, it's a mix of the two, where protected areas are increasingly actually managed by indigenous or customary people.*

Special care must be paid to the trade-off posed by using land anew for carbon storage and that land's prior uses and value to local development. To minimize such a trade-off, R88 argues that monoculture forestry must give way to diverse, locally tailored ecosystems:

> *If … you wanted to get loads of carbon taken out of the atmosphere: spruce monoculture, boom. Fastest-growing, do it, right? But it's not providing any of those potential other co-benefits that might actually bring society on board and might meet some of the other societal objectives around biodiversity, resilience, flood mitigation.*

R58 argues for *"soil carbon sequestration or agroforestry"* as examples of *"co-location"* between small-scale forestry and agriculture.

This logic is carried over from terrestrial ecosystems management into marine areas through 'blue carbon': the protection of mangroves and other coastal systems that poses some carbon storage, as well as benefits for aquaculture, flood resilience, and age-old socioeconomic systems that are only recently being incorporated into carbon removal (R10, R44, R54, R76). For R76, straightforward carbon capture is secondary:

> *Blue carbon, with poverty and hunger, has an overall positive feedback … because restocking the mangroves improves the local situation… We do need to introduce a system where even though blue carbon's overall effect on carbon sequestration might be miniscule, through that process you would reduce emissions [in more diffuse ways].*

3.2.3. Decision-making

MRV issues endemic for nature-based approaches are exacerbated in soft pathways, given the diversity of approaches, scales, ecosystems, and derived benefits. R29 fears "*a deception risk*", where "*getting CO_2 safely and permanently out of the way [is] already hidden behind a co-benefits agenda…*". Moreover, a move towards protecting existing carbon stocks through 'avoided deforestation' presents fresh difficulties with calculating the additionality of emissions reductions. R80 points out:

> *… we claim carbon credits associated with protecting this forest, when there were no real credible threats to the forest in the first place, So, there is the risk of gaming the system with REDD+, and with peatland protection [by] establishing an unrealistic counterfactual or baseline.*

R23 adds that perverse incentives to count avoided emissions twice, for the issuer as well as for the recipient of the credit, stem from North-South inequities: "*it goes back to climate finance, in terms of countries that feel there is an obligation in the UNFCCC for developing countries to receive climate finance – and so when the only way that is offered is via Article 6 [offsets and trading], then you get into double-counting issues.*".

Others make a virtue of these difficulties, casting carbon calculability – the "*primary innovation need [of] measurement, quantification, and especially ways to do it in a cost-effective way*" – as secondary to " *like reforestation, ecosystem restoration, because of their other benefits*" (R58). Experts call for innovative mechanisms for such efforts in agriculture and forestry. R88 cites the UK's *"shift to Environmental Land Management payment systems that pay for the public good*" as an example of changing "*how land is valued, how ecosystems services are valued, and how that translates to land policy*". R87 points out that high-standard, forest-carbon credits necessitates better forest monitoring and governance as a preceding condition.

Many therefore see soft nature-based paths as a means to prioritize protection of existing ecosystems, recreate lost ones, and engage in new, even combined modes of agricultural, aquaculture, and forestry management. A focus is placed on multi-purpose use of space with emergent, systemic co-benefits, rather than narrower framings set within carbon-crediting or global temperature management. R46 argues:

> *The amount of carbon management we need to do, in term so of carbon drawdown, could be met by simply reinvesting in healthy tropical forests, ocean systems, wetlands. If we can … repair ecological systems and get lots of other co-benefits, then the social cost of carbon that will allow us to compute the need to do carbon removal, I think, will go down. That's not an inviting lesson for some big industrialists, but in terms of a strategy to get and stay under 1.5 or 2C, it's massive clean energy plus healthy ecosystems.*

These perspectives on co-benefits signal steps into multi-regime, multi-issue assessment and governance, rather than situating governance mainly within the UNFCCC or broadly relying on carbon-focused instruments. Experts particularly highlighted biodiversity and food security (R17, R23, R69, R82, R84), with some noting how the biodiversity regime (the Convention on Biological Diversity, CBD; and its assessment body, IPBES) have been widening concepts of ecosystem services and smallholder rights (R7, R15). Others cite ongoing conversations on marine carbon removal at the Intergovernmental Conference on Marine Biodiversity of Areas Beyond National Jurisdiction (R86).

4. Results: pathways of engineered carbon removal

For many, the scale of forestry and agricultural approaches within AR5′s most ambitious emissions pathways is unfeasible, and engineered approaches must be assessed as a way to fill the sequestration gap. In contrast to nature-based approaches, engineered carbon removal relies more on technological and chemical components. The preceding but still unscaled field of point-source, flue-gas carbon capture and storage, or CCS, creates a partial path dependence for the more novel – and potentially more distributable – carbon removal approaches of direct air CCS (or DACCS) and bioenergy CCS (or BECCS), since the back-end storage components are the same. There are overlaps here with nature-based approaches in heavy spatial use - bioenergy CCS couples with biomass cultivation in terrestrial and potentially marine environments. Chemical carbonization approaches such as enhanced weathering – or its marine variant, ocean alkalinization – leverage potentially large tracts of physical space. In contrast to direct economic subsistence in spatial use, hard and soft paths for engineered approaches have to contend more strongly with life-cycle component demands.

The term 'co-location' describes this balancing of demands. Engineered approaches must balance the source and cost of the energy input (the capital expenditure posed by fossil fuels, biomass, or renewables); the need for other resources (water, mined rocks for enhanced weathering); the location of storage areas for carbon-as-waste, or alternatively, utilization demands and facilities for new carbon products (new fuels, cement); and logistical and transportation requirements (pipelines, trucking, and shipping).

Engineered approaches similarly must contend with spatial-use conflicts and power inequities. Energy, storage, and transport infrastructures that face NIMBY dynamics are more readily located near lower-income, marginalized areas – and may be exacerbated with increases in industrial scale. Unlike land and marine subsistence use, direct air CCS infrastructures pose a comparatively high technical barrier to entry. Many states, particularly in the global South, do not possess needed capacities in innovation and industry, a sufficient renewable energy matrix, state-sponsored and private financing, and regulatory incentives. Rich states or industries must still foot the bill for high-technology carbon removal to be implemented – which creates immediate imbalances in the calculus of co-location.

4.1. Industrial capture – hard pathways

4.1.1. Resources

For those who see value in direct air CCS, scale of sequestration is a pressing concern. R32 sets this in opposition to nature-based solutions:

> *… for direct air CCS and for fossil CCS [there] doesn't really seem to be any technical limit on the amount of CO2 that you can inject, but … if you plant a bunch of monoculture trees where native grasslands used to be, yes, you could store a lot of carbon, but eventually you're going to run out of land to do that on.*

In turn, carbon removal efforts should be structured by cost-effective and high-leverage energy and resource use, which favors the high-temperature, liquid-sorbent variant. While distributed forms of energy supply and smaller-scale infrastructure for modular, solid types of direct air CCS scale linearly (see Section 4.2), liquid types of direct air CCS, based at large-scale facilities, with reliable supply of energy and chemical inputs, benefit from economies of scale and higher technology readiness (R6, R13, R24, R28, R30, R87). R28's comment is representative:

> *[Modularity] is used almost as a buzzword, and to be at climate-relevant scales you need large plants. [We] consider a 100-kilowatt-per-year plant and 1-mega-tonne-per-year plant to look at the cost differences, and it appears that solids costs do not change as much from the smaller plants. But for liquids, they definitely benefit from larger plants. So why would you have a lot of smaller plants?*

In turn, high energy costs favor natural gas, whose prospective use is described by many as a "*bridging option*" – in line with how gas has come to be described as a necessary part of climate governance since the hydraulic fracturing revolution of the mid-2000s (R6, R12, R22, R28, R35). R87 highlights that:

> *If you think about this from an engineering point of view, all you care about is tons. So you should couple with whatever is the cheapest option in scale … If you hook a carbon-removal machine to a solar panel in Germany… everyone is thrilled with themselves, but you're not moving a lot of molecules through the system … Go and find some cheap gas in the Algerian desert, or anywhere in North America.*

Carbon is treated more conventionally as waste to be stored at scale. Infrastructure co-location more strongly emphasizes transmitting power towards capture facilities close to storage reservoirs, rather than a distribution of facilities based on the diverse end-use of carbon (CCU for materials and synthetic fuels; enhanced oil recovery). R13 notes:

> *It's not like [bioenergy] where you have a bunch of [bio]refineries in different places [and] you would actually have some sort of difference between the spatial character of where you want to actually generate the CO_2 and where you want to store it… For direct air capture … you just put it where the reservoirs are.*

Energy costs for industrial-scale CCS could be met by renewable sources – but these would be concentrated to attain the needed economy of scale, or harness competitive advantages in the energy matrices and geologies of different countries and regions. The key concept is co-location where there is an abundance of energy without corresponding demand (alongside infrastructure-building capacity): solar energy in the desert regions of the Middle East, Australia, and the Americas (R11, R24, R45, R83), hydro and geothermal energy in Nordic regions (R1, R4), and even ocean-current conveyor belts (R64). Large-scale, monoculture approaches to biomass production immediately generate bioeconomy conflicts, and is generally unsupported (Section 3.1). R81 notes that biomass demand for bioenergy CCS could create "*a new 'green OPEC'*", where countries with high growing capacity "*when there is a reliance, become dominating the markets.*" R34 recalls that *"[now] wind parks are the perfect incarnation of very large-scale centralized technology options … I mean, even PV can be sought to be of… gigantic PV parks [like] DESERTEC*". However, waste industrial heat, and the stranded or transitioning assets of post-industrial economies (a combination of fossil and incoming renewables, re-purposable facilities and zones) could support capture efforts – the scale and intent here begin to intersect with soft paths (R6, R28, R35).

4.1.2. Infrastructure, livelihood, and ownership

Industrial carbon capture leverages incumbent systems with necessary infrastructure and expertise. There are fears that industry actors with the necessary capacity in capital or operations expenditures, or who acquire a first-mover advantage, may squeeze out smaller innovators. For now, this privileges the oil and gas industry, which not only produce the "*bridging fuels*" that could power capture, but whose otherwise stranded assets – skill sets, finance, facilities, pipelines, and reservoirs – are arguably pragmatically used to sequester rather than extract carbon, and help bring the costs down for direct air CCS (R35, R55, R84, R88, R90). Enhanced oil recovery – the use of carbon to extend existing oil fields and "*partnering with oil companies to actually sell fuel"* – is a key example, to which "*the business model of Carbon Engineering and of several of the other leading carbon removal firms*" already caters (R90).

But this could also lock in a "*deliberate offset for continued fossil-fuel use rather than as a mopping-up and residual technology*" – an example of the "*capture*" of potentially transformative technologies into "*incremental adaptations*" for incumbent industries (R55). Industrial capture may be tied, moreover, to the geopolitics of oil: creating new profit incentives for entwined private and national oil interests. R24 speculates:

> *I think the Saudis … have got more solar resources than they know what to do with. So they can build extremely cheap solar-powered direct air capture and offset all the emissions from their oil … They can not only build direct air capture to offset their own emissions – they could sell offsets [and] it could become a separate business for them, is to just 'grow' direct air capture.*

Leveraging extractive industries also invokes antecedents of "*hazardous siting and environmental racism*" (R48). Factories, nuclear plants, pipelines, and pollution zones have historically been more easily sited amongst marginalized communities with limited capacity for the more (sub)urban phenomenon of NIMBY-ism, creating "*fenceline communities*" (R22) and "*sacrifice zones*" (R35) with social structures underpinned by low-wage labor (R6, R10, R48). Supply-chain assessments of centralized systems are arguably more calculable (R6, R46), but the life cycle assessment of direct air CCS powered by gas in particular would be subject to methane leakage (R6, R22). Storage scale and location, furthermore, has a geopolitical element: technology-capable countries fearing NIMBY-ism or lacking storage capacity may promise funds and technology transfer to transport and sequester carbon in other countries – exporting (opposition to) their stored pollution (R4, R47, R83).

4.1.3. Decision-making

Direct air CCS and bioenergy CCS leverage the same storage infrastructures as point-source CCS and can be seen as an expansion of this system (R47, R77). Still, point-source CCS has yet to be scaled to the degree originally envisioned, and experts emphasize that it should have priority over direct air and/or bioenergy CCS (R6, R16, R74, R78). R78′s comment is representative:

> *Eventually, hopefully, we remediate all the flues that we can remediate and now we have got no alternative but to start capturing from direct air. But it should be in that order … Either way though, however we capture the carbon, there is then the whole backend infrastructure of pipelines and sequestration facilities…*

All but a handful of experts pragmatically cite the need for governments to set agendas for market-driven carbon management: a stronger carbon price, and offset markets with higher, more replicable standards for MRV and accreditation, to account for the fact that carbon is mostly a waste product with no intrinsic value. R60 notes that these demands have been made since the Kyoto Protocol, with a hint of exasperation:

> *Policy makers always think they can switch off, switch on, these markets as they wish, but this will not work in the long term … Again, it's clear that any option that is linked to geological storage just incurs cost … There is no standalone business model that is viable without political intervention. And the trust of the private sector depends on the experience with such political interventions, which has not been positive in the past 20 years.*

Others, however, cite hopeful developments in government-led incentives and funding – in the US, California's Low Carbon Fuel Standard and 45Q (a sequestration tax credit); in the EU, the European Commission's Innovation Fund. Still, R31 highlights differences in the character of incentivization: in Europe, the conversation is still about certification, while in there is debate in the US of direct air CCS as a field of innovation with geopolitical implications deserving of greater governmental resources (R31).

A conversation is emerging, as R29 puts it, on how to "*reframe direct air capture as a way to deal with legacy emissions and to climate restoration on a global scale and frame it as a justice issue, or frame negative emissions as a way for industrialized countries to pay back their historical carbon debt*", citing a recent comment by the Indian minister for Electric Power calling for carbon removal to create room in the remaining carbon budget for the global South (Mohan et al., 2021). R30 adds that this intersects with transitioning carbon-intensive industries across the North and South: "*Think about all of those millions of workers in coal mines and plants in India, there may be a greater opportunity for them to transition away from that and not lose their livelihoods – if we have carbon removal that can help us slow the severity of the near-term transition.*".

4.2. Distributed capture – soft pathways

4.2.1. Resources

Set in opposition to gas-powered, industrial direct air CCS, many envision low-temperature, solid absorbent variants catering to a distributed and diverse range of renewable energy sources and carbon products (R35, R37). This alternative understanding of economy of scale emphasizes two components.

The first describes a bespoke approach, where more design-intensive infrastructures cater to location-specific combinations of available energy, storage, use, and transport. Supporters emphasize smaller-scale diversity and flexibility (R35, R37, R73). A much-cited project is the Climeworks facility in Iceland, harnessing a combination of low humidity (facilitating the sorbent's efficacy), storage availability, and a ready supply of cheap geothermal energy. The key uncertainty is whether such examples represent "*niche opportunities*" that cannot be easily scaled (R6) – or whether they can galvanize a further range of bespoke efforts (R1, R28, R31, R73).

Energy costs remain central: areas with plentiful – and available or spare - renewable energy are rare. Dispersed projects could pursue power purchase agreements to couple with energy and electricity grids – but distance would increase costs (R28). The overall fear is that renewable energy re-purposed for direct air CCS will pose trade-offs for the use of existing capacity. Many experts pointed out that renewables must be upscaled specifically for capture infrastructures on top of incoming energy demands – a tall order (R6, R17, R30, R33, R31, R35, R37, R58, R68, R71, R73). R71 points out this double-edged potential: "*if you can power [direct air CCS] systems with more innovative and non-fossil fuel-based energy production, there is a synergy, but until we reach this energy, it is a trade-off.*"

Still, bespoke applications begin to dovetail with the second component of modularity, if now-competitive solar energy is a viable template. Solar panels and other infrastructure components can be mass-manufactured, allowing direct air CCS to be more flexibly stationed – as long as transport towards storage is viable (R30, R35, R37, R73). According to R35:

> *[There is a] difference between design-intense and manufacturing-intense technologies. Design-intense are where … every nuclear plant is very specific to its area. Whereas solar panels are solar panels … So, my understanding of low-temperature direct air CCS is that it's much more possible to manufacture the capture modules at scale in one place in a factory, get … economies of scale in production, but also learning about doing the repeated production of small modules. Then those modules can go and be put places which will be site specific.*

4.2.2. Infrastructure, livelihood, ownership

Rather than the scale of carbon capture involved, distributed direct air CCS emphasizes co-benefits extending across the life cycle, from resource inputs, to innovation, assembly, upscaling, and carbon utilization. Small-scale is a virtue, providing opportunities for versatile niche-market applications that reduce costs. Again, the evolution of the solar photovoltaics industry provides the key antecedent (R30, R35). R73 notes:

> *… there were decades of niche-market applications for solar PV, like watches, satellites, roof-top. That's where the initial cost reduction happened that enabled the utility to scale solar. So, the modularity of that technology was imperative… we are really limiting ourselves in the innovation space by thinking that these monolithic megaton plants are the way to go.*

In turn, financing and innovation are argued to spill over more easily by "*things like batteries, solar panels, technologies that have multiple material science inputs, opportunities, and have multiple applications*" (R46), from renewable energy upscaling to the (re)use of carbon for synthetic fuels, soil amendments, plastics, and carbon-sequestering construction materials (R30, R35, R37, R68, R73, R82). R34 speaks for many by pointing out the potential of diverse end uses and co-benefits:

> *This engineering passion with upscaling… means lumpiness, high complexity, persistent cost overruns, and very structured ways of building technologies and operating the technologies - which are at odds to my value system of a pluralistic, chaotic society in which users provide important feedbacks, but also important sources for selection of technologies.*

Still, there is a prevailing sense amongst experts that proposed economies of scale for the end-use of carbon will remain aspirational. End-use diversity may be oversold, and the bulk of carbon will need to be stored as waste. Some suggest that innovators are only "*defaulting to co-benefits as a selling point [due to] the absence of a strong carbon price [and] consistent funding*" (R67).

4.2.3. Decision-making

Soft and hard paths contain many similar accounting, funding, and incentivization needs, but the latter emphasizes diverse distribution and carbon use. A key activity for a dispersed direct air CCS economy would be life cycle emissions and calculability of MRV, which grows more uncertain across a multiplicity of unique projects. According to R6:

> *I had someone call me other day and they were talking about rooftop direct air CCS systems. Then they would just haul the CO2 out in trucks. But when you start looking at the lifecycle emissions, [is] that entire fleet is going to be electric [?] You're going to hear me say this 100 times: it's all about the life cycle. So, each one of those individual little projects needs to have a life cycle assessment associated with it.*

A proposed diverse end-use economy, at this early stage, also relies on niche markets as a means to reduce costs. Much of this navigates a funding-starved landscape. R31, for example, notes efforts to combine niche markets with offsets markets. Alongside government action (see Section 4.1, on *Decision-making*), experts cite kinds of private sector or philanthropical funding that are needed to galvanize an innovation ecosystem – examples included Stripe (an internet technology services company that established a 'Climate Program' to purchase credits from novel approaches), the financial contributions made by Jeff Bezos of Amazon to ClimateWorks (a non-profit funding distributor), and XPRIZE (a non-profit that hosts funding competitions) (R31, R87). R87 summarizes:

> *… you need a whole bunch of early-stage, in effect, advance materials, separate membranes, different kinds of technologies, catalysts … Then, eventually, my guess is … the high-quality stuff will scale almost on its own in response to market pull. [But] you've got to find some way to bring the $1,000 down [the cost of high-quality offsets], and that's going to be some blend of philanthropy and public-sector funding.*

At the same time, experts note that the aggregation of niche innovations in an end-use-driven carbon removal economy is limited in comparison to the volume of carbon that must be sequestered as waste and requires concerted governmental intervention (R50, R51) – or worse, that different kinds of carbon products in a "*circular economy [could be] taken to represent a form of [permanent] carbon removal, which it might not be*" (R47).

In another thread – as noted in Section 4.1 – direct air CCS is being discussed as a means to create more room in the carbon budget for developing countries. But a softer pathway might see global infrastructures for direct air CCS as an avenue for funding, technology transfer, and local energy development. R33 argues that, as:

> *[energy] performance is highly region-specific, it could happen that the best location is in a developing country. Then … we could help these countries to deploy these technologies, so therefore it could contribute to the development of this area. I see that there is an opportunity by promoting the removal in the best locations … if we think about solar, for instance, in Africa.*

5. Discussion: scale, carbon management, and the open-ended future of pathways

Our results show how notions of 'hard' and 'soft' pathways can capture leading, alternative expert perspectives on how carbon removal infrastructures can be designed and coupled to existing – or aspirational – energy systems, sectors and societies. For both nature-based (Section 3) and engineered approaches (Section 4), co-location is a root node for mapping rationalizations, practices, and impacts. Infrastructures are sited where a balance of interests (phrased another way, co-benefits or tradeoffs) can be found between different resource supplies and usage demands. Nature-based carbon removal must navigate synergies and tradeoffs between energy, agriculture and aquaculture, and storage (and ecosystems services). Engineered approaches must bridge the locations of their energy inputs, storage, utilization, and transportation. In turn, hard and soft archetypes of these balances of interests break down stereotypes about engineered and nature-based carbon removal. Direct air CCS gives the impression of having a lesser direct spatial footprint than terrestrial and marine approaches but require tremendous energy resources; nature-based approaches give the impression of being 'natural' (for a critique, see Osaka et al., 2021), posing greater and more diverse co-benefits. But experts note that engineered approaches might synergize with distributed renewable systems, and warn that nature-based approaches could lean into monocultures and land- and coast-grabs.

Having posed alternatives for nature-based and engineered approaches *separately*, we now aim for an analysis of hard vs. soft pathways *across* carbon removal approaches. In Section 5.1, we show that hard and soft paths diverge most strongly on two concepts: whether carbon capture or co-benefits is the 'economy-of-scale' emphasized; and how carbon as a product is to be managed – how carbon is stored or recycled into a variety of second-life uses. We further note two key uncertainties: whether renewables can be upscaled to allow synergies rather than tradeoffs between carbon removal and more widespread energy demands, and whether carbon certification can expand spatially to navigate long supply chains, and conceptually to incentivize diverse co-benefits. In Section 5.2, we emphasize that carbon removal stands at a formative enough stage that future developments may contain both hard and soft elements (e.g. both small-scale, customary rights focused ecosystems management and large-scale agricultural and forestry management) or some hybrid space in-between (modular components for direct air capture). We do not want to under-state this openness by adhering strictly to hard or soft alternatives – rather, we use ideal-type alternatives to emphasize room for manoeuvre. Section 5.3 concludes with near-term policy implications.

5.1. Hard vs. soft: economies of scale, and the role of carbon removal

Hard and soft paths are most clearly differentiated through two concepts: economies of scale, and carbon removal's role in climate response strategy. Hard paths see the scale of energy inputs and carbon capture as paramount, and carbon removal as a means to buy time for difficult emissions reductions in the mid-term, while removing residual carbon in the long term. The positive dimensions of hard pathways emphasize scale of carbon capture, more reliable calculability in MRV, and the leveraging of pre-existing, scale-proven energy or storage systems – whether based on fossil fuels and biomass energy, monoculture-dependent carbon stocks, transportation, and infrastructures in oil and gas, mining, or dredging. Advocates rationalize these choices in recognition of the scale and urgency of necessary carbon drawdown, and the need for near term and pragmatic integration of carbon removal into energy policy and emissions-reduction efforts as they are currently – if imperfectly – configured.

On the other hand, hard paths lean into 'ecological modernization' (Bäckstrand and Lövbrand, 2016), in which flexibility in achieving difficult emissions cuts is sought through carbon offsets and trading or bridging fuels in order to balance climate protection with the prevailing mode of carbon-fueled capitalism (Low and Boettcher, 2020; McLaren et al., 2019; Delborne et al., 2020). Opponents to hard paths filter their concerns through antecedents in extractive industries, GMO agriculture, or control of technologies relevant to national security. There is a sense that MRV and achieving economies of scale with carbon removal are more technically straightforward in hard pathways. Yet, the history of land-use and food systems governance shows that hard-path terrestrial (and perhaps, marine) carbon removal may be prone to bioeconomy conflicts, particularly amongst marginalized communities in the global South (Ericksen, 2008; Gerber, 2011). Industrial-scale direct air CCS warns of siting issues, especially regarding exporting of pollution, to areas whose demographics possess less capacity for resistance (Buck, 2021). By leaning into existing power structures in energy and climate governance, hard paths contain immediate traction and may create further opportunities for more difficult future actions: the logic of bridging or time-buying (Buck et al., 2020). On the other hand, they may surrender transformative potential and reinforce the macro-level logics that feed carbon geopolitics and food insecurity (Carton et al., 2020; Lamb et al., 2020; Low and Boettcher, 2020).

Soft paths, meanwhile, see a different economy of scale as relevant: that of diverse, micro-scale options with an emphasis on co-benefits (what Lovins might have seen as synergizing with diverse end-use), in spite of an unclear aggregate capacity to capture carbon. This is entwined with an alternative view on the role of carbon removal: not necessarily tied to climate governance alone, but to biodiversity, food security, energy poverty, sustainable development, and other cross-cutting issues for global governance. There is an eye to macro-level and incremental change, rather than high-leverage, cost-effective action. Measuring the carbon captured is not paramount: rather, integrating carbon removal into systemic efforts at sustainability might reduce emissions in ways that cannot yet be calculated. These perspectives echo Olson's (2012) and Martindale's (2015) earlier prospections of designing bottom-up, society-facing modes of 'geoengineering' (a term for large-scale efforts to manage the climate system that continues to be applied to carbon removal).

Soft paths offer opportunities to design co-benefits with local economies and renewable energy, while also representing disruptive innovations for hard infrastructures and uniform strategies. The need to avoid tradeoffs between the use of renewable energies for emerging direct air CCS and incoming power commitments signals the pressing need to scale up sufficient renewable capacity for both – a scale that in itself would be transformative. Co-location between energy, storage, utilization, and transport would be bespoke to different regions and localities. Modular supply chains might serve a network of both small and industrial-scale direct air CCS facilities. Navigating tradeoffs on the use of terrestrial and marine areas for production of food, fuel, or carbon storage can generate diverse kinds of multi-spatial, multi-purpose use with developmental co-benefits (e.g. agroforestry or blue carbon).

Yet, (the promise of) soft paths contain a double edge. Soft renewable energy systems may never scale sufficiently to overcome tradeoffs between powering modular direct air CCS as well as the rest of the next century's energy requirements. A globally dispersed carbon-removal ecosystem that combines modular and bespoke infrastructures, logistics chains, and practices would ideally spread social co-benefits – but conversely, would also hide the technical and social costs. Assessment and aggregation of both benefits and harms – crucial to steering future action - may be lost in the noise. Prospective life cycle assessments of engineered approaches, or calculating the scale and permanence of captured carbon across and by combining nature-based approaches with different temporal and spatial scales (e.g. Carton et al., 2020), already pose challenges. Perversely, this may also entrench climate inaction – laggards seeking flexibility in meeting their Paris NDCs could use the messiness of soft-path accounting to hide their carbon. And on a more systemic level, treating carbon removal as a tool for multiple purposes, in service to the competing mandates of diverse global challenges (e.g. energy vs. food vs. fiber vs. storage), may cause efforts to lose coherence (Fig. 3).

5.2. Middle ground: An open future of hard and soft potentials

Still, pathways are ideal-type distinctions that begin to break down in systems that stretch across large spatial scales or extended life cycles and supply chains. The most fascinating implications come from overlaps, or 'intermediate' dimensions that lean in hard and soft directions, with different kinds of benefits and risks. What might this mean for future transitions? We point out several key aspects.

Our experts in nature-based approaches almost uniformly rejected hard pathways for approaches with clear antecedents in large-scale

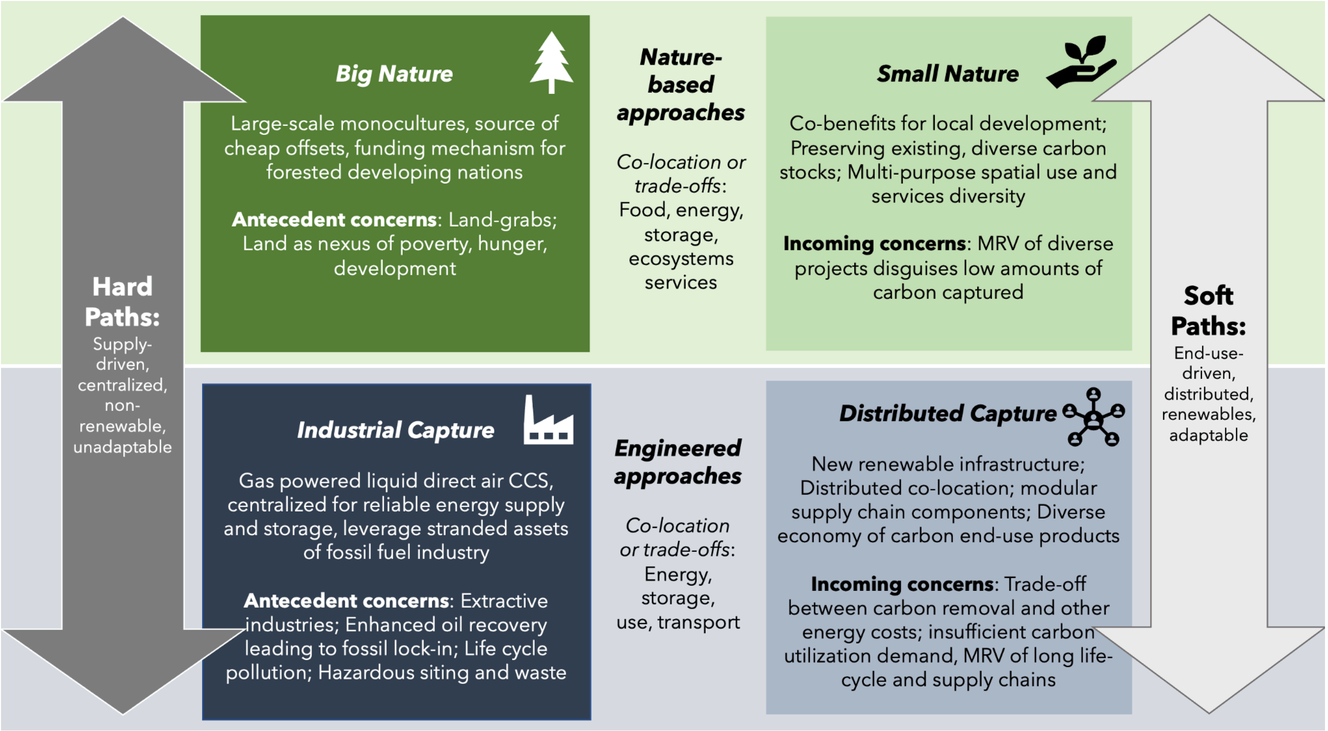

Fig. 3. Key elements of hard and soft paths for nature-based and engineered carbon removal.

forestry and agricultural management – bioenergy CCS, reforestation, and afforestation. But perspectives were much more unformed when it came to marine biomass, biochar, marine and terrestrial enhanced weathering, and other approaches with less clear precedents and statuses in recent climate assessment and governance. Marine biomass might replicate the hard-path approach to terrestrial biomass, for instance. Marine enhanced weathering might create abiotic zones in the ocean. Biochar might relieve dependence on fertilizers but reinforce monoculture plantations. There was an overarching sense, even from experts that supported soft paths, that MRV and societal benefits would be unclear at a high level of diversity and upscaling.

Similarly, in direct air CCS, an aspirational renewable-energy infrastructure can lean towards hard paths dependent on sheer scale in particular locales (Lovins, 1976) – "*a new 'green OPEC'*" (R81) or "*gigantic PV parks [like] DESERTEC*" (R34). Our experts (at least, those who did not favor gas inputs) found it difficult to reconcile the trade-offs posed by energy costs of direct air CCS with current renewable-energy capacity, and tended to be unsure about whether the eventual scale and scope of renewables demands supply-side centralizations rather than the more desired archetype of "*rooftop direct air CCS*" powered by more distributed, bespoke means (R6).

The stranded assets of the fossil fuel industry also have multiple potentials. Experts noted the ills of "*fenceline communities*" (R22), but also argued that re-purposing locations already used to such operations for industrial-scale capture and storage may offer opportunities to remake their employment and social structures while sustaining those communities (R6, R10; see also Buck, 2021). Using gas-powered direct air CCS, or carbon for enhanced oil recovery, could act as bridging strategies or lock-in fossil-fuel infrastructures. Fossil fuel resources coupled with carbon removal could be a developmental asset or a resource curse in the global South; it could create new profit motives and geopolitical implications for private and national oil interests – Royal Dutch Shell, Saudi Aramco, Gazprom – for both good and ill (Goldthau et al., 2019). Many supported the soft path of a diverse economy for carbon products – but eventual energy inputs could require hard energy paths (R31).

Industrial and distributed forms of air capture, moreover, have common aspects at various parts of the life-cycle or the supply chain. Mass-produced modular components could service both industrial plants and more flexibly distributed units (R37). Waste carbon has to be centrally processed for disposal, whether the capture comes from centralized or more distributed systems (R28). For bioenergy CCS, sustainable biomass would ideally come from best from distributed smaller-scale agricultural processes but would need to be coupled to CCS components that work best at a large scale (R68).

5.3. *Policy implications*

To close, we note early governance and policy actions raised by our experts that would be valuable and viable – regardless of which pathway various carbon removal approaches take. Most of these can be found in contextual literature and do not break new ground. If anything, it shows that although long-term pathways remain open, agreement is beginning to coalesce around a number of pragmatic near-term actions.

R68 cited several key principles that serve as a fair summary of expert recommendations, following Tanzer and Ramirez (2019): to prioritize long-term or permanent storage, to document emissions across a given approach's full life cycle and supply chain, and ensure that more carbon is removed than emitted. These signal for the improvement of modeling and other assessments to aid monitoring (R49), to more stringent, internationally-harmonized standards for carbon accreditation and offsets (R60), to the consideration of carbon storage forms that – while not permanent – are long-term enough to arguably buy time for decarbonization (R74).

To aid MRV, many experts supported a separation of targets, metrics, and emissions baskets between conventional emissions reductions and carbon removal (R15, R29, R55) – in order to prevent fungibility between measurements of carbon removal and mitigation activities (see also McLaren et al., 2019). Others call for distinguishing between kinds of carbon removal with different geographies and lengths of sequestration (see also Carton et al., 2020), and preventing heavy industries (R4) – or more (purportedly) progressive technology companies

(R55) – from continuing to use cheap, non-permanent offsets derived from the land sector via voluntary carbon markets.

Carbon may embody a significant scale of second-life products in a circular economy. (R30, R35, R37, R68, R73, R82). However, the vast majority of our experts saw carbon primarily as a waste product to be governed as a public good, and hedged between policies catering to today's market-based governance and more government-led funding and development efforts. At the least, treating carbon as waste demands consistent (inter)governmental backing of a carbon price and rules for MRV and offsetting, to create a stable incentive and regulatory environment for the market-based efforts still dominant in climate governance.

Finally, experts note two areas – one nature-based, the other engineered – in which incoming forms of carbon removal are stealing attention from related areas where action is already viable, and where the cart should be put back behind the horse. Endemic point-source CCS should lay the infrastructure of transportation and storage for direct air CCS or bioenergy CCS in the future (R6, R16, R78; see also Haszeldine et al., 2018). Avoided deforestation – preserving existing, diverse forms of carbon stocks and their services – should take priority over subsequent reforestation and afforestation efforts (R23, R77). The latter has received recent high-level support with the Glasgow Leaders' Declaration on Forests and Land-Use, at the 2021 COP26.

6. Conclusion

We have shown that 'hard' and 'soft' pathways remain useful for parsing how 90 experts and technologists are thinking about and planning around carbon removal, including different modes of resource and energy inputs, infrastructure and livelihoods, and decision-making vis-a-vis established climate governance (Tables 2 and 3). We show that, across a range of prospective nature-based and engineered carbon removal systems, hard and soft paths reflect different conceptions of space and society: especially economies-of-scale (scale and calculability of carbon captured and reliable energy provision, against systemic co-benefits in purpose-fit ecosystems services or carbon utilization economies) and carbon management (as a waste product within conventional climate governance, against diverse end-uses and values governed across many global governance levels and regimes).

We note that the greatest uncertainties on which hard and soft pathways hinge, along with where they most substantively diverge, are the support and need for new renewable-energy infrastructures and the significance of monitoring, reporting and verification processes (MRV, or carbon accounting and certification). Renewables have to be massively, diversely upscaled to allow synergies, rather than tradeoffs, to emerge between the aims of carbon removal and more widespread energy demands. MRV processes must expand spatially to navigate long supply chains and life cycles, and conceptually beyond carbon accounting and certification to incorporate and incentivize diverse co-benefits. Given the need for upstream innovation, we follow R73 in warning against false choices in the face of deep uncertainty:

> *[We need both] 'K species' and 'R species'. So, you have the humans of the ecosystems [large scale] and then you have the ants of the ecosystem [small scale]. It's their interaction that's important … a spill-over in interaction between various forms of a technology … it's very surprising for me to hear people so certain about what it needs to look like in 50 years, or in 30 years or 100 years.*

Indeed, carbon-removal development and policy stand at an early enough stage to follow either hard or soft pathways, but many experts, motivated by antecedent concerns over land-use management and extractive industries, worry that – without guardrails – hard paths will be replicated through inertia. We echo calls for pragmatic near term action on improving MRV concepts and processes, new rules for offsetting, stable government support for carbon pricing, and leveraging both carbon capture and storage and ecosystems management to galvanize further carbon removal efforts.

CRediT authorship contribution statement

Sean Low: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Chad M. Baum:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Benjamin K. Sovacool:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex 1. List of carbon removal approaches addressed.

Type	Option	Description
Nature, Marine	Blue carbon and seagrass	Harnessing the ability for coastal mangrove forests, tidal marshes, and seagrass meadows to accelerate their uptake of carbon dioxide
Hybrid, Marine	Ocean iron fertilization	Utilizing planktonic algae and other microscopic plants to take up CO_2 and convert it to organic matter, some of which sinks and is sequestered in ocean
Hybrid, Terrestrial and Marine	Enhanced weathering and ocean alkalization	Deploying physical or chemical mechanisms to accelerate the geochemical processes that naturally absorb CO_2 at slow rates.
Engineered, Terrestrial	Carbon capture and utilization and storage	Employing technologies, processes or solvents that extract, capture, transport, utilize, and/or store carbon dioxide
Engineered, Terrestrial	Direct air capture	Capturing carbon dioxide from the air via engineering or mechanical systems, and then using solvents or other techniques to store it safely
Hybrid, Terrestrial	Bioenergy with carbon capture and storage	Harnessing specific energy crops (e.g., perennial grasses, or short-rotation coppicing) or increased forest biomass to replace fossil fuels, and capturing and storing consequent carbon dioxide
Hybrid, Terrestrial	Biochar	Managing the thermal degradation of organic material in the absence of oxygen to increase soil carbon stocks and improve soil fertility

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Type	Option	Description
Nature, Terrestrial	Soil carbon sequestration or enrichment	Growing cover crops, leaving crop residues to decay in the field, applying manure or compost, using low- or no-till systems, and employing other land management techniques to improve soil
Nature, Terrestrial	Afforestation and reforestation	Planting trees or vegetation to absorb carbon dioxide
Nature, Terrestrial	Ecosystem restoration	Managing the restoration of ecosystems (including wetlands, peatlands, and grasslands) to reverse environmental damage and increase their ability to absorb greenhouse gases

Source: Authors. Referencing: Shepherd et al., 2009; Minx et al., 2018; McNutt et al., 2015a; McNutt et al., 2015b.

Annex 2. List of 90 semi-structured expert interview respondents.

Name	Actor Type	Gender	Country	Institution
Asayama, Shinichiro	Universities + Research Institutes	Male	Japan	National Institute for Environmental Studies
Bazilian, Morgan	Universities + Research Institutes	Male	USA	Colorado School of Mines
Bellamy, Rob	Universities + Research Institutes	Male	United Kingdom	University of Manchester
Beuttler, Christoph	Private Sector + Industrial Associations	Male	Switzerland	Climeworks
Biermann, Frank	Universities + Research Institutes	Male	Netherlands	Utrecht University
Boettcher, Miranda	Universities + Research Institutes	Female	Germany	German Institute for International and Security Affairs
Brickett, Lynn	Government + Intergovernmental Organizations	Female	United States	US Department of Energy
Briggs, Chad	Universities + Research Institutes	Male	USA	University of Alaska, Anchorage
Brown, Marilyn	Universities + Research Institutes	Female	USA	Georgia Institute of Technology
Bruce, John	Private Sector + Industrial Associations	Male	Canada	Carbon Engineering
Buck, Holly Jean	Universities + Research Institutes	Female	USA	University at Buffalo
Burns, Wil	Universities + Research Institutes	Male	USA	American University
Caldeira, Ken	Universities + Research Institutes	Male	USA	Breakthrough Energy, Carnegie Institution for Sciences, and Stanford University
Carton, Wim	Universities + Research Institutes	Male	Sweden	Lund University
Chavez, Anthony E.	Universities + Research Institutes	Male	USA	Northern Kentucky University
Clarke, Leon	Universities + Research Institutes	Male	USA	University of Maryland
Clarke, William S. (Sev)	Private Sector + Industrial Associations	Male	Australia	Winwick Business Solutions
Cobo Gutiérrez, Selene	Universities + Research Institutes	Female	Switzerland	ETH Zurich
Cox, Emily	Universities + Research Institutes	Female	United Kingdom	Cardiff University
Creutzig, Felix	Universities + Research Institutes	Male	Germany	Mercator Research Institute on Global Commons and Climate Change (MCC)
Di Marco, Leon	Private Sector + Industrial Associations	Male	United Kingdom	FSK Technology Research - Consultant
Dooley, Kate	Universities + Research Institutes	Female	Australia	University of Melbourne
Draper, Kathleen	Civil Society	Female	USA	International Biochar Initiative
Elliott, David	Universities + Research Institutes	Male	UK	The Open University
Erbay, Yorukcan	Private Sector + Industrial Associations	Male	United Kingdom	Element Energy
Florin, Marie-Valentine	Universities + Research Institutes	Female	Switzerland	EPFL International Risk Governance Center (IRGC)
Forster, Piers	Universities + Research Institutes	Male	United Kingdom	University of Leeds
Frumhoff, Peter	Civil Society	Male	USA	Union of Concerned Scientists
Fuhrman, Jay	Government + Intergovernmental Organizations	Male	United States	Pacific Northwest National Laboratory (PNNL)
Fuss, Sabine	Universities + Research Institutes	Female	Germany	Mercator Research Institute on Global Commons and Climate Change (MCC)
Gambhir, Ajay	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Geden, Oliver	Government + Intergovernmental Organizations	Male	Germany	German Institute for International and Security Affairs (SWP)
Ghosh, Arunabha	Civil Society	Male	India	Council on Energy, Environment and Water (CEEW)
Grant, Neil	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Gruebler, Arnulf	Universities + Research Institutes	Male	Austria	International Institute for Applied Systems Analysis (IIASA)
Guillen Gosalbez, Gonzalo	Universities + Research Institutes	Male	Switzerland	ETH Zurich
Haberl, Helmut	Universities + Research Institutes	Male	Germany	BOKU Vienna
Hamilton, Clive	Universities + Research Institutes	Male	Australia	Charles Sturt University
Hartmann, Jens	Universities + Research Institutes	Male	Germany	University of Hamburg
Hawkes, Adam D.	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Healey, Peter	Universities + Research Institutes	Male	United Kingdom	Oxford University
Heap, Richard	Civil Society	Male	United Kingdom	Carbon Removal Centre, Foresight Transitions
Hepburn, Cameron	Universities + Research Institutes	Male	United Kingdom	Oxford University
Herzog, Howard	Universities + Research Institutes	Male	United States	MIT
Heyward, Clare	Universities + Research Institutes	Female	Norway	UiT - the Arctic University of Tromso

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Name	Actor Type	Gender	Country	Institution
Honegger, Matthias	Universities + Research Institutes	Male	Switzerland	Perspectives Climate Change
Kammen, Daniel	Universities + Research Institutes	Male	USA	UC Berkeley
Keller, David	Universities + Research Institutes	Male	Germany	GEOMAR - Helmholtz Centre for Ocean Research Kiel
Keller, Klaus	Universities + Research Institutes	Male	USA	Penn State University
Kruger, Tim	Private Sector + Industrial Associations	Male	UK	Origen Power
Lawrence, Mark	Universities + Research Institutes	Male	Germany	Institute for Advanced Sustainability Studies (IASS)
Lehmann, Johannes	Universities + Research Institutes	Male	USA	Cornell University
Lenton, Andrew	Government + Intergovernmental Organizations	Male	Australia	CSIRO
McLaren, Duncan	Universities + Research Institutes	Male	United Kingdom	Lancaster University
Mengis, Nadine	Universities + Research Institutes	Female	Germany	GEOMAR - Helmholtz Centre for Ocean Research Kiel
Merk, Christine	Universities + Research Institutes	Female	Germany	Kiel Institute for the World Economy
Michaelowa, Axel	Universities + Research Institutes / Private Sector + Industrial Associations	Male	Switzerland	University of Zurich / Perspectives Climate Group
Montserrat, Francesc	Universities + Research Institutes	Male	Brazil	Project Vesta / University of Sao Paulo
Morrow, David	Universities + Research Institutes	Male	USA	American University
Muri, Helene	Universities + Research Institutes	Female	Norway	Norwegian University of Science and Technology (NTNU)
Obersteiner, Michael	Universities + Research Institutes	Male	United Kingdom	Oxford University
Parson, Edward (Ted)	Universities + Research Institutes	Male	United States	UCLA
Pasztor, Janos	Civil Society	Male	Switzerland	Carnegie Climate Governance Initiative
Pidgeon, Nick	Universities + Research Institutes	Male	United Kingdom	Cardiff University
Pongratz, Julia	Universities + Research Institutes	Female	Germany	University of Munich
Preston Aragonès, Mark	Civil Society	Male	Norway	Bellona Foundation
Raimi, Kaitlin T.	Universities + Research Institutes	Female	United States	University Michigan
Reiner, David	Universities + Research Institutes	Male	United Kingdom	Cambridge University
Renforth, Phil	Universities + Research Institutes	Male	United Kingdom	Heriot-Watt University
Rickels, Wilfried	Universities + Research Institutes	Male	Germany	Kiel Institute
Rothman, Dale	Universities + Research Institutes	Male	USA	University of Denver
Rouse, Paul	Universities + Research Institutes	Male	United Kingdom	University of Southampton
Schleussner, Carl	Civil Society	Male	USA	Climate Analytics
Schmidt, Jörn	Universities + Research Institutes	Male	Denmark	International Council for the Exploration of the Sea
Schneider, Linda	Civil Society	Female	Germany	Heinrich Böll Foundation
Scott, Vivian	Universities + Research Institutes	Male	United Kingdom	Edinburgh University
Simonelli, Lucia	Civil Society	Female	United States	Carbon 180
Smith, Pete	Universities + Research Institutes	Male	United Kingdom	University of Aberdeen
Smith, Steve	Universities + Research Institutes	Male	United Kingdom	Oxford University
Smith, Wake	Universities + Research Institutes	Male	USA	Harvard University
Spangenberg, Joachim	Universities + Research Institutes	Male	Germany	Sustainable Europe Research Institute SERI Germany e.V
Stoefs, Wijnand	Civil Society	Male	Belgium	Carbon Market Watch
Sugiyama, Masahiro	Universities + Research Institutes	Male	Japan	University of Tokyo
Sunny, Nixon	Universities + Research Institutes	Male	United Kingdom	Imperial College London
van Vuuren, Detlef	Government + Intergovernmental Organizations	Male	Netherlands	PBL Netherlands Environmental Assessment Agency
Vaughan, Naomi (Nem)	Universities + Research Institutes	Female	United Kingdom	University of East Anglia
Victor, David	Universities + Research Institutes	Male	USA	UC San Diego
Vivian, Chris	Government + Intergovernmental Organizations	Male	UK	GESAMP
Wolske, Kimberly S.	Universities + Research Institutes	Female	United States	University of Chicago
Workman, Mark	Universities + Research Institutes	Male	UK	Energy Futures Lab, Imperial College London

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