Exploring the roles of technology-based carbon dioxide removal to make the grand challenges of decarbonization and socioeconomic equity more governable

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Abstract

(slightly revised from Conference programme)

The understanding of climate change has evolved over time into a behemoth, multi-faceted quandary of multiple interconnected forms (e.g., man vs. nature, man vs. society, man vs. man). Technological innovations such as carbon dioxide removal (CDR) put more options on the table for policymakers; however, expanding the menu of policy options complicates further the decision context and creates demand for policy analysis. This paper reports the progress of such policy analysis for net-zero emissions targets and was developed through an ongoing interdisciplinary project led by a team of engineers, legal scholars, and an economist on a CDR approach called direct air capture (DAC). Key project goals are to employ methodological innovations for policy analysis to give shape to the potential of DAC technology to provide Canadians opportunities in low-carbon and potentially more just futures that expand energy access. The project serves as an example of policy analysis that aims to make the grand challenges of decarbonisation and socioeconomic equity more governable and aims to shape policy processes affecting the future of Canadian climate policy. To unpack the politics of knowledge production around novel CDR approaches like DAC, the paper applies Geels' Multi-level Perspective to a regulatory analysis of 100 relevant Canadian policies as well as a review of 700 integrated assessment modelling scenarios. Focusing on the issue of mitigation deterrence, we conclude that moral hazard could be regulated around by clarifying the definition of mitigation such that emissions reductions and CO_2 removals be treated separately. A primer on a methodological innovation for policy analysis over a long time horizon, namely dynamic adaptive policy pathways, is also provided.

1. Introduction

Knowledge production around the global climate system began in the 19th century; however, within 100 years, it became apparent that human activities were influencing it. Policy-relevant questions about the human dimensions of climate change (i.e., the interaction between the climate system and human societies) drove mutations and transformations in our understanding of the global climate system as well as new governance structures. Today, questions about whether human activities affect the climate have largely been supplanted with questions about how to adapt to committed climate change, how to compensate victims of unavoidable loss and damage due to the impacts of committed climate change, and how to mitigate further greenhouse gas emissions. This paper focuses on the latter issue and the controversial finding from the Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5 °C (IPCC SR1.5) that slow decarbonization pathways can meet Paris Agreement targets through unprecedented deployments of technological carbon-dioxide removal (CDR). The paper investigates two key questions. First, what are the political (and we would argue, socio-technical) conditions that enable or constrain different approaches to how the Paris Agreement will be achieved? Second, what might be the role of direct air capture (DAC), a novel CDR technology, under different approaches?

The paper is organized as follows. In Section 2, we first lay out a brief history of the mutations and transformations in knowledge production around the insoluble problem of climate change. We note that the contemporary site of continued politics in knowledge production surrounds concerns of mitigation deterrence and related fears of moral hazard. We also introduce the particular approach to technological CDR that motivated our study, which is DAC. In Section 3, we introduce Geels' (2002) Multi-level Perspective (MLP) on socio-technical change as an appropriate theoretical framework for understanding how, and by what coalitions, policy analysis in climate-related technological change is being produced and selected. In Section 4, we report the findings of a two-pronged policy analysis applying MLP. The first prong focuses on Canadian regulations that might support national DAC development and deployment, while the second prong focuses on integrated assessment model simulations projecting global demand for DAC. In Section 5, we interpret our findings in the context of IPCC SR1.5 findings that have motivated two opposing coalitions, one that advocates for rapid decarbonization *versus* another that advocates for slower decarbonization. We conclude that fears that mitigation deterrence will invite moral hazard should not be treated as inevitable but rather something that can be regulated around. We also briefly reframe how DAC might be a key part of a net-negative emissions future with large infrastructural investments that might improve socioeconomic equity. Section 6 concludes.

2. A brief history of the insoluble problem of climate change

Historian of science and physicist Spencer Weart describes the discovery of global warming as a multi-decadal process spanning over 100 years (Weart, 2023, 2008). He depicts mutations and transformations in the scientific understanding of the global climate across the history of knowledge production, which now continues with the IPCC and policy analysis. Early research on the global climate originated in scientific curiosity; however, contemporary climate change research now informs societal decisions about what substances and processes in the earth system should be monitored, how economies and markets should be operated, and what technologies should be produced. In short, conceptions of the climate system transformed from first understanding a force of nature (man vs. nature) to appreciating the influence of the aggregate of human activities on the climate system (man vs. society). Although there is now the Paris Agreement for the UN Framework Convention on Climate Change (UNFCCC) to guide governance of the climate crisis, contemporary tensions in knowledge production around climate change remain, pitting coalitions (i.e., man vs. man) against each other in policymaking. This section provides background on the history of how climate change came to be understood as a behemoth problem and multi-faceted quandary.

2.1. Knowledge production on climate change before the Intergovernmental Panel on Climate Change (IPCC), mid-19th century to 1987

Early scientific questions about the global climate system were spurred by the discovery of ice ages in earth's history during the mid-19th century. Thus, at first, the global climate system was viewed by experts as a force of nature. Research primarily aimed to identify the mechanisms of the global climate and why it could change dramatically over millennia. In 1859, it was concluded that the chief atmospheric gases that trap heat are water vapor and carbon dioxide (CO_2). In 1896, the Swedish scientist Svante Arrhenius was the first to acknowledge that human activities related to industrialization added CO_2 to the atmosphere as a by-product and, in theory, could increase the atmospheric concentration of CO_2. Arrhenius and his contemporaries nevertheless believed that it would take centuries of human activity for increased CO_2 concentrations to become an issue if ever at all. The dominant scientific view was that natural processes preserved a stable global climate.

In the 1930s, the scientific community measured that the US and North Atlantic region had warmed significantly over the past 50 years. Scientists knew that regional climates could fluctuate for short periods of time such as years or generations due to human activities in land use change (e.g., the leveling of forests). The prevailing scientific view was that the regional temperature anomaly was unlikely to be anything special. However, an English steam engineer and amateur scientist, Guy Stewart Callendar, published empirical research about emissions from human industrial activity and concluded that CO_2 concentrations must be increasing according to Arrhenius' theory, thereby explaining the observed temperature anomaly. Callendar concluded that such global warming may be beneficial, protecting humanity from the next ice age.

Callendar's paper didn't spur much further research attention until the next generation of scientists significantly improved detailed measurements of atmospheric CO_2, and concentrations were rising year after year (Keeling et al., 2001; Scripps Institution of Oceanography, 2023). The global climate was not yet a policy issue; however, knowledge production from a variety of contexts in the 1960s that would later congeal into the field of Environmental Science raised questions about whether technological innovations were in fact improving life. For example, the first edition of Rachel Carson's highly influential book for environmentalism as a social movement, *Silent Spring*, was published in 1962. Similarly, climate scientists continuing their empirical and computational research arrived at the worrying result that global warming was a likely outcome from human activities. The climate system was also being understood as complex and therefore capable of dramatic changes under comparatively small perturbations. Scientists were becoming concerned that the aggregate effect of greenhouse gas emissions from socioeconomic activities were altering the global climate. The most organized scientific assessment predating the creation of the IPCC was a 1979 report from the US National Academy of Sciences, *Carbon Dioxide and Climate* (National Research Council, 1979).

2.2. Knowledge production on climate change after the IPCC, 1988 to present

About 10 years after the National Academies report, in 1988, climate modeller James Hansen testified to the US Congress that global warming was underway, was due to an enhancement of the greenhouse effect, and would increase the frequency of drought (Kerr, 1989). That same year, the IPCC was established by the World Meteorological Organization (a scientific body) and the UN Environment Programme (an international governance body). The charge of the IPCC has been to provide information to world governments that is policy relevant but not policy prescriptive. These developments marked additional turning points in the history of climate change research, with scientists gaining the attention of policymakers. However, scientific knowledge production around climate also became subject to political interference (Schneider, 2009); in battles for climate action and public opinion, so-called climate skeptics regularly cast doubt on knowledge production around anthropogenic global warming (Oreskes and Conway, 2010).

Despite political headwinds, across its various Assessment and Special Reports, the IPCC has aimed to answer key policy questions about global climate change posed by policymakers through a 'three-legged stool' of scientific knowledge comprised of empirical evidence, theory, and computerized simulation. The scientific consensus is that climate is changing globally, and such changes are due to human activities. The IPCC has also advised what level of climate change should be considered "dangerous" (codified in the Paris Agreement as 2 °C, with efforts to limit climate change to 1.5 °C), and what policy actions might be most effective for adapting to committed levels of climate change as well as mitigating greenhouse gas emissions. In tandem, the UNFCCC has evolved to coordinate global efforts to avoid dangerous interference with the climate system in light of scientific information assessed by the IPCC and geopolitical realities.

In its objective to be policy relevant but not policy prescriptive, the IPCC aims to identify alternative policy actions that make the seemingly insoluble policy problem of the climate crisis governable. To support governance, we interpret the objective of the honest broker of policy alternatives according to Pielke Jr. (2011), which is "to expand (or at least clarify) the scope of choice" (p. 18) Knowledge production that has been most influential for informing the policy targets of UNFCCC mechanisms has been integrated assessment modelling, or IAM (van Beek et al., 2020).[1] The most recent IAM studies that have strongly influenced current policy

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[1] Similar modelling approaches are also used for quantitative policy analysis, i.e., Morgan et al. (1992).

discourses around national "net-zero" emissions targets appeared in the IPCC SR1.5 (Masson-Delmotte et al., 2018; see also van Beek et al., 2022).

Prior to the IPCC SR1.5, the technical feasibility of meeting Paris targets had been explored with IAM studies representing "negative emissions technologies", or NETs (van Beek et al., 2022). The IPCC SR1.5 showed that pathways with higher emissions (and therefore a slower rate of decarbonization) could achieve 1.5 °C if they employed unprecedented amounts of nature- and technology-based CDR. Such a scenario is based on a socio-economic pathway known as "The Highway: Fossil-fueled development", or SSP5 for short (O'Neill et al., 2017). Over the history of the UNFCCC, political tensions with respect to action and knowledge production are particularly acute around mitigating emissions from the energy and other hard-to-abate sectors (e.g., cement and steel production, aviation). Products and services from such sectors (and therefore upstream and use-phase emissions) lie at the heart of most economic activities and are responsible for the largest share of global greenhouse gas emissions (Lamb et al., 2021). The fossil-fuel sector in particular is an incumbent and powerful agent in setting policy agendas; that slower decarbonization futures such as SSP5 were found to be capable of achieving 1.5 °C by 2100 with large-scale CDR was an example of honest brokerage in knowledge production to expand the menu of policy options.

2.3. Tensions in contemporary knowledge production around goals for "net-zero" emissions

From a global governance perspective, keeping as many actors as possible (including the incumbent fossil fuel sector) invested in the long-term goals of the Paris Agreement may help make climate change governable. However, there is a real concern that perceiving the SSP5 scenario as technically feasible introduces a moral hazard, which McLaren (2016) defines as "any situation in which one person makes the decision about how much risk to take, while someone else bears the cost if things go badly" (pp. 596-597). In this case, the decision about how much risk to accept is taken by current generations, while future generations bear the cost if technological CDR development and deployment don't go as anticipated.[2] The significant CDR interventions required to achieve 1.5 °C in SSP5 do not currently exist at the scale depicted as necessary. Of particular concern is that attention and resources directed to NETs in the present may have the effect of "mitigation deterrence", which is defined by Markussen et al. (2018) as the "prospect of reduced or delayed mitigation resulting from the introduction or consideration of another climate intervention" (p. 1). The real (and not merely opportunity) cost of delayed mitigation is an increased atmospheric concentration of greenhouse gases that will have to be removed later to achieve a lower temperature target by 2100.

The authors' particular interest in the politics of knowledge production around net-zero is inspired by advances in direct air capture (DAC), a technology for CDR. DAC removes CO_2 from the ambient air (independent of source and location), so it could be an important part of a NET portfolio (Breyer et al., 2019). CO_2 removed by DAC may be stored for long-term sequestration or utilized for various applications such as low/zero-carbon fuels, agriculture (e.g., algae cultivation), or as an input for materials in the construction sector (e.g., cement). However, DAC

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[2] Importantly, this is an anthropocentric view. Non-human species also bear the costs of climate change.

includes several energy-intensive steps (Erans et al., 2022). First, there are large-scale fans to draw in air, which is then directed through a contactor system containing materials that react with CO_2. Second, when the capturing capacity of the material is reached, CO_2 must be separated from the capturing material through different energy intensive methods such as heating, changing pressure, chemical reactions, or a combination. Finally, the separated CO_2 needs to be compressed for transportation, utilization, or storage. Widespread deployment of DAC would be a sector in and of itself, requiring careful consideration of the sector's energy requirements and, in turn, upstream environmental footprint (Madhu et al., 2021). Regions with abundant and inexpensive clean energy resources or wase heat (Fasihi et al., 2019) are most favourable for deploying DAC technology.

While energy requirements and cost are important factors influencing various aspects of DAC development and deployment, it is essential to acknowledge the deep uncertainty of the role of this technology in climate policy. DAC has been demonstrated but has limited deployment due to its energy requirements and high cost. A new DAC sector will introduce new interactions with adjacent socio-technical systems and the surrounding natural environment (Fuhrman et al., 2020). Near-term delays to mitigation put more of an onus on DAC to perform later in the century, and nontrivial uncertainties arise under long-term planning horizons (Marchau et al., 2019). Readers interested in a methodological advancement for policy analysis over a long time horizon under deep uncertainty called dynamic adaptive policy pathways (Haasnoot et al., 2013) should consult the Appendix for an introduction.

Two key questions for the current state of politics around knowledge production for net-zero emissions are taken up in this paper. First, what are the political (and we would argue, socio-technical) conditions that enable or constrain different approaches to how the Paris Agreement will be achieved? Second, what might the role of DAC be under the different approaches?

3. Theoretical framework for understanding the production and selection of net-zero policy analysis: The Multi-level Perspective (MLP) of socio-technical change

The policy analysis for net-zero goals has been predominantly quantitative. Van Beek et al. (2022) examined the highly influential role of IAM in developing the Paris Agreement through the concept of "techniques of futuring" (Hajer and Pelzer, 2018; Oomen et al., 2022). They examined the interplay between the unique capabilities of process-based IAMs to quantify systems analysis and the regular interactions between IPCC and UNFCC processes. Their analysis, however, privileges the role of the scientific community and analysts in contributing to governance of the climate crisis. We expand their analysis to explain how the systemic pressures of governance – namely the need to domesticate apparently insoluble problems to ensure their compatibility with the repertoire of instruments and actions available (broadly defined to include policy, legal, technological, and cultural instruments) – shape what futures are plausibly entertained and legitimizes governments to act. Geels' (2002) Multi-Level Perspective (MLP) of socio-technical change is a particularly apt theoretical framework for characterizing how socio-technical systems come to be arranged in particular ways as well as the political struggles to fashion the future of systems in starkly different terms.

The MLP explains socio-technical change (or alternatively, stability) with three constituent 'levels' wherein level-specific perturbations can act as system transition forces

(Figure 1). The landscape level includes factors exogenous to the socio-technical system such as geopolitical priorities, global economic conditions, and the physical constraints of the system's layout and function. The regime level is composed of the rules, actors, and norms that make up most of how the system operates. Geels (2002) further breaks down the regime level into seven distinct parts representing the dominant characteristics of society when in equilibrium: culture and symbolic meaning, industrial networks and strategic games, techno-scientific knowledge, sectoral policy, markets and user practices, technology, and infrastructure. The niche level encompasses novel technologies and practices, which result from constant experimentation. Over time, niche innovations may succeed or fail to gain traction, and niche technologies may have different effects on regimes. A successful niche might join the array of technologies already in the incumbent regime; alternatively, it may radically change the whole system if its success 'reshapes' an historical socio-technical regime. The concept of the alternative effects of niche innovations on regimes, rooted in evolutionary economics, explains how large-scale system change can result from singular technological breakthroughs. For example, the invention of the telephone (Boulding, 1991; Geels, 2006) changed the dominant means of communication (e.g., telegraph, letters, in-person meetings and sales), thereby updating previous habits and creating new infrastructure as well as cultural conceptions of time and space. Telephony also created entirely new markets and industrial networks. Once a technological innovation reconfigures a regime, policymakers develop specific policies to both regulate the technology in the regime and aid its further development. However, system change can also be initiated by landscape-level conditions or landscape shocks, such as natural disasters, war, or resource scarcity. Such changes at the landscape level may also create instability in the incumbent regime that may provide an opening for a useful niche to enter the regime and restabilize it.

4. Findings from an MLP of knowledge production for widespread direct air capture (DAC) deployment

Currently, DAC is a niche technology, and its research and development (R&D) will need to be supported to make it more affordable for widespread deployment if needed. If DAC is to become integrated into the socio-technical regime, societal norms will also have to shift, existing legislation may be adapted, and new policy incentives will be needed (Schenuit et al., 2021). As previously mentioned, changes at the landscape level exogenous to the incumbent regime may pressure it to reshape. Under the Paris Agreement, a landscape change is underway, where CO_2 emissions that were previously ignored are increasingly recognized as a pollutant that must be managed at the global level. This paper focuses on two strands of policy analysis that are relevant for informing how a new regime compatible with the Paris Agreement might stabilize: a regulatory analysis (in the Canadian context) and a review of findings from IAM studies that have projected global demand for DAC. Across both analyses, a fundamental tension for the future of DAC arises between changes at the landscape level (i.e., building a new global governance architecture that recognizes CO_2 as a pollutant that should be globally managed) and changes at the regime level (i.e., ensuring favourable regime conditions for DAC such that there is a market niche for it to occupy).

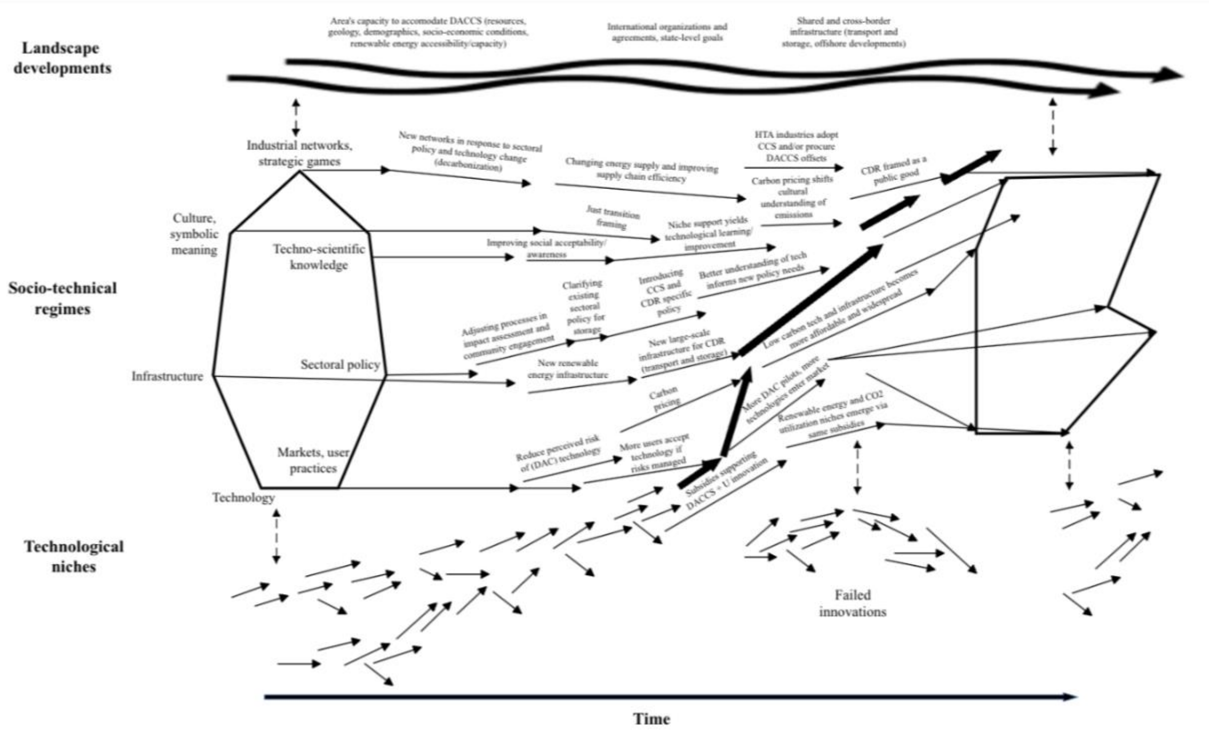

Figure 1. A Multi-level Perspective of direct air capture technology with carbon capture and sequestration (DACCS). Adapted from Cortinovis (in preparation).

4.1. Regulatory review of Canada’s nascent carbon management regime

The regulatory review focused on Canadian policies that could be adapted or are in development to establish market niches for DAC (and potentially for CO_2 utilization) and to support the nationwide deployment of CDR. Approximately 400 policies collected at the Canadian Climate Institute’s 440 Megatonnes climate mitigation policy database (Canadian Climate Institute, 2023) were reviewed, and approximately 100 policies were selected as relevant to establishing a Canadian DAC sub-system. It was found that the policies covered six thematic sections including policies supporting public acceptability and welfare (e.g., job reskilling programs, information campaigns), policy for financing innovation and scale-up (i.e., targeted subsidies and tax credit programs), climate mitigation policies (e.g., carbon pricing, technology standards, and goal setting), energy policy and local resource constraints (e.g., R&D for renewables, energy regulations), carbon transportation and storage regulations, and finally, regulations and policies specific to carbon capture and removal (i.e., policy plans that differentiate between the needs and outputs of NETs) (Cortinovis, in preparation). A subset of findings are summarized in Table 1.

It was found that the coverage of relevant existing and new Canadian policies are fairly comprehensive, mapping onto all levels and components of the MLP framework. However, two aspects are especially key for the future of DAC. First are issues of sectoral policy and use policies at the regime level. Capturing carbon from the atmosphere creates a need for storing said carbon elsewhere durably and safely; the imperative to store carbon, in turn, begets a need for a new legal framework to locate and secure appropriate capture and storage sites. In Canada, most of the policies for regulating things like carbon storage already exist in some capacity or exist in a relevantly similar policy context that can act as a guide for new regulations. This means that many existing policies applicable to sectors such as mining and fossil fuels could be adapted to fulfill DAC needs rather than crafting new policies from the ground up. Specific carbon storage policy, for example, already exists in some provinces (i.e., in Alberta and Saskatchewan, provinces with prominent fossil fuel economies that host several well-established projects for carbon capture and sequestration, or CCS). Similarly, the regulatory foundations for storing materials like natural gas; determining ownership of geological pore space, minerals, and sub-surface water; and deciding post-closure liability for well sites are all established in provincial laws. They will simply need to be clarified for CO_2 specifically (Craik et al., 2022). Second, decreased regulatory uncertainties at the regime level alone will not spur widespread deployment of DAC. Market signals instituted at the landscape level, such as a carbon pricing system, will incentivize capturing carbon or decarbonization. Canada has a Pan-Canadian Framework that ambitiously mandates carbon pricing nationwide (Environment and Climate Change Canada, 2016).

A fundamental tension for the future of DAC arises between these two aspects functioning at the regime and landscape levels. On the one hand, adaptations of existing policies in the fossil fuel sector (the incumbent energy regime) are favourable for DAC deployment. Focusing on these regime changes only, one might conclude that DAC could become a new feature in a refashioned low-carbon or net-zero fossil-fuel sector. On the other hand, landscape pressure from carbon pricing (and subsequent new dynamics at the regime level for the energy sector, with up-and-coming competitors from zero-carbon energy technologies) will affect other regime elements that might unseat the fossil-fuel incumbent. New dynamics are emerging already in energy markets, for example, with coal no longer being the cheapest fuel in mature markets such as the US. Such dynamics will also alter industrial networks and strategic games among firms in the energy sector. Such outcomes from landscape pressure might accelerate decarbonization, thereby decreasing the demand for DAC or making its development largely irrelevant. Explorations of these tensions have been taken up in global IAMs, which are discussed in the next section.

4.2. Review of integrated assessment modelling (IAM) for DAC

4.2.1. Limitations of IAM

The field of integrated assessment aims to build comprehensive and formal (i.e., mathematical) representations of multiple socio-ecological subsystems. The most mature global IAMs were developed to study climate change with the objective of informing policy decisions, advancing knowledge, and identifying crucial uncertainties (Parson et al., 1997). IAMs are computer simulations based on economic theory and engineering processes that attempt to portray the intricate interplay between socio-economic and natural systems (van Beek et al., 2020).

Our review of IAM projections (Motlaghzadeh et al., 2023) is on detailed process IAMs (Weyant, 2017) that produced global projections for the IPCC Sixth Assessment Report. Such IAMs represent the driving forces and mechanisms of global energy and land-use systems, which are most responsible for greenhouse gas pollution. Moreover, economic activities attributable to these sectors are closely intertwined with the broader economy (i.e., global markets that exchange *inter alia* energy commodities, energy services, food, wood products). Furthermore, process-based IAMs represent both biophysical and socioeconomic processes, reflecting human preferences to some extent (Wilson et al., 2021). In a discussion of the politics of knowledge production for climate policy, it is important to acknowledge the limitations of IAMs, which include:

1. Lack of transparency for characterizing epistemic uncertainty (due to modeling assumptions and choices) and related political and ethical implications (e.g., the social discount rate) (Beck and Krueger, 2016; Caney, 2014). In other words, value-laden assumptions or conditions in the modelling may be hidden (Schneider, 1997).
2. Insufficient consideration of issues of justice, equity and fairness (e.g., responsibility for historical emissions), and inappropriate acknowledgement of these issues in pathways modelled by IAMs for alternative futures (Muttitt and Kartha, 2020; Rubiano Rivadeneira and Carton, 2022)
3. Lack of realism, such as assuming decision-makers are rational (Keppo et al., 2021; McCollum et al., 2017); underrepresentation of heterogenous actors, institutions, and decision-makers who might play essential roles in the real-world implementation of modeled policies (De Cian et al., 2020). Similarly, the high level of aggregation in IAMs to the country or continental region level neglects micro-level processes happening in the real world (Rotmans and van Asselt, 2001) such as political disagreements, legal disputes, and delays in permitting and implementing infrastructural or land conversion projects.
4. Not being inclusive in their model or scenario development process, such as not including people from disciplines other than those familiar with computer programming, economics, and engineering processes. Moreover, most of the global models have been built by analysts in countries in the Global North, such as the REgional Model of Investment and Development or REMIND based in Germany (Luderer et al., 2022), the Global Change Analysis Model or GCAM based in the USA (Calvin et al., 2019), and the Asia-Pacific Integrated Model or AIM based in Japan (Nyairo et al., 2022). A regional distribution of modellers is shown in Figure 2 (Integrated Assessment Modeling Consortium, 2020).

Table 1. Selected Canadian policies supporting the development and deployment of direct air capture. Adapted from Cortinovis (in preparation).

Policy objectives	MLP mechanisms (relevant parts of the system are bolded)	Canadian policy examples
Carbon capture and removal technology and policy • Introduce CDR and CCS-specific regulations, development plans, and near-term incentives/R&D programs (and diversify investments in them) • Differentiate between types of CDR, NETs, and DAC to plan around their respective needs, limitations, potential, and impacts • Define the regime's model for DACCS policy (e.g. public utility/waste management model?)	• Introducing specific, **sectoral policy** for CCS and CDR may also send **market** signals and influence regime change by signalling which **technologies** the government plans to prioritize and deprioritize in the transition, as well as reducing regulatory uncertainties • Gathering **techno-scientific knowledge** to properly define the needs and impacts of CCS and different **niche** CDR technologies • Situating CDR as a public good shifts the **cultural and symbolic meaning** of the practice in climate action	• NRCan: Carbon Management Strategy (in development) • NRCan-Energy Innovation Program: Carbon capture, utilization and storage RD&D Call • Department of Finance: Investment tax credit for carbon capture, utilization, and storage

Carbon transport and storage (pore space) regulation:
Have a protocol or regulation in place to regulate permanent geological carbon storage, that differentiates between types of CO2 storage and their respective level of security and risks (particularly when issuing offset credits for storage)
• Clarify pore space ownership and establish liability (particularly in the case of new offshore developments)
• Have guidelines for siting CDR projects proximate to known, accessible storage space; make maps of existing storage publically accessible
• Design transport and storage infrastructure networks and repurpose existing infrastructure or shared infrastructure where possible
	• **Landscape** conditions, in part, determine where projects can be sited based on the geology of the region, though transport **infrastructure** would make more pore space available and therefore more sites (with renewables and other resources) eligible for hosting a DAC plant
	• Regulating pore space in Canada, thus far, has been a matter of clarifying how to apply regulations that already exist in oil and gas **sectoral policy**, particularly for natural gas injection and storage, EOR, mineral rights, and water ownership (for saline aquifer storage)
	• Whether pore space ownership (as well as post-closure liability) is private or Crown controlled will determine the kinds o**f industrial networks** that need to be established for firms to access pore space (for example, CCS for HTA industries)
	  • **User practices** are also variable because, with a lack of clear regulation and appropriate post-closure liability agreements, firms may not be as willing to initiate CCS and CDR projects in the region due to uncertainty/risk
		• Canadian Environmental Protection Act (CO2 and other GHGs designated 'toxic substances')
		• British Columbia: Carbon capture and storage regulatory framework
		  • British Columbia: Petroleum and Natural Gas Act: PETROLEUM AND NATURAL GAS STORAGE RESERVOIR REGULATION
		  • British Columbia: Energy Statutes Amendment Act
		• Alberta: Mines and Minerals Act
		  • Alberta: Carbon Sequestration Tenure Regulation
		  • Alberta: Technology Innovation and Emissions Reduction (TIER) Regulation
		  • Alberta: Alberta Emission Offset System (part of TIER; generates double credits)
		  • Alberta: Alberta Carbon Trunk Line, Quest, and the Alberta Carbon Grid
		• Saskatchewan: Oil and Gas Conservation Act, O-2
		• Department of Finance: Investment tax credit for carbon capture, utilization, and storage (only geological storage and concrete are 'eligible uses' because they are permanent)
		• NRCan cannot issue seabed CO2 injection licenses under the Federal Real Property and Federal Immovables Act, while ECCC cannot issue permits for seabed CO2 injection under CEPA (Webb & Gerrard 2021, iv)

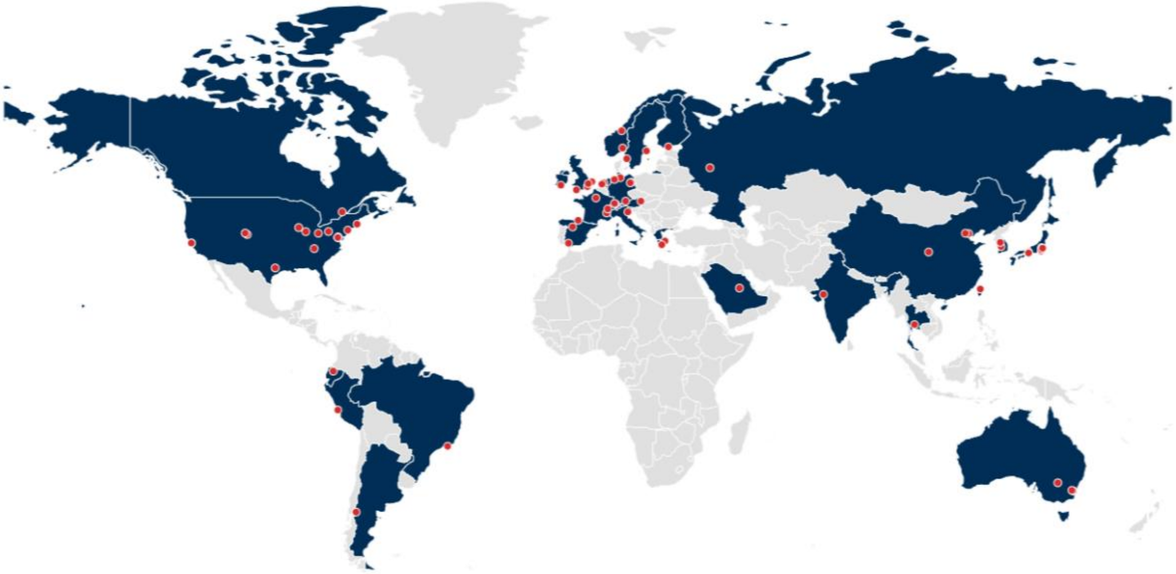

Figure 2. Members of the Integrated Assessment Modeling Consortium (Integrated Assessment Modeling Consortium, 2020)

Despite the aforementioned limitations, IAMs have played a pivotal role in transforming the seemingly insoluble climate change problem into actionable solutions as acknowledged previously (van Beek et al., 2020). This is because IAMs can explore and quantitatively illustrate alternative policy options that can achieve the same target (e.g., Paris Agreement goals). Such differences in alternative policy options and social priorities are referred to as ‘pathways’ and have significant implications for the necessity of CDR, particularly DAC, as a means of achieving net-zero emissions.

4.2.2. Findings from IAM studies projecting global demand for DAC

There is large variation in projections for global demand for DAC by 2100, so we conducted a review to determine the key sources of scientific uncertainty (Motlaghzadeh et al., 2023). We reviewed 700 IAM simulations from the IPCC Sixth Assessment Report database (Bray et al., 2022) along with a detailed analysis of 54 IAM scenarios published in peer-reviewed literature that modelled DAC.

In the IPCC database, we found that DAC was not widely modelled, appearing in only 27% of scenarios (i.e., 189 out of 700). When comparing scenarios that achieved Paris targets with DAC to those without, we observed that the latter group relied on other CDR methods to achieve net-negative emissions, namely bioenergy with carbon capture and storage (BECCS) and afforestation. However, the widespread implementation of such land-based CDR methods raises concerns about their sustainability implications. Issues related to negative impacts on water systems, competition for land resources, and a subsequent rise in food prices and poverty have been widely discussed in previous literature (Buck, 2019; Creutzig et al., 2021). A recommended sustainable threshold for land-based CDR is 5 $GtCO_2$/year (Fuss et al., 2018); however, we found that nearly 60% of IPCC database scenarios surpassed the recommended sustainable threshold for afforestation and reforestation, and 85% surpassed the threshold for BECCS. These findings emphasize the importance of considering a diverse range of CDR methods (Fuhrman et al., 2023) to find pathways to 1.5 °C by 2100 that are environmentally sustainable.

Focusing on IPCC database scenarios that modelled DAC, we conducted a statistical analysis to investigate the potential correlation between different variables, including the expansion of renewable energy sources, final energy demand, alternative pathways for fossil fuel deployment, and the necessity of net-negative emissions for meeting targets to limit global warming below 2 ^{o}C. We found that scenarios with high levels of CDR deployment often correspond to scenarios where reductions in fossil fuel deployment are relatively lower, i.e., slow decarbonization scenarios.

A key question becomes what is happening in such slow decarbonization scenarios. One of the crucial factors influencing the deployment of DAC and other CDR is a landscape-level issue, the timing and level of mitigation ambition modelled by different scenarios. Such decisions reflect assumptions about intergenerational impacts and determine the acceptability of temporarily overshooting temperature targets for the year 2100 (Geden and Löschel, 2017), which in turn affects the demand for DAC deployment. The application of a social (intergenerational) discount rate (SDR) is a standard practice in economics to calculate the net present values of near-term policy actions (Caney, 2014). Whether SDR values are higher or lower plays a critical role in determining the extent of deployment for DACCS and other CDR. Higher SDRs are typical for decision making in the private sector, which more steeply discounts the present value of impacts in the future, such as on future generations. Higher SDRs result in lower investments in near-term emissions reduction and rely on higher levels of CDR later. Studies of variations in SDR values have been found to affect CO_2 emissions, mitigation investments, renewables deployment, energy demand reduction, and the share of fossil fuels. For instance, Grant et al. (2021) found that doubling the SDR from 1% to 5% approximately doubles the DACCS deployment in 2100 for both 1.75°C and 2°C scenarios.

Moreover, the concept of overshoot, where global average temperature surpasses the 1.5 °C threshold temporarily before the end of the century, poses risks of triggering tipping points and irreversible climate impacts. To minimize such risks, it is advisable to limit the magnitude and duration of overshoot; similarly, it is advisable to hew to a lower temperature target rather than relax it to 2 °C. Some studies showed that restricting overshoot leads to reduced cumulative DAC deployment by around 30% to 40%, as emissions are reduced sooner (Fuhrman et al., 2020). Alternatively, raising the temperature target from 1.5 °C to 2 °C decreases the cumulative DACCS deployment in many scenarios due to the higher carbon budget (i.e., allowable emissions) over the century and less need for CDR to compensate (Fuhrman et al., 2021; Grant et al., 2021).

Another crucial factor is a regime-level issue, the cost of DAC, which varies significantly in techno-economic analyses and commercial projects, making it challenging to reach a consensus on its likely costs. The evolution of DAC costs over time is influenced by socio-economic, technological, and political factors, as well as DAC deployment itself. IAM studies have differentiated between initial costs and floor costs, with the latter representing the minimum cost achievable with learning rates. Predicting the learning rate for DAC is highly uncertain, and different studies have used conservative and baseline estimates based on literature and similar technologies. Sensitivity analyses have been conducted to examine the impacts of cost variations on DAC deployment. Fuhrman et al. (2020) found that decreasing unit costs from \$300/tCO2 to \$180/tCO2 resulted in increased cumulative DAC deployment in different scenarios. Realmonte et al. (2019) also observed an increase in deployment when the initial cost of DAC changed. The different model assumptions and limits set on DAC deployment might explain the variations in sensitivity between the studies. Finally, the availability of other CDR technologies that are cheaper, namely BECCS and enhanced weathering, may decrease the demand for DAC.

5. Discussion: Mitigation deterrence as the site of contemporary politics around knowledge production for net-zero goals

As mentioned previously, the authors' particular interest in the politics of knowledge production around net-zero is inspired by advances in DAC. However, the MLP dynamics and key scientific uncertainties specific to widespread deployment of DAC are not unique and apply to all NETs; indeed, it extends to the overall vision of goals for "net-zero" emissions (in contrast to the goal of ambitious decarbonization). In this section, we return to the state of knowledge production for governing mitigation of emissions causing the climate crisis. The simulation of alternative policy pathways to Paris goals have recruited different problem owners, creating different coalitions with different interests advancing different climate policy proposals.

In the Background section, an SSP5 pathway with high reliance on technological and nature-based CDR was introduced. Another pathway to Paris goals is more intuitive, one called the Low Energy Demand (LED) pathway. Some key contrasts in the LED and SSP5 pathways in the IPCC SR1.5 are summarized below in Table 2.

Table 2. Key differences in selected pathways to 1.5 °C featured in the IPCC SR1.5

LED illustrative pathway	SSP5 illustrative pathway
• Social, business, tech innovations result in lower energy and resource demand	• Resource and energy-intensive lifestyles become widespread globally, e.g., high demand for transportation fuels (multiple passenger vehicles per household powered with fossil fuels, aviation), livestock products
• Downsized energy system	• Larger energy system
• Rapid decarbonization	• Slower decarbonization
• CDR option: afforestation only	• CDR options include afforestation, fossil fuels with CCS, BECCS
• Cumulative CCS is 0 $GtCO_2$	• Cumulative CCS is 1218 $GtCO_2$
• No or limited overshoot	• Higher overshoot

Importantly, both illustrative pathways achieve a rise in living standards for all countries, although economic growth for the Global North is slower on the LED pathway compared to SSP5. Qualitatively, the alternative futures are very different, giving rise to different conceptions of who the problem owners for emissions mitigation should be, and in turn, different coalitions with different interests. The LED pathway envisions **consumers** as problem owners, where decreased or more efficient consumption shrinks demand for energy and resources produced. In turn, lower energy and resource demands are easier to meet with renewable technologies, thereby making rapid decarbonization more feasible. In contrast, the SSP5 pathway envisions **producers** as problem owners, where they must meet high consumer demand while also engineering ways to divert or remove CO2 emissions from the atmosphere. Energy- and resource-intensive lifestyles are more readily supported through continued fossil-fuel use, as such fuels are more energy dense than renewables. Coalitions who respectively support these opposing pathways have different interests in what landscape changes should be set as global targets with concomitant implications for regime changes that will also affect DAC development.

Advocates of the LED pathway (LED coalition) see the landscape goal of limiting overshoot above 1.5 °C as ideal. The intergenerational values of this coalition are reflected in IAM simulations with a low SDR, which result in the lowest emissions profiles overall (i.e., high mitigation reductions) thereby decreasing cumulative demand for CDR technologies like DAC. Furthermore, regime-level implications of priorities of the LED coalition are twofold. First, the current energy regime should be rapidly replaced with clean, zero-carbon technologies. Second, such a transformation would mean that DAC development may be delayed until there is demand for such technology, such as under a policy agenda of accelerated climate restoration (Lempert et al., 2018).

Advocates of the SSP5 pathway (SSP5 coalition) see maintaining the stability of national economies (and the global economic system by extension) as optimal. A primary concern for this coalition is “transition risk”, a scenario where rapid emissions reductions destabilize labour pools, energy markets, and potentially economies (e.g., increased fossil fuel prices raise the prices of other goods; expensive fossil fuel infrastructures become stranded assets much earlier than anticipated because they become too costly to operate). The SSP5 coalition – which includes actors comprising the incumbent energy regime – is often tarred as being in opposition to climate action, but the SSP5 pathway demonstrates how the global target of 1.5 °C might still be achieved with slower decarbonization than the LED pathway. However, slower decarbonization opens the door to mitigation deterrence, with policy outcomes such as higher or longer overshoot above 1.5 °C. As discussed above, IAMs have confirmed that this would increase cumulative global demand for DAC. Another landscape-level possibility is that the Paris target adjusts to the higher temperature target of 2.0 °C, perhaps as a result of political pressure due to perceived transition risk. Should climate impacts under this higher level of climate change be deemed tolerable, IAMs have found that the cumulative demand for DAC may decrease, as a higher temperature target raises the ceiling of allowable CO_2 emissions, and subsequent CO_2 drawdowns may not be needed.

The regime-level implications of the SSP5 pathway are, first, that the energy and industrial sectors will remain carbon-intensive longer, as fossil fuels and carbon-intensive feedstocks are phased out more slowly compared to the LED pathway. Second, IAMs have shown that such a scenario increases cumulative demand for DAC by the end of the century, so early investments in DAC technology will be important for this pathway. However, the possibility that things might turn out badly -- i.e., that cost reductions for DAC turn out to be very slow, making it a persistently expensive technology -- introduces the risk of moral hazard. Although managing the risk of moral hazard from mitigation deterrence is an important consideration for crafting policies related to CCS and CDR, it should not be treated as inevitable but rather something that can be regulated around as discussed further in the next section.

5.1. Revisiting concerns of moral hazard, carbon lock-in, and the need to clarify the definition of mitigation

As introduced previously in the Background section, moral hazard refers to the concern that incumbent industries, in advocating for a slow decarbonization pathway, ‘place bets’ (Fuss et al., 2014) on the future performance of CDR, which is not guaranteed. A slow decarbonization pathway is an example of what systems and transition literatures call *lock-in*. More specifically, “carbon lock-in” describes how the dominant regime reinforces itself to the detriment of global climate goals, since the status quo regime has long been reliant on fossil-fuel-intensive production and consumption. The immense capital investments (i.e., financial, economic, and human) sunk into fossil-fuel-intensive infrastructure has created path dependencies that are perpetuated by the market and reinforced through exercises of political power. Even when efficient and sustainable energy innovations become available, they are costly compared to the incumbent technologies, which are effectively subsidized by the physical and institutional infrastructure and competencies that make them cheaper and easy to use (Unruh, 2000).

Arguably, a technology like CCS that would be part of a DAC subsystem is predicated on CO_2 emissions. Indeed, a pragmatic approach to policy analysis to domesticate the climate crisis such that mitigation actions are compatible with the repertoire of available policy or technological instruments and actions may be criticized as necessarily incremental. Such incrementalism may also be subject to ‘regulatory capture’ by the incumbent carbon-intensive regime. If expectations remain low for industrial and energy-sector processes to be less carbon-intensive, CDR as a policy option can worsen lock-in. If producers merely capture CO_2 emissions instead of seeking alternative energy and resource inputs to decarbonize production, then the economy will never fully decarbonize. Such a criticism has been levelled at DAC, with some arguing that it will be used by fossil-fuel-reliant industries to justify continued CO_2 emissions and fossil fuel extraction. If polluters merely pay to offset the emissions they create, offsets will have a net neutral impact on the stock of atmospheric carbon (Asayama, 2021), which is already 39% higher than pre-industrial times (Lindsey, 2023).

Although managing the risk of mitigation deterrence is an important consideration for crafting policies related to CCS and CDR, it should not be treated as inevitable but rather something that can be regulated around. IPCC Working Group III, which focuses on mitigation, defines it as human interventions that reduce greenhouse gas emissions or enhance sinks of greenhouse gases, i.e., processes, activities, or mechanisms that remove a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere (IPCC, 2022). Under this definition, avoiding and reducing the flow of CO_2 and other greenhouse gas emissions is the chief means of mitigation. However, removing some of the stock of carbon already in the atmosphere is another means of climate mitigation, particularly because CO_2 can remain in the atmosphere and contribute to planetary warming for hundreds of years (Friedlingstein et al., 2014). States have established emission reduction goals at the core of their climate policies and constructed policy and methodologies for carbon accounting accordingly; these ensure uniformity in emissions reporting and accuracy in calculating how many tonnes of additional greenhouse gas emissions would be allowable.

As new technologies like DAC become available, policymakers should specify whether CO_2 *removal* targets should be separate from emissions *reduction* targets (McLaren et al., 2019). In other words, though removals contribute to climate mitigation as currently defined, determining whether removals should count toward mitigation is complicated because atmospheric concentrations alone do not reflect the actual state of decarbonization in the country and across the world. Removals that take place while emissions have not yet reached net-zero levels are not true removals because they do not result in net-negative emissions, i.e., a reduction in the stock of atmospheric carbon. However, so long as removals are conflated with reductions, states may treat removals as such despite still emitting much more than they have the capacity to remove, thereby resulting in a net-increase in atmospheric carbon regardless. Equating removals with reductions also suggests that the role they play in climate crisis management is the same, which is not true; we will never reach net-zero without reducing emissions. Setting a clear distinction between reductions and removals will make clear that the two are not fungible, ideally helping to avoid mitigation deterrence from CDR efforts.

5.2. The continuing relevance of DAC for climate restoration and, potentially, socioeconomic equity

Continued knowledge production around DAC holds significant potential for redefining possible net-negative emissions futures and legitimizing government actions. As we confront the climate crisis and acknowledge the inadequacy of current climate mitigation measures, it becomes increasingly clear that climate restoration should be our next objective (Friedmann, 2019), considering it as an intergenerational issue. DAC can play a crucial role in this endeavour by establishing itself as a new sector working to reduce CO_2 concentrations and achieve tolerable levels of global warming.

Additional capabilities of DAC are that it removes CO_2 emissions regardless of source, which includes not only anthropogenic emissions but also unavoidable emissions resulting from from climate impacts such as ecosystem degradation or forest fires. As long as permanent geological storage remains the primary method for CO_2 disposal with DAC, rather than utilizing it for enhanced oil recovery as in traditional CCS, DAC proves valuable for achieving near-term mitigation goals and long-term net-negative removals.

Given the concerns around mitigation deterrence, it is important to view DAC not as a competitor to existing low-carbon technologies in the socio-technical transition, but rather as a group of technologies that rely upon low-carbon infrastructure, such as renewables (Sovacool et al., 2022). DAC addresses the need for climate mitigation solutions by offsetting excess emissions and unambiguously accounting for CO_2 removals compared to other CDR approaches such as afforestation and reforestation. By recognizing this perspective, DAC supports the deployment of renewables and zero-carbon energy sources, creating an environment where both clean energy and DAC can coevolve.

To ensure the expansion of DAC beyond pilot facilities and research projects, it is crucial to establish a protected niche market that enables these technologies to reduce their capital and operating costs. Given the limited co-benefits of DAC beyond CDR and the current minimal demand for CO_2 in utilization markets (Nemet et al., 2018), near-term government support for early-stage DAC becomes imperative.

Finally, early-stage DAC technology can provide several benefits to communities willing to host it including in Canada. Benefits include energy-secure infrastructure and investments in local training to establish a pipeline for a specialized local workforce in DAC. Currently, the United States is witnessing the emergence of redefined futures centered around DAC hubs, where climate justice principles and local-level socioeconomic benefits anchor investments in novel net-negative infrastructure (Scott-Buechler et al., 2023). Similarly, DAC may be a vehicle to engage developing economies in a net-negative future. For example, in many parts of Africa, the development of an electricity grid requires the involvement of large energy users like manufacturing (Sengupta, 2023). Potentially, in such contexts, maturing DAC sectors could provide an international development opportunity that improves socioeconomic equity between countries.

6. Conclusion

Since its conceptualization by Svante Arrhenius in 1896, anthropogenic global warming has mutated and transformed from a theoretical possibility that might protect humanity from the existential threat of the next ice age to a multi-faceted international quandary regularly assessed by the IPCC. Policymakers seek guidance from scientific assessment and policy analysis to set global and national goals for how quickly greenhouse gas polluting sectors should decarbonize. After a period of direct political interference in knowledge production around the climate crisis (i.e., climate skepticism largely bankrolled by the fossil fuel sector), global climate governance has turned a corner with the Paris Agreement and the IPCC Special Report on Global Warming of 1.5 °C. In the report, the IPCC showed that slow decarbonization scenarios could also achieve 1.5 °C by 2100. However, in order to do so, unprecedented amounts of atmospheric CO_2 would need to be removed later in the century, and in the meantime, the 1.5 °C target is likely to be temporarily exceeded (so-called “overshoot” of the end-of-century target). These findings have caught the interest of governments in “net-zero” emissions goals, which depend upon deployments of carbon dioxide removal (CDR) and negative emissions technologies. Critics of net-zero fear that it is a form of mitigation deterrence with the risk of moral hazard.

To unpack the interests of differing coalitions with respect to net-zero, we applied Geels’ Multi-level Perspective (MLP) to a regulatory analysis of 100 Canadian policies relevant to direct air capture (DAC), a technological approach to CDR. The MLP was also applied to a review of 700 integrated assessment modelling scenarios. Across both analyses, fundamental tensions related to landscape- and regime-level dynamics raise questions for the future demand and deployment of DAC. The landscape level uncertainty pertains to how the Paris Agreement will be interpreted. If interpreted ambitiously (i.e., 1.5 °C by 2100 with virtually no overshoot), DAC development may be paused or the technology may become irrelevant. However, if Paris targets are interpreted less ambitiously (i.e., 1.5 °C by 2100 with higher overshoot), significant DAC development this century is likely a necessity. Regime-level uncertainties for widespread DAC deployment pertain to whether it will become an affordable CDR option as well as whether regulatory or market incentives to support deployment will be put in place. With these uncertainties in mind, we revisited the concerns of moral hazard under mitigation deterrence. Moral hazard may be avoided if the definition of mitigation is clarified to separate emissions reductions from CO_2 removals. Setting a clear distinction between the two will make clear to regime-level actors that the they are not fungible.

Importantly, continued knowledge production around DAC holds significant potential for redefining possible net-negative emissions futures and legitimizing government actions. DAC has additional benefits compared to other CDR methods that include serving as a means for climate restoration, removing unavoidable emissions from climate impacts such as ecosystem degradation or forest fires, and providing incentives for expanding investments in low-carbon energy infrastructure. The latter benefit may also support investments in energy security and workforce training that could improve socioeconomic equity within and between countries. The relationship of DAC to clean energy sources demonstrates the distinctiveness of DAC from related technologies associated with the fossil-fuel sector (i.e., carbon capture and sequestration). Thus it is a mistake to presume that investments in DAC necessarily increase the risk of moral hazard. At this early stage in DAC technological development with no market incentives, costs for DAC will only come down through continued learning by doing (i.e., demonstration projects) sponsored significantly by government investments.

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8. Appendix: The methodological innovation of dynamic adaptive policy pathways for DAC development and deployment

As mentioned at the close of Section 2.3 (Tensions in contemporary knowledge production around goals for “net-zero” emissions), nontrivial uncertainties arise under planning horizons that reflect the long term (Marchau et al., 2019). Here we provide an overview of a methodological innovation for policy analysis over a long time horizon under deep uncertainty called dynamic adaptive policy pathways, or DAPP (Haasnoot et al., 2013). In our ongoing research project, we will develop DAPP for DAC development and deployment in a Canadian context to inform the achievement of national net-zero goals by 2050.

DAPP makes use of the same decision-relevant information that is customary in policy analysis. Its main innovations are how it organizes and displays the information for sequential decisions over time (summarized in Figure A-1) as well as the process by which decision-makers engage with the DAPP. The prevailing analogy and visualization tool is that of a transit map, helping decision-makers better understand the link between early decisions and future options by focusing on the sequential nature of decisions and their respective dependencies as well as opportunity costs. When developing and assessing policy strategies, decision-makers consult the DAPP visualization along with scorecards that summarize the costs and benefits of different pathways (or ‘itineraries’) through the DAPP map. Deltares explains how to read Figure A-1 as follows.

> In the map, starting from the [current] situation, targets begin to be missed after four years, signaling an “adaptation tipping point”. Following the grey lines of the current plan, one can see that there are four options. Actions A and D should be able to achieve the targets for the next 100 years in all scenarios. If Action B is chosen, a tipping point is reached within about five more years; a shift to one of the other three actions (A, C, or D) will then be needed to achieve the targets. If Action C is chosen after the first four years, a shift to Action A, B, or D will be needed after approximately 85 years in the worst-case scenario (follow the solid green lines). In all other scenarios, the targets will be achieved for the next 100 years …. The colors in the scorecard refer to the actions: A (red), B (orange), C (green), and D (blue). The point at which the paths start to diverge can be considered as a decision point. Taking into account a lead time (e.g., for implementation of actions), the decision point lies before an adaptation tipping point (Deltares, n.d.).

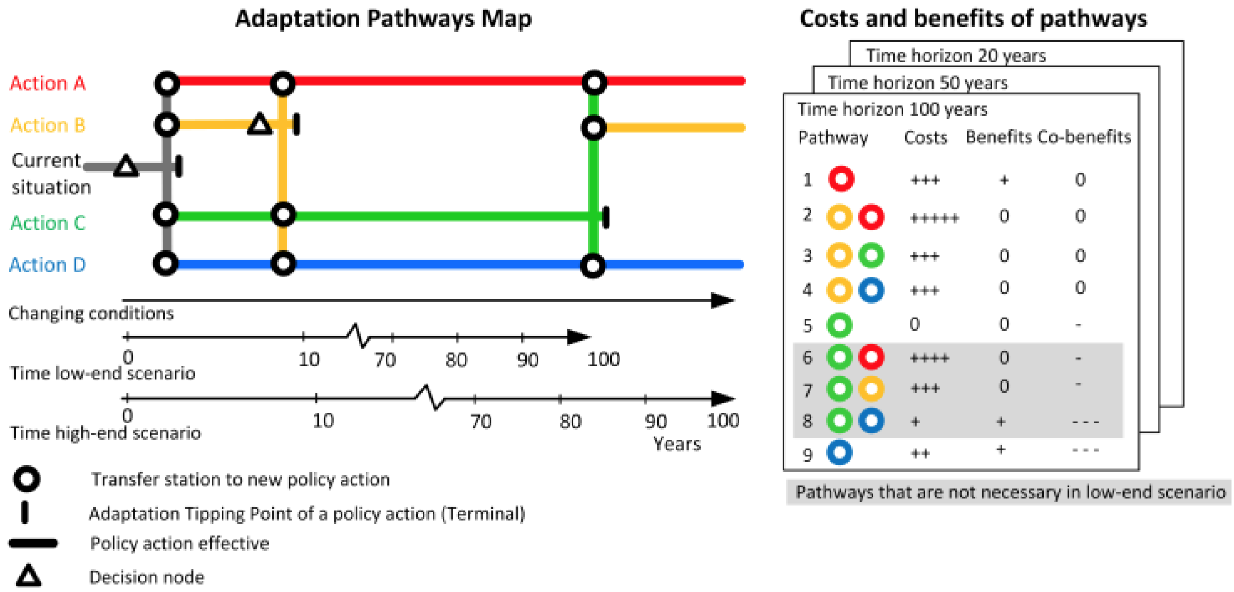

Figure A-1. Illustrative example of dynamic adaptive policy pathways. LEFT: An adaptation pathways map; RIGHT: scorecards that summarize the costs and benefits of different pathways (or 'itineraries') through the map. Image courtesy Deltares (n.d.).

Our project will develop the DAPP for DAC in Canada in pieces by depicting key uncertainties affecting DAC development and deployment as follows (see Figure A-2).

- Elements of scenario uncertainty. We will consider best, worst, and middle-of-the-road cases for:
  - Global climate policy targets relevant for CDR demand
  - Maturity of intermediate carbon capture technologies (i.e., costs of CCS; carbon capture and utilization, or CCU)
  - Financial or regulatory incentives/barriers (as appropriate, at the national or provincial level)
  - Rate of decarbonization internationally
- Elements of options in the Canadian context. As Canada is a confederation, it should be noted that provinces have a high level of political autonomy.
  - Locations of pore space (for CCS)
  - Locations of carbon utilizers (for CCU)
  - Energy infrastructure/capacity at locations
  - Potential future demand for energy infrastructure, e.g., to address equity issues of energy access, economic development
  - DAC technology: low-temperature DAC, high-temperature DAC
  - Siting processes at locations
  - Financial or regulatory incentives/barriers at locations
  - Opportunity costs of individual options

- Pathways mapping. To build the map, we will focus on dependencies between outcomes that must be achieved in the near- or mid-term to hit targets for DAC deployment later in the century and vice versa. We will consider questions such as what near-term actions
    - Have dependencies on future developments?
    - Keep more options open for future actions?
    - Delay access to alternative actions?
    - In what ways might scenario uncertainty alter the pathway map?
- Cost-benefit quantification of alternative pathways, or policy strategies. The questions below will help us develop scorecards (Figure A-1); however, decisionmakers might also have such questions in mind when utilizing the DAPP for decision support.
    - Is there an optimal pathway for DAC development and deployment in Canada?
    - What are the costs of switching between options?
    - What, if any, benefits/co-benefits might come from more flexible strategy?
    - Are particular pathways more robust to scenario uncertainty?

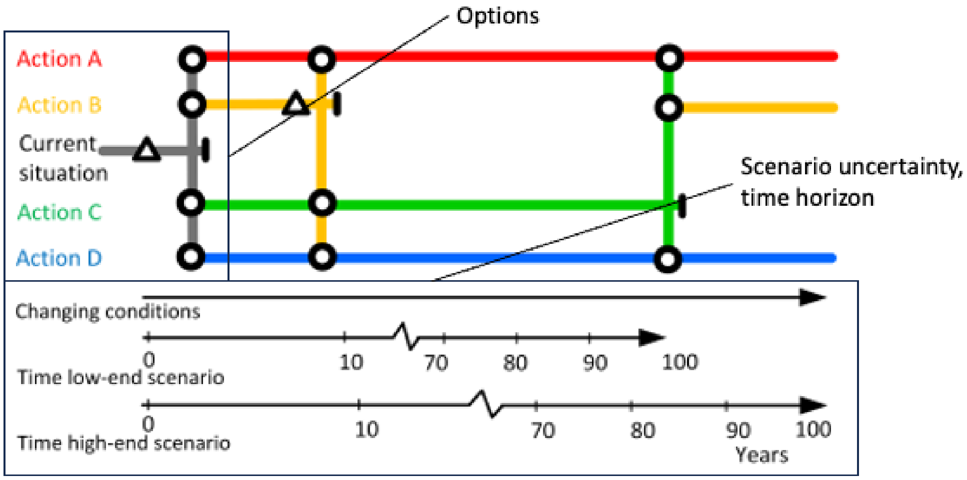

Figure A-2. Illustrative example of DAPP map with pieces sectioned off.

The benefit of the DAPP approach compared to traditional policy analysis is that more information is provided about contingencies over a longer planning horizon. The decision maker is also better empowered to exercise anticipatory governance through monitoring scenario conditions over the full time horizon. If shifts in scenario uncertainty are detected, the decisionmaker will have an idea of what alternative options will be feasible to switch to and may be more appropriate to adopt.